PROMOTION APPLICTION FOR DR. DAVID GARRISON

TO THE RANK OF FULL PROFESSOR OF PHYSICS

SUBMITTED 2017

PROMOTION FOR DR. DAVID GARRISON

4.11. 2012 Annual Report
4.12. 2013 Annual Report
4.13. 2014 Annual Report
4.14. 2015 Annual Report
4.15. 2016 Annual Report

5. **CORRESPONDENCE: 3RD YEAR REVIEW**
6. **CORRESPONDENCE: TENURE REVIEW**
7. **CORRESPONDENCE: PROMOTION TO FULL PROFESSOR**
8. **Publications**
9. **Letters**

1. STATEMENT

My career in Physics began in 1993 at the Massachusetts Institute of Technology. I was fortunate to be advised and mentored by three Nobel Prize winners: Phillip Sharp (1993 Biology), Clifford Shull (1994 Physics) and Wolfgang Ketterle (2001 Physics). During my time at MIT, I participated in several research projects in many different aspects of physics research. I worked with several professors including: Prof's David Pritchard, John King, Clifford Will, Michael Ogilvie and Jacqueline Hewitt.

After MIT, I attended graduate school at The Pennsylvania State University where I worked with Dr.'s Jorge Pullin and Pablo Laguna in The Center for Gravitational Physics and Geometry. While there, I also had the privilege to work with several distinguished researchers (such as Prof's Gabriella Gonzalez and Lee Samuel Finn) on a variety of projects. My primary work was in the area of numerical relativity, a field that combines computational physics with Einstein's general theory of relativity in order to simulate astrophysical events.

I was originally hired as a Visiting Assistant Professor at the University of Houston Clear Lake (UHCL), in the fall of 2002. During the negotiation of my contract with UHCL, I was told that my position would be reviewed during the first year and that a tenure-track position may become available. I was given the option to apply the visiting year toward my probationary period if the position became tenure-track.

After joining the faculty of UHCL, I was led to believe that the Physical Sciences program was unfocused and lacking in students who were qualified to assist in research efforts such as mine. I was also led to believe that the university wanted to rebuild not only the Physical Sciences program but also establish a Physics program. Because of this, I have devoted a large amount of my time to date developing both programs' curricula and infrastructures so that these issues could be resolved. My mission was to give students a solid foundation in physics and to increase the enrollment of the program.

In the spring of 2003, changing my position to tenure-track became a high priority within the school; however, a statewide hiring freeze made this impossible for several months. During the summer of 2003, the hiring freeze was lifted and my position was converted to tenure-track assistant professor. I received one year of credit as promised by the administration.

In the Spring of 2008, I was promoted to Associate Professor with Tenure. Since then, I have continued to develop as an instructor and researcher while working in service to my program, the university and our community. My efforts have resulted in a complete Physics program, which now offers a Bachelors, Masters and Collaborative PhD in Physics. I have also served in several leadership positions in the school and university including the SCE Dean search committee, the UHCL Presidential search committee and the Faculty Senate as President.

This report will detail my efforts to establish a physics program while developing my research program. These two programs were designed to meet the needs of the local community and involve students in cutting-edge physics research. In the process of building these programs, I have committed myself to excellence in teaching, research and service. I feel that these areas are all part of any successful career in physics.

I believe that excellence in teaching must involve not only solid teaching evaluations, but also a strong record of individualized instruction and curriculum/program development.

Within a few weeks of coming to UHCL, I began work on developing a Physics program, which has been one of the most successful in the state of Texas. The idea was to develop a degree plan that prepares students for work in Physics research, while maintaining the Physical Science program's support of Space Science. This was made possible by a web-based survey program, which I developed and sent out to the local community using an email distribution list of interested parties. The data that was collected from the surveys was used to justify the formation of a new masters degree in physics in 2004. The new Physics Program not only prepares students to do physics research, it also prepares them for PhD work in Physics and Astronomy while enhancing the skills of practicing engineers.

The biggest difference between the Physics program I developed and the old Physical Sciences program is the requirement that all students complete a set of core physics courses and do an independent research project before graduating. Because of these requirements, not only are all students in the new program qualified to participate in research, they are also required to have this experience. In the physics community, research experiences are an invaluable part of the educational process.

This Physics Program requires that the other faculty and I developed several new undergraduate and graduate courses. I developed the following courses:

- Mathematical Methods in Physics 1 and 2 (Including an Online version of Mathematical Methods in Physics 1)
- Methods in Computational Physics
- Classical Mechanics
- Electrodynamics 1 and 2
- Fundamentals of Space-time
- Using Mathematica to Solve Physics Problems
- Research Seminar
- General Relativity

I also facilitated the development of:

- Laboratory for Modern Astronomy
- Graduate Astronomy
- Modern Physics
- Quantum Mechanics 1 and 2
- Statistical Mechanics

- Plasma Physics
- Mathematical Methods for Physics and Engineering 1 and 2
- Thermodynamics and Statistical Mechanics
- Mechanics of Materials
- Fluids and Heat Transfer

In addition to developing this program, I also devoted a significant amount of effort in promoting it. I attended several academic fairs, hosted public talks on campus and developed new ways to promote the program through posters, fliers, websites and articles. In order to serve the local community better, I conducted an electronic survey about once every two years (2002, 2003, 2004, 2006 and 2009). The first two surveys lead to the approval of the Physics Master's Degree. The third, in 2004, helped me establish the Professional Physics Sub-Plan in Technical Management. The 2006 survey, led to the development of a Collaborative PhD Physics Program with the University of Houston Central Campus (UH) and later the BS in Physics. In 2010, we discontinued the general needs assessment surveys and started a Physics Advisory Board. The board's advise lead to the development of our Engineering Physics sub-plan. In 2012, I developed a proposal for planning authority to convert our Collaborative Physics PhD program into a full Joint PhD program. The data supporting this proposal came from a 2012 survey of UHCL Physics alumni, current graduate students and potential graduate students. These developments were only possible because of the success of the Physics Master's degree program.

In 2004, I developed a strategic plan for the development of the Physics program as part of our biennial planning process. Aspects of the plan include the development of the Professional Physics MS, for training technical managers; developing the steps to web-enhance the core physics courses in order to make them more accessible to our students; a plan to develop more undergraduate leveling courses; and the development of a Physics PhD, which could be implemented on our campus. Although many people thought this plan was overly ambitious, every element of this plan was accomplished before I was granted tenure in 2008. In 2013, I performed a thorough strategic analysis of the physics program including an Environmental Analysis, 5 Forces Analysis and Core Capabilities Analysis. I found that the program should focus on countering misperceptions about the difficultly of introductory level physics courses and lack of physics career options by utilizing the latest Physics Education Research (PER) and working harder with our career services office to get our students professional employment. In 2014, the AIP officially recognized our Masters program as the 7th out of 25 highest producing Masters-level Physics Departments in the US for years 2010, 2011 and 2012.

In the classroom, I was one of the first physicists anywhere to utilize lecture capture technology in an advanced physics class. I began doing this in the Spring of 2011 when one of my students broke his jaw and had to miss several classes throughout the semester. Despite that being an extremely difficult class (Jackson Electrodynamics) the student was able to pass because of the recorded sessions. I now use this technology for almost all my classes. I've improved on my technique and now use a graphics tablet, portable USB microphone and Blackboard Collaborate to capture my lectures in any standard UHCL classroom. Using a combination of screen capture and Blackboard Collaborate's whiteboard along with my audio recordings, students and watch my recorded lectures and receive almost the same experience as attending class. Students seem to like this because even students who don't miss class can rewatch parts of the lectures until they get the material. Even with this technology, students still prefer to attend class although some have logged in remotely into the live class. In Fall 2016, I used this technology to "flip" an advanced physics class (our Graduate Mathematical Methods in Physics). In Fall 2017, I plan to teach a section an online section of this class, something that is generally unheard of for such advance material. The online course passed UHCL's quality assurance review in Spring 2017.

Excellence in research is the result of being an independent researcher capable to training students to participate in original research projects.

Although the pool of qualified physics research students was small before I came to UHCL, I stayed active in research through collaborative work with Penn State and developed a collaborative research effort with NASA/JSC's Advanced Space Propulsion Laboratory (ASPL). Since coming to UHCL, I produced 11 publications in peer-reviewed journals and conference proceedings and 2 books. I gave over 20 invited talks and several submitted talks. In November of 2002, I was awarded an FRSF grant to begin my research at UHCL. In 2003, I traveled to Brazil to give two talks at the Tenth Marcel Grossman meeting on Gravitational Physics. In 2004, I received both an ISSO postdoctoral grant and an ASEE-NASA summer faculty fellowship to develop my research with ASPL. Unfortunately, we were unable to identify and hire an appropriate postdoctoral associate. In 2005, I won the CGS/Sloan Professional Science Master's Degree Implementation Grant. In 2008, I appeared on an episode of "The Universe" on the History Channel. In 2009, I went on a faculty development leave to work on my GRMHD code. In 2010, I was the PI on a $10 million dollar FAA proposal. By 2011, I was sitting on two Physics PhD committees as part of our Collaborative PhD proposal and was chair of one of the committees. Also, in late 2011, I developed a successful research collaboration with Haverford College and Princeton University to develop the first computer simulation of early universe inflation without the use of a scalar field. In 2012, I was interviewed for the HistoryMakers oral history project, ScienceMakers. In 2013, I was Co-I on a successful $592,468 NSF S-STEM grant proposal. Over the years, I have built an international reputation for my studies of relativistic magnetohydrodynamic turbulence and cosmological gravitational radiation.

Since coming to UHCL, I have worked with several different computational and theoretical research projects that were not related to my previous work at Penn State. Between 2002 and 2005, I worked with the JSC Advanced Space Propulsion Lab on a computer code to simulate the flow of plasma through the VASIMR engine. In 2004, I also worked on theoretical research involving a modified theory of Special Relativity. However, the majority of my research effort since coming to UHCL has been devoted to the study of numerical cosmology. After talking to Dr. Shebalin from JSC, about his research, and reading several papers by the numerical relativity group at the University of Illinois, I began to study the interaction between the primordial relativistic plasma and gravitational waves. I realized that this has never been studied using modern computational techniques. I have been developing a numerical code to study this interaction since 2005.

To be excellent in service, one must be a good university citizen, ready to participate when needed.

During my time at UHCL, I have served as program chair for both the Physical Science and Physics programs and have been heavily involved in outreach activities. Because my primary responsibility is to develop the Physics program, most of my service is either directly or indirectly related to this purpose. For example, I have served on and chaired the SCE curriculum committee as a representative of the Physics program. I also served on the SCE Student Affairs, Library, Research & Computing, Policy, Post-Tenure Review, Curriculum and Dean Search Committees. I was the faculty advisor for the Physics Club and Black Student Association. I mentored students both officially and un-officially. I judged science fairs and scholarship competitions for the Houston community. I served on the Faculty Senate Research Committee from 2007-2009 and was chair during the 2008-2009 academic year. I also served on the Faculty Senate Executive Committee, University Planning & Budget Committee, Academic Council and University Council. In 2012, I was elected President-elect of the Faculty Senate and served as President during the 2013-14 academic year. In 2015, I was re-elected to a second term as Faculty Senate President when the previously elected president became ineligible to serve. Because of this, I served on the Faculty Senate Executive Committee, Academic Council and University Council from 2012 through 2016.

Since coming to UHCL, I worked towards a Memorandum of Understanding (MOU) between the Physics Program and JSC as well as an IPA agreement, which effectively added a full-time faculty member to the UHCL Physics program at no cost to the university. In 2008, this lead to a Space Act Agreement between UHCL and JSC. During the spring of 2006, I hosted a public lecture that was given by our distinguished visitor, Professor Sylvester James Gates, Jr. 200 people attended and the proceeds were used to fund our search for a Visiting Assistant Professor of Physics. Between 2007 and 2010, I hosted 4 more distinguished Physics Lectures.

In addition, I worked on several outreach projects to benefit the community at large. I was featured on NASA's African-Americans in Space Science Poster. I helped to send surplus library books to a village in Nigeria. I helped my colleagues produce a web-based survey for the faculty senate's research task force. I traveled to Florida to serve as a counselor for the Ethnic College Consulting Center's College Tour. I worked to develop a summer institute to get kids interested in physics. I also served on the 2005 and 2006 Convocation Committees and chaired a session on academic new initiatives at the 2006 Convocation. Also in 2006, I hosted a visit with Congressman Nick Lampson and the Science Faculty. In 2008, I arranged tours of JSC and Ad Astra Rocket Company for several UHCL faculty/administrators. Since 2011, I have served on the boards of Latin Deaf Services, Inc., Space Center Houston and AUM Clean Energy Group.

As a result of my work in teaching, research and service, I was featured in the University of Houston System's Success Stories as well as The Egret magazine. I have only been a part of the Clear Lake community for about fifteen years and my work has become well known around both the UHCL/JSC community and throughout Texas.

I am currently the Director of Graduate Studies for the College of Science and Engineering and oversee all aspects of our 13 graduate programs. During my time in this position, we had as many as 1,100 students enrolled in these programs and we received up to 3,500 applications each year. Some of my notable accomplishments in the position so far are the improvement of our admissions process, the initialization of an Advising and Registration event, the rewriting of our assistantship policy, the development of a recruiting plan, the implementation of a targeted marketing program and other efforts to increase domestic graduate student enrollment.

2. SUMMARY

2.1 TEACHING AND EDUCATIONAL ACTIVITIES AT UHCL

2.1.1 Coursework

At UHCL, I taught a total of 83 courses during the fifteen-year period from the fall of 2002 through the spring of 2017.

Fall 2002
PHYS 5931 Research Topics in Physics: Classical Mechanics
PHYS 4331/5931 Principles of Electromagnetism/Research Topics in Physics: Electromagnetism

Spring 2003
PHYS 5931 Research Topics in Physics: Mathematical Methods in Physics I
PHYS 5931 Research Topics in Physics: Special Relativity
ASTR 6230/6838 Research Methods in Space Science/Research Project and Seminar

Summer 2003
PHYS 5931 Research Topics in Physics: Mathematical Methods in Physics II

Fall 2003
PHYS 5931 Research Topics in Physics: Mathematical Methods in Physics I
PHYS 5931 Research Topics in Physics: Classical Mechanics
PHYS 5931 Research Topics in Physics: Spacetime Physics

Spring 2004
PHYS 5331 Electrodynamics
ASTR 6230/6838 Research Methods in Space Science/Research Project and Seminar

Summer 2004
PHYS 5931 Research Topics in Physics: Using Mathematica to Solve Physics Problems

Fall 2004
PHYS 5531 Mathematical Methods in Physics I
PHYS 5431 Classical Mechanics
PHYS 6131 Fundamentals of Spacetime

Spring 2005
PHYS 5331 Electrodynamics
ASTR 6838/PHYS 5033/PHYS 6838 Research Project and Seminar/Modern Physics Research/Research Project and Seminar
PHYS 6132 General Relativity

Summer 2005
PHYS 5533 Numerical Methods in Physics

Fall 2005
PHYS 5531 Mathematical Methods in Physics I
PHYS 5431 Classical Mechanics
PHYS 6838 Research Project and Seminar

Spring 2006
PHYS 5331 Electrodynamics
ASTR 6838/PHYS 5033/PHYS 6838 Research Project and Seminar/Modern Physics Research/Research Project and Seminar

Fall 2006
PHYS 5531 Mathematical Methods in Physics I
PHYS 6131 Fundamentals of Spacetime

Spring 2007
PHYS 6132 General Relativity
ASTR 6838/PHYS 4732/PHYS 6838 Research Project and Seminar/Modern Physics Research Seminar/Research Project and Seminar

Fall 2007
PHYS 5331 Electrodynamics
PHYS 5531 Mathematical Methods in Physics

Spring 2008
PHYS 5332 Electrodynamics II
PHYS 4839 / PHYS 6838 Modern Physics Research / Research Project and Seminar

Summer 2008
PHYS 5533 Methods in Computational Physics
PHYS 6838 Research Project and Seminar

Fall 2008
PHYS 4331 Principles of Electromagnetism
PHYS 5531 Mathematical Methods in Physics I
PHYS 5919 Recitation for Mathematical Methods in Physics I
PHYS 6838 Research Project and Seminar

Spring 2009
PHYS 5311 Recitation for Electrodynamics I
PHYS 5331 Electrodynamics I
PHYS 6132 / PHYS 7397 General Relativity
PHYS 4732 / PHYS 6838 Modern Physics Research / Research Project and Seminar

Fall 2009
Faculty Development Leave

Spring 2010
PHYS 5311 Recitation for Electrodynamics I
PHYS 5331 Electrodynamics I
PHYS 4732 / PHYS 6838 Modern Physics Research / Research Project and Seminar

Fall 2010
PHYS 4331 Principles of Electromagnetism
PHYS 5511 Recitation for Mathematical Methods in Physics I
PHYS 5531 Mathematical Methods in Physics I

Spring 2011
PHYS 5311 Recitation for Electrodynamics I
PHYS 5331 Electrodynamics I
PHYS 4732 / PHYS 6838 Modern Physics Research / Research Project and Seminar

Summer 2011
PHYS 6132 General Relativity

Fall 2011
PHYS 4331 Principles of Electromagnetism
PHYS 5511 Recitation for Mathematical Methods in Physics I
PHYS 5531 Mathematical Methods in Physics I

Spring 2012
PHYS 5311 Recitation for Electrodynamics I
PHYS 5331 Electrodynamics I
PHYS 4732 / PHYS 6838 Modern Physics Research / Research Project and Seminar

Summer 2012
PHYS 4333 / PHYS 5931 Special Relativity / Introduction to Spacetime

Fall 2012
PHYS 5511 Recitation for Mathematical Methods in Physics I
PHYS 5531 Mathematical Methods in Physics I

Spring 2013
PHYS 5311 Recitation for Electrodynamics I
PHYS 5331 Electrodynamics I
PHYS 4732 / PHYS 6838 Modern Physics Research / Research Project and Seminar

Fall 2013
PHYS 5511 Recitation for Mathematical Methods in Physics I
PHYS 5531 Mathematical Methods in Physics I

Spring 2014
PHYS 4231 Intermediate Mechanics
PHYS 4732 / PHYS 6838 Modern Physics Research / Research Project and Seminar

Summer 2014
PHYS 4333 / PHYS 5931 Special Relativity / Introduction to Spacetime

Fall 2014
PHYS 5511 Recitation for Mathematical Methods in Physics I
PHYS 5531 Mathematical Methods in Physics I

Spring 2015
PHYS 5311 Recitation for Electrodynamics I
PHYS 5331 Electrodynamics I
PHYS 4732 Modern Physics Research

Fall 2015
PHYS 5511 Recitation for Mathematical Methods in Physics I
PHYS 5531 Mathematical Methods in Physics I

Spring 2016
PHYS 4732 Modern Physics Research / PHYS 6838 Research Project and Seminar
PHYS 5911 Computational Physics with Cactus

Fall 2016
PHYS 2125 Laboratory for University Physics
PHYS 5511 Recitation for Mathematical Methods in Physics I
PHYS 5531 Mathematical Methods in Physics I

Spring 2017
PHYS 1301 College Physics I
PHYS 4732 Modern Physics Research / PHYS 6838 Research Project and Seminar

For each course the objectives, contents, schedule and grading criteria were all clearly stated in the syllabus. Most courses were taught using a traditional chalk/blackboard lecture format using advanced lecture capture technology. In an effort to web-enhance my courses, I hired a TA in the fall of 2003 to type up my notes for Mathematical Methods 1 and Classical Mechanics but later opted to use my hand-written notes. I also began using Wimba and Blackboard Collaborate to record and webcast my lectures in the graduate Electrodynamics and Seminar classes in Spring 2011. Since then, I've begun using that technology with almost all my classes. All the homework and exam grading was done by me. Typically this consisted of 5-6 biweekly problem sets consisting of 5-10 problems each and 3-5 problem midterm and final exams. I store all grade records electronically for future reference.

I am responsible for the addition of 40 courses to the ASTR and PHYS curriculum.

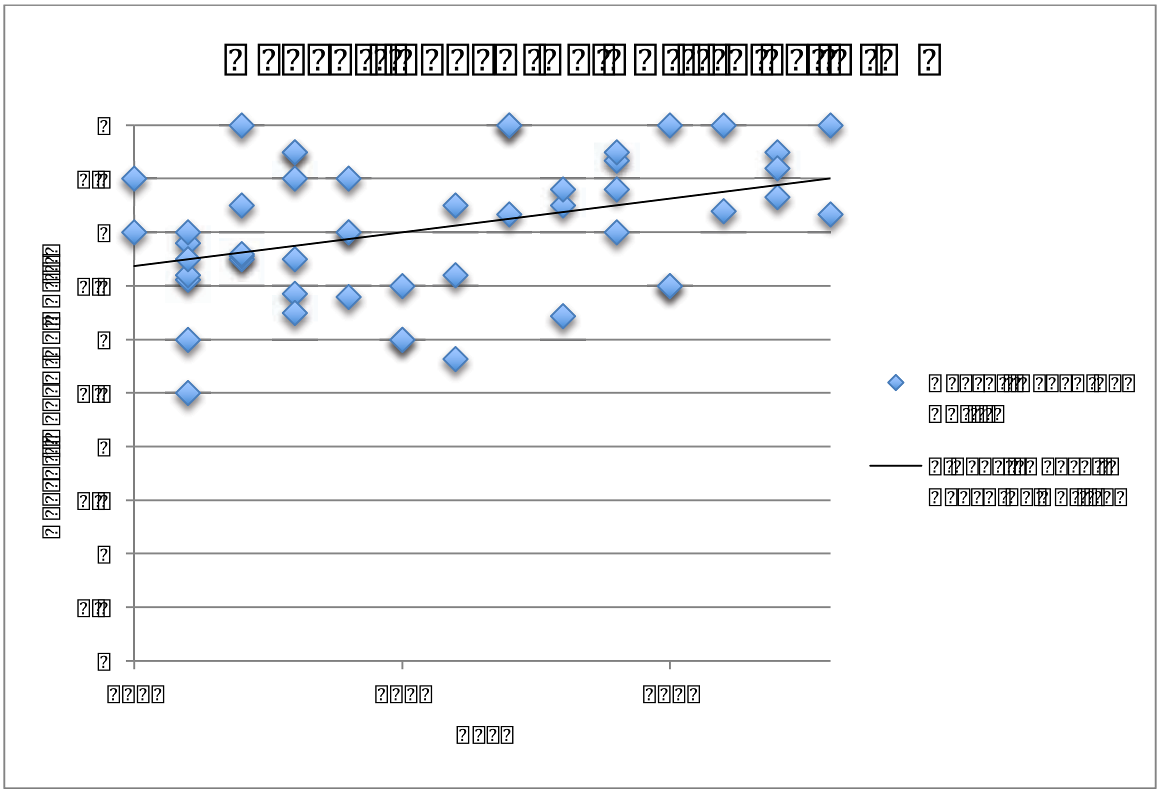
ASTR 3111: LABORATORY FOR MODERN ASTRONOMY
ASTR 5131: GRADUATE ASTRONOMY
PHYS 3303: MODERN PHYSICS
PHYS 3311: MATHEMATICAL METHODS FOR PHYSICISTS AND ENGINEERS I
PHYS 3312: MATHEMATICAL METHODS FOR PHYSICSITS AND ENGINEERS II
PHYS 3321: INTERMEDIATE MECHANICS
PHYS 3351: THERMODYNAMICS & STATISTICAL MECHANICS
PHYS 4101: LAB METHODS IN THE PHYSICAL SCIENCES
PHYS 4301: METHODS IN THE PHYSICAL SCIENCES
PHYS 4322: STATICS & MECHANICS OF MATERIALS
PHYS 4333: SPECIAL RELATIVITY
PHYS 4352: FLUIDS AND HEAT TRANSFER
PHYS 4372: RESEARCH SEMINAR
PHYS 4379: INTERNSHIP IN PHYSICS
PHYS 4195: COOPERATIVE EDUCATION WORK TERM
PHYS 5311: RECITATION FOR ELECTRODYNAMICS
PHYS 5331: ELECTRODYNAMICS I (later renamed ELECTRODYNAMICS)
PHYS 5332: ELECTRODYNAMICS II
PHYS 5411: RECITATION FOR CLASSICAL MECHANICS
PHYS 5431: CLASSICAL MECHANICS
PHYS 5511: RECITATION FOR MATHEMATICAL METHODS IN PHYSICS I
PHYS 5531: MATHEMATICAL METHODS IN PHYSICS I
PHYS 5532: MATHEMATICAL METHODS IN PHYSICS II
PHYS 5533: METHODS IN COMPUTATIONAL PHYSICS
PHYS 5611: RECITATION FOR QUANTUM MECHANICS I
PHYS 5612: RECITATION FOR QUANTUM MECHANICS II
PHYS 5631: QUANTUM MECHANICS I
PHYS 5632: QUANTUM MECHANICS II
PHYS 5711: RECITATION FOR STATISTICAL MECHANICS
PHYS 5731: STATISTICAL MECHANICS
PHYS 5739: INTERNSHIP IN PHYSICS
PHYS 5911: SPECIAL TOPICS IN PHYSICS
PHYS 5915: COOPERATIVE EDUCATION WORK TERM
PHYS 5919, 5939: INDEPENDENT STUDY IN PHYSICS
PHYS 6131: FUNDAMENTALS OF SPACETIME
PHYS 6132: GENERAL RELATIVITY
PHYS 6231: PLASMA PHYSICS
PHYS 6838: RESEARCH PROJECT AND SEMINAR
PHYS 6939: MASTER’S THESIS RESEARCH

These courses were added to support the redeveloped BS in Physical Sciences, the BS in Physics, the MS in Physics and the Collaborative Physics Ph.D. program as well as to increase student knowledge in several areas of research.

2.1.2 Teaching

2.1.4.3 Teaching Evaluation Summary

While reviewing my teaching evaluations, I noted four areas: Pace, Quality of Course, Overall Teaching Ability and my ability to Stimulate and Challenge Students. I was typically rated between 4.00 and 5.00 in each of these categories for almost all of my classes. I believe that this reflects well on my ability to create an enjoyable and challenging course for my students. In many areas, I improved greatly after teaching the course a second time. I also noticed that there is a direct correlation between the amount of time, which I can devote to teaching on a giving semester, and my evaluation scores. Based on both my evaluation scores and students comments, I think it is fair to say that students find my classes both challenging and rewarding.



2.1.4.3 Written Comments

- "Excellent command of the course's math, added the "between the lines" math solutions to compliment the text book"
- "Enthusiastic and enjoys his work. He is friendly and will always try help."
- "Hire more physics teachers to help even the load. Dr. Garrison is good but he can not do everything."
- "Knowledge of material provides excellent instruction & enthusiasm."
- "Great class, great instructor, extremely effective at teaching seem to truly care about the students and the subject. Plan on taking more class from him."

- “Enthusiastic, Bringing the physics program to U of H! Encourages group study and always allows questions to be asked in class. Grades all homework/tests without the aid of a teachers assistant.”
- “Dr. Garrison is very organized in class – class notes, assignments, etc. Dr. Garrison is also flexible with regards to work schedules, work-related travel, etc. This is important since almost all students work.”
- “The course covered all of the background math needed for graduate Physics courses. By the end of this course, I feel I have a background in complex analysis, differential equations, linear algebra and integral transforms.”
- “Dr. Garrison was fun to participate with in his class. I would gladly take another course taught by him.”
- “Dr. Garrison took a complex and confusing subject and broke it down into smaller pieces.”
- “Professor knows subject thoroughly. Responds to questions and follows up later.”
- “Allows you to ask questions in class any time. Very enthusiastic and enjoys the subject material.”
- “Hire more physics teachers to help even the load. Dr. Garrison is good but he cannot do everything.”
- “Excellent coverage of much material to an audience of mostly full-time employees. I learned quite a bit in this class.”
- “Well prepared notes for class: explains steps missing in book explains subject matter well.”
- “Good coverage, kept compatibility with scope at other university mechanics courses.”
- “Concise and follows text & schedule. Thorough treatment of material and coverage of difficult textbook.”
- “The course covered a lot of material. By the end I feel I have a good understanding of a complex subject. Topics were tied together very well.”
- “Enjoyed the course.”
- “Very knowledgeable about the material. Can answer questions about the lecture content readily.”
- “Part of the problem may be that Dr. Garrison teaches an awful lot of classes, making it difficult to prepare. He needs more professors.”
- “Very prepared and approachable. Covered large amount of material in a short time in a way that made sense.”
- “Dr. Garrison could probably use some more faculty so that he has more time to prepare for class and fix these problems.”
- “He will become an outstanding professor!”
- “-knows the subject well; -good presence and presentation; -good sense of humor”
- “Dr. G is destined to be a really great professor.”
- “Dr. Garrison is well prepared for this class. He enjoys the subject and strives to ensure that students are grasping the concepts.”

- “I enjoyed this class, the lectures and problems sets. I learned several new concepts.”
- “He knows the subject material extremely well and is able to clearly communicate the core ideas.”
- “He is very encouraging of students to think and ask questions.”
- “The instructor was very knowledgeable about the material. A complex subject was presented in a way that was relatively easy to understand.”
- “Great instructor and great subject”
- “Knows how to solve problems & explain enough detail to allow student to grasp solutions.”
- “very strong mathematical understanding”
- “Likes topic, cares about students”
- “Dr. Garrison was very knowledgeable about all the different subjects & very organized in how he presents them.
- “Instructor cared about students”
- “Great knowledge -> Easy to communicate material”
- “Very helpful & interested in helping us learn.”
- “Dr. Garrison is well-acquainted with the methods taught in his course and more importantly, the application of them.”
- “The instructor is very knowledgeable about physics and computer science.”
- “Knowledgeable and concise.”
- “Dr. Garrison is well prepared for the lectures and is well versed in using the various compilers.”
- “Expert in subject material truly cares about the subject.”
- “The instructor is very knowledgeable and excited about the course material. I learned very much about difficult material. Lecture notes were provided after students struggled to keep up with note taking.”
- “-Tremendously knowledgeable”
- “-very good nature – likes seeing students learn”
- “-interested in his field”
- “I was really excited to be involved in this course, because that helped to have better understanding about my major and possible future explorations. Now I know why people should appreciate science.”
- “Very organized, can get the point across effectively”
- “… willing to work with student”
- “Willing to focus on problem areas of course material”
- “Prepared, knowledgeable, and runs thru lecture material quickly.”
- “Very prompt in answering questions, knowledge in subject, accommodating to student’s needs”
- “Makes topic interesting, relates material to other aspects of physics curriculum”
- “Appreciate breath of coverage, recitation class was very helpful”
- “He understands the students and is willing to take time out to discuss some of the more difficult subjects”
- “Knowledge of the Subject and was well-prepared with practice questions.”

- “Good at expressing what is expected of the student in the course”
- “Very knowledgeable of the subject and was consistent with his help and support with problems/concerns.”
- “The instructor in this course was very helpful and very knowledgeable of the subject being taught.”
- “I think this course is very well taught and I would not recommend any changes.”
- “The recitations are good. Prof. Garrison knows what he is doing. Smart guy.”
- “Very knowledgeable and well prepared. Articulates effectively.”
- “Available additional office hours upon request”
- “Very knowledgeable. Used real-world examples”
- “Knowledgeable, prepared organized”
- “There was a lot of material”
- “He used good practical examples to explain difficult topics. This was helpful to engage me.”
- “He knows the material well – a lot of material, and can cover them in a short amount of time, i.e. we covered tensor calculus in 3 hours.”
- “Good examples given in class”
- “knows his stuff”
- “Fills in gaps from text derivations”
- “He is extremely knowledgeable on the course material”
- “good communication, knowledgeable, very friendly, professional!!”
- “Knows the extremely difficult & complex material well, which is very impressive. Gives nice physical examples to arcane mathematical formulations of electrodynamics.”
- “This particular topic & textbook is known to be among the hardest in physics graduate school. The course provided a nice overview of the textbook and allowed me to work through ample problems in detail.”
- “It is so wonderful to have a physics instructor whose intention is to make the material accessible. Keep up the great work, it’s much appreciated.”
- “Passionate about the subject (public speaking)“
- “The reverse class setting was advantageous for a graduate level course. It aligned the students to spend most of the time in class clarifying things they didn’t understand.”
- “Strong visualization skills. Provided many real world examples to keep us engaged.”
- “Thank you for a good year. I know I wasn’t the best student, but you were a great teacher!”
- “He manages the speakers very well & knows who to bring”
- “Knowledgeable of most presented topics”
- “Very knowledgeable of the course material. Useful examples.”
- “Provides notes, records lectures, good w/ office hours and answering questions and providing sample review tests for midterm and finals”

- “Dr. Garrison always showed a strong understanding of the material. His ability to properly weigh the difficulty of the subject allowed an objective approach to the material”
- “I like how structured the course is. I know exactly what to expect and when assignments are due”
- “Very knowledgeable, is able to connect to other fields to give adequate examples”
- “Dr. Garrison is expertly knowledgeable in advanced math methods!”

2.1.3 Other Educational Activities

2.1.4.3 Faculty Advisor

I served as the faculty advisor for all graduate students majoring in Physics and undergraduates majoring in Physical Sciences until the Physics and Physical Sciences programs were officially split in 2005. Dr. Blanford continued to serve as Faculty Advisor for the students completing the MS in Physical Sciences degree until it was phased out. As additional faculty were hired into the Physics program, we shared the advising responsibilities. My major duties include assisting students with their course selections, Candidate Plan of Studies (CPS), career planning and research projects.

2.1.4.3 Individual Instruction

I have been heavily involved in individual instruction since coming to UHCL. I advised about 30 students in independent research. In the fall of 2002, I advised one student, Greg Chamitoff, on his final project for the MS in Physical Science Program. The project involved developing a computer program to optimize the landing location for future Mars missions. This project was directly motivated by Greg’s work as an astronaut.

In the spring of 2003, I advised five students on capstone research projects (Phillip Burley, James Devlin, George James, Christie Matthew and Tom Smith). I also advised one student Andrew Coleman on his thesis project proposal.

In the spring of 2004, I advised three students on capstone research projects (Brian Derkowski, Kirk McVey and James Rhodes). I also taught an independent study class in General Relativity for John Hirasaki.

In the summer of 2004, I advised one student, Jacob Collins, on a thesis project proposal. I also taught an independent study Quantum Mechanics course for Thomas Londrigan.

In the fall of 2004, I advised three students; Jacob Collins on his thesis work, John Hirasaki on an individual research project in theoretical physics and Jason Gibson on an independent research project directly related to my research interest in Doubly Special Relativity.

In 2005, I supervised 8 independent study research projects: “Space Radiation Research”, “Field Relationships”, “Magnetohydrodynamics”, “Theory of Pair Production”, “Initial Conditions for GRMHD”, “Optimization of GRMHD Code”, “Data Analysis for GRMHD Code” and “Visualization of GRMHD Data”. That year I graduated 7 Physics and 2 Physical Science graduate students.

In 2006, I supervised 4 independent study research projects – topics included: Plasma Physics, Data Visualization, Early Universe Gravitational Wave production, Cosmology and Computational Physics. Also in 2006, I graduated a total of 4 Physics and 3 Physical Science graduate students.

In 2007, I supervised 1 capstone research project, which led to a publication with a student. I also taught 2 independent studies and graduated a total of 4 Physics and 1 Physical Science graduate students.

In 2008, I taught 1 independent study and graduated a total of 5 Physics graduate students. I also Chaired a PhD Thesis Committee through the Collaborative Physics PhD Program. In addition, I attended the 2008 Institute on Teaching and Mentoring in Tampa Florida.

In 2009, I taught 2 independent studies and we graduated a total of 9 Physics graduate students. I also, chaired a PhD Thesis Committee through the Collaborative Physics PhD Program.

In 2010, I taught 5 independent studies and we graduated a total of 9 Physics graduate students and 1 Physics undergrad student making us the second largest producers of Physics Master’s degrees in the state of Texas.

In 2011, I advised one PhD student through our Collaborative Physics PhD program and served on one additional PhD thesis committee through our Collaborative Physics PhD program. I also Taught 1 independent study. In 2011, we graduated a total of 6 Physics graduate students and one Physics undergrad student which still makes us one of the largest producers of Physics Master’s degrees in the state of Texas.

In 2012, I chaired 2 MS Thesis committees and supervised 2 independent study students. That year we graduated 2 MS and 2 BS students.

In 2013, I had advised 1 PhD student thesis through our Collaborative Physics PhD program, 1 MS student and 3 graduate student independent study projects.

In 2014, I advised 1 PhD student through our Collaborative Physics PhD program, 1 MS thesis student (completed in Fall 2014) and 2 independent study graduate students interested in developing thesis projects.

In 2015, I advised 1 PhD student through our Collaborative Physics PhD program and I've been working with two RA's (1 Graduate and 1 Undergraduate) on my research.

In 2016, I worked with an RA who is currently writing a Master's Thesis. I have been working with another graduate student (unofficially) on a project to study magnetogenesis from MHD turbulence. I also supervised 2 undergraduate independent studies.

2.1.4.3 Organized Mentoring

In 2002, I participated in the Compact for Faculty Diversity's ninth annual Institute on Teaching and Mentoring in Arlington, Virginia. In the fall of 2003, I mentored a student (Daniel Jou) from Clear Lake High School on an independent study project in Special Relativity. Also during the 2003-2004 school year, I mentored a student (Stephanie Noreiga) through UHCL's Total Success Plus Program. In the spring of 2004, I flew to Florida, at my own expense, to serve as a counselor to the Ethnic College Counseling Center in an effort to introduce underrepresented minority students to institutes of higher education. That summer, I mentored one high school student and one college freshman. In 2007, I again participated in the Total Success mentoring program at UHCL. That year I was also Co-advisor for the Black Student Association and served on the New Student Orientation faculty panel twice. In 2008, I continued to advise the Black Student Association and attended NSBE's Engineer for a Day to encourage kids to pursue careers in science and engineering. In 2008, I served twice on the New Student Orientation faculty panel. In 2015, I joined the APS Mentoring Program and attended their 2016 meeting in Houston Texas.

2.1.4 Program Development

2.1.4.3 New Program Development

I feel that my greatest contribution to UHCL has been in the area of New Program Development. Between 2002 and 2004, I oversaw the development and approval of a revamped BS in Physical Science and a MS in Physics. In addition, I developed a new Professional Physics Master's Degree (2004-2006), Collaborative Physics PhD program with UH (2007-2008), a new BS in Physics (2009-2010) and an Engineering Physics sub-plan (2011) under our Physics BS. All of this is part of a strategic plan that I developed for the Physics Program to improve enrollment, increase research and better meet the needs of the local community.

The BS in Physical Sciences was revamped in 2003 in order to better meet the needs of students. In addition to preparing students for technical careers, this degree had the option of certifying students to teach both physics and chemistry. In 2006, we split the Physical Science BS into two sub-plans, one prepares students for teacher certification while the other is more technical and prepares students specifically for graduate study in physics. I oversaw several aspects of the development, approval and implementation of this degree program.

The MS in Physics was developed to prepare students for research in physics and to better serve the needs of the NASA community. Students can use this degree to enhance their engineering knowledge base, move on to PhD programs in Physics, Astronomy or related fields or become involved in advanced research at JSC. I developed this degree from its basic concept to its final implementation.

The Professional Physics MS was designed to help fill the local community's need for technically skilled managers. I was awarded a planning grant from the Council of Graduate Schools and the Sloan Foundation to perform a feasibility study for this degree. In 2004, I worked to collect data on the needs of local industry and potential students through online surveys and focus groups. As a result of this effort, I won an implementation grant to develop and promote the program. The success of this concept led to the desire in local industry to develop an Engineering Management degree at UHCL.

The Collaborative Physics PhD program was developed in response to several unsolicited requests from the local community. I conducted a survey in the fall of 2006, to document the need for such a program and then used the results to establish an agreement with UH. I worked with Dr. Pinsky, Dean Davari and Dean Bear to develop the agreement. This is a new type of program that will effectively allow the UHCL Physics program to train students at the PhD level in Clear Lake with the help of UH. For the first time, UHCL faculty were able to advise PhD students on our campus. In 2012, I wrote a THECB planning authority proposal to upgrade this program to a full Joint Physics PhD program. This proposal is still pending the administrative approval to move forward.

The Physics BS was a natural development that resulted from the success of the Physics graduate program. In order to teach PhD candidacy courses at the proper level, we needed to consistently teach the upper-level undergraduate physics core. This, combined with the fact that Physical Sciences is not a recognized degree plan to most employers, made phasing out the Physical Sciences BS in favor of a Physics BS a no-brainer. We opted for a curriculum that was minimal in core requirements and gave maximum flexibility to students so they would have the option of pursuing a large variety of career options.

The first sub-plan added to the Physics BS was the Engineering Physics plan. The Physics Advisory Board suggested that we take advantage of the fact that Physics is closer to some of the traditional engineering areas (Mechanical, Civil, Industrial, Aerospace…) than any other program offered at UHCL. We then developed the sub-plan based on an ABET accredited Engineering Physics degree plan. Several students who graduated from this program have passed the FET exam and are making progress towards becoming certified professional engineers.

Between my dual roles as Faculty Senate President and Chair of Physics, I was able to develop a university policy to introduce academic minors to our undergraduate programs and develop minors in Physics and Astronomy within the first cohort of UHCL minor programs. These programs will both expand educational opportunities for all UHCL students and further grow our enrollment in the Physics Program.

In addition to the development of these programs I also served as a member of the Aerospace Engineering Task Force to help determine the feasibility of an Aerospace Engineering degree at UHCL. I served on the review committees for both San Jacinto College's natural science curriculum and the Management Technology program. I also worked with Dr. Masood to improve our teacher education program and build the UHCL Physics and Astronomy Teaching Lab. In my attempts to develop an undergraduate program that could feed into our graduate Physics program, I proposed the curriculum for an interdisciplinary Scientific Computing Undergraduate and Graduate Program.

I also worked on several program development projects. I worked with Dr. Talent to plan for the development of an Astronomy Teaching Observatory, which we have yet to implement. One possibility that we discussed was a partnership with the George Observatory where by their telescopes could be remotely accessed from UHCL. I worked with Dr. Tarditi to develop a plasma physics lab on campus, which allowed us to better connect to NASA's research interests. I met with the CEO's and HR departments of several companies such as GHG and MEI Technologies to help determine their educational needs. I have also been in communication with the Physics Department Chairs at Texas Southern University, Rice University and the University of Houston in order to discuss potential educational and research collaborations. I attended three conferences including the Texas Spin-up Conference, Physics Chairs National Meeting, and Building a Thriving Undergraduate Physics program in order to learn how to improve our physics program and grow it's enrollment. I also attended two meetings in San Juan, PR and Washington, DC on improving our Professional Master's degree program.

Other development activities included: writing two Program Reviews for the Physics program, getting the UHCL Physics program officially recognized by the American Institute of Physics (AIP), Joined PhysTec, Joined the APS Bridge Program, created a Physics Candidacy Certificate, participating in the planning for downward expansion, participated in the development of a Space Act Agreement with JSC, conducted several assessment surveys, wrote a Graduate Student Guide, developed an advisory board, maintained the physics teaching lab computers, chaired four search committees, two third-year reviews and two tenure review committees.

2.1.4.2 Program Marketing

As program chair, a large part of my time was spent marketing the Physics program. Since coming to UHCL I have attended at least a dozen academic fairs, eight open houses, three community college lunches, several meetings with representatives from local industry and a World Space Conference. In addition, I have helped to develop fliers, brochures and websites for the program. I also facilitated the development of a poster for the program, which was distributed at JSC and at several Texas and Louisiana universities, four-year colleges and community colleges.

In addition to the direct marketing of the program, I also promoted the Physics program in other ways. I was featured in the African Americans in Space Science Exhibit poster and the Egret magazine. I published two articles on non-traditional physics student education. I promoted the program at several national conferences. I gave talks at other organizations such as Jacobs, BAHEP, United Space School and San Jacinto College. Developed a Facebook page for the program. I gave an interview for the Houston Chronicle's "Meet a Scientist Monday #12". Appeared on an episode of "The Universe" on the History Channel. I was interviewed as part of the HistoryMakers (ScienceMakers) oral history archive project. I also had a 4' x 8' poster board installed for the Physics program and made sure the new program was listed on the training and development websites for JSC and the major contractors. As the Director of Graduate Programs, I have implemented many of these strategies for our other graduate programs.

However, the greatest marketing strategy for the program has been the Physics Seminars that I host for the local community. The Spring Seminar Series features 12 speakers with an average attendance between 15 and 30 people per week. I have successfully managed to attract over 100 new potential students to the UHCL campus each academic year as a result of these lectures. Also, special lectures, such as the one I organized around a visit from Professor Gates, resulted in about 200+ visitors at a single event. I've hosted talks by Dr. Neal Lane, Prof. John Hawley, Dr. Joseph Romm, President Allen Sessoms and author Jeffery Bennett in addition to the talk by Professor Gates. I also co-hosted the Space Center Lecture Series.

2.1.4.3 Student Enrollment

Since I joined the faculty of UHCL in 2002, the total number of undergraduate and graduate SCHs in physics and astronomy has grown significantly. The number of majors has also increased to the point where our enrollment at the graduate level was the highest nationwide for any Master's level Physics Program (about 40-50 graduate students per semester). In 2014, the AIP officially recognized us as one of the most productive Masters level physics programs in the United States for 2010-2012 in their Graduate Physics Degrees report. I also graduated over 50 Master's students from 2005 – 2015. This is extraordinary for a new master's level physics program. Much of this growth is due to the new programs that I initiated and my efforts to promote these programs. In 2012, I attended three conferences focusing on how to increase enrollment in our physics: the Texas Strategic Initiatives for Improving Undergraduate Physics (Spin-up), the Physics Chair's bi-annual meeting and the Building Thriving Physics Programs workshop. In 2014, the APS Bridge Program began sending us applications for more potential students. We are currently working to become a funded APS Bridge Site.

2.2 RESEARCH AND SCHOLARLY ACTIVITIES

2.2.1 Research Interests

Before coming to UHCL, much of my research was focused on numerical relativity. I spent my first year finishing projects from Penn State and presenting the results. The first project that I finished at UHCL was also the basis of my PhD thesis. I developed a technique to test the stability of a numerical relativity code using cosmological spacetimes. I presented the results of this work at several conferences including the Tenth Marcel Grossman Meeting in Brazil. The paper was later published in the Proceedings.

The second project involved developing a technique for analyzing seismic activity as a source of noise for gravitational wave interferometers such as LIGO. This project was completed in collaboration with Gabriela Gonzales at LSU. It was also presented at the Marcel Grossman Meeting and published in the Proceedings.

The third project focused on black hole spectroscopy using gravitational wave detectors. I worked with several people whom I knew from Penn State on this project. The idea was to develop a test of the "no hair" theorem, which states that information cannot escape from the horizon of a black hole. Our paper suggests the only test of this theorem. This paper was published in Classical and Quantum Gravity.

Although I continued to attend the weekly numerical relativity teleconferences with Penn State, I allowed my research to move in other directions. These new topics of research were more in the interest of the local community than my previous work but still within the knowledge level and time constraints of potential student collaborators.

The first of these topics involved the development of a theory called Deformed (or Doubly) Special Relativity. This theory is relatively new and the first papers on it were written in 2002. The basic idea of the theory is to modify the theory of special relativity to incorporate a fundamental length and energy scale so that it is consistent with theories of quantum gravity. The Physics program curriculum teaches students enough (in Fundamentals of Space-time, General Relativity and Mathematical Methods in Physics 2) to begin to work with this theory. My first student for this project worked on it during the fall of 2004.

A second topic of research involved collaboration with the Advanced Space Propulsion Lab at JSC. I worked on developing a computer code to simulate the flow of plasma through the VASIMR engine. This project resulted in a summer faculty fellowship at JSC and two ISSO postdoc grants. This computer code was specifically designed to be modular and easy to understand so that students at UHCL could contribute to it given only a limited amount of time to work on research.

More recently, the focus of my research has been numerical cosmology. By applying the lessons that I learned from both plasma physics and numerical relativity, I realized that gravitational waves in the early universe could have excited turbulent modes in the primordial plasmas, which could have led to observable gravitational wave and may have even contributed to cosmic structure formation. This idea has never been explored numerically since the technology needed to test this idea is relatively new. Since 2005, I've been developing a General Relativistic Magnetohydrodynamic (GRMHD) code capable of testing this hypothesis.

For the first part of the project, the focus of the numerical cosmology work was on primordial gravitational waves both studying their evolution and predicting their spectrum. This resulted in a publication with one of my students, Rafael de la Torre. We studied whether or not the birefringence of primordial gravitational waves could be detected by future gravitational wave observatories.

In 2009, I went on a faculty development leave in order to develop the GRMHD code. After which, I was able to write different versions of the code to focus on relativistic plasmas and primordial gauge field interactions. My 2011-12 collaboration with Harverford College used parts of this code to study a new theory of cosmic inflation in the absence of scalar fields. In 2013, this work led to a peer reviewed publication with student Chris Underwood. Additional peer-reviewed publications were written (or are currently being written) with Phu Nguyen, Christopher Ramirez and John Gouveia.

As a result of this work, I've uncovered several interesting aspects of theoretical cosmology and managed to develop our computational infrastructure by building a computational physics lab, data visualization workstation, mini-cluster and Beowulf supercomputer. If successful, this project could lead to a major change in the theory of cosmic with observable results. The 2014 potential discovery of Primordial Gravitational waves in the Cosmic Microwave Background increased the level of interest in my work. LIGO's 2016 announcement provided further justification for my work.

2.2.2 Publications and Talks

My record of publications and talks demonstrate a sustained scholarly effort and a track record of steady research productivity. This record includes:

- One internal NASA-JSC report
- Two articles in industry newsletters
- Two books (one printed, one eBook which was translated and distributed in China)
- Seven publications in peer-reviewed journals (6 as 1st/corresponding author)
- Six peer-reviewed proceedings articles
- Twenty-one invited talks
- Several contributed talks at national and international conferences
- One National Television appearance
- One Interview with a large national oral history archive project

- Several local talks on my research interests, the history of physics and the development of the physics program at UHCL

I believe that this level of research productivity is competitive especially given that I was hired into an undeveloped program. Since coming to UHCL, I have single-handedly run the physics program while managing up to 10 adjunct faculty and training students capable of working with me. Even though the Physics program now has 5 full-time faculty and utilizes about 7-8 adjunct faculty per semester, this is still far less support than at similar programs. Meanwhile, I also worked to develop the infrastructure needed to perform my research (and physics research at UHCL in general), since no high-performance computing resources were available at UHCL when I was hired in 2002.

Publications since coming to UHCL

1. Relativistic Magnetohydrodynamic Turbulence in the Early Universe by *David Garrison*, to appear in the Proceedings of the 10th Chaotic Modeling and Simulation International Conference.
2. Extracting Gravitational Waves Induced by Plasma Turbulence in the Early Universe through an Averaging Process by *David Garrison* and **Christopher Rameriz**, 2015. arXiv:1503.04764, Classical and Quantum Gravity 34, 145008 (2017).
3. Using Gravitational Waves to put limits on Primordial Magnetic Fields by *David Garrison*, arXiv: 1608.01005, Global Journal of Science Frontier Research, *GJSFR-A Volume 17, Issue 1 (2017)*
4. Invariants in Relativistic MHD Turbulence by *David Garrison* and **Phu Nguyen**, Journal of Modern Physics, **7**, 281-289. doi: 10.4236/jmp.2016.73028, arXiv:1501.06068 (2016)
5. Gauge Field Turbulence as a Cause of Inflation in Chern-Simons Modified Gravity by *David Garrison*, to appear in the Proceedings of the 7th Chaotic Modeling and Simulation International Conference.
6. Numerical Relativity as a tool for studying the Early Universe by *David Garrison*, Journal of Gravity, vol. 2014, Article ID 407197, 11 pages, 2014. doi:10.1155/2014/407197, gr-qc/1207.7097
7. A Numerical Simulation of Chern-Simons Inflation by *David Garrison* and **Christopher Underwood**, Advances in Astronomy, Volume 2013, 207218, hep-th/1208.2660.
8. What Every Successful Physics Graduate Student Should Know by *David Garrison*, Smashwords, 2013 [translated into Chinese and distributed internationally in 2015]

9. TESTING BINARY BLACK HOLE CODES IN STRONG FIELD REGIMES: UNDERSTANDING NUMERICAL INSTABILITIES THROUGH COMPUTATIONAL EXPERIMENTS by *David Garrison*, LAP Lambert Academic Publishing, 2011
10. Numerical Cosmology: Building a dynamical universe by *David Garrison*, AIP Conf. Proc., 2010 -- Volume 1280, pp. 65-69.
11. Gravitational Waves and the Evolution of the Universe by *David Garrison*, AIP Conf. Proc. -- July 6, 2009 -- Volume 1140, pp. 42-45.
12. Did Gravitational Waves Affect the Evolution of the Universe? by *David Garrison*, gr-qc/808.1764.
13. Numerical analysis of simplified Relic-Birefringent gravitational waves by *David Garrison* and **Rafael de la Torre**, Classical and Quantum Gravity 24 (2007) 5889
14. Serving Nontraditional Graduate Students by *David Garrison*, Physics Today, January 2007
15. Development of a Comprehensive Physics Program at a non-traditional upper-level undergraduate and graduate small university by *David Garrison*, APS Forum On Education Spring 2006 Newsletter
16. Testing Binary Black Hole codes with Cosmological Spacetimes by *David Garrison*, Proceedings of the Tenth Marcel Grossman Meeting on General Relativity, 2006
17. Gravity Gradients in LIGO: a proposal for Data Analysis by *David Garrison* and Gabriela Gonzalez, Proceedings of the Tenth Marcel Grossman Meeting on General Relativity, 2006
18. Black Hole Spectroscopy: testing general relativity through gravitational-wave observations by Olaf Dreyer, Lee Finn, Ramon Lopez-Aleman, Badri Krishnan, Bernard J. Kelly, *David Garrison*, Classical and Quantum Gravity 21 (2004) 787-803

Invited Talks since coming to UHCL

1. Commerce, TX – March 26, 2015 – Invited talk on Characterization of Gravitational Waves from Primordial Relativistic Turbulence.
2. Houston, TX: University of Houston – April 4, 2014 - Invited talk on Numerical Relativity as a tool for studying the Early Universe.
3. Houston, TX: Rice University – October 23, 2013 – Invited talk on Numerical Relativity as a tool for studying the Early Universe.
4. Houston, TX: WALIPP TSU Preparatory Academy – September 27, 2013 – Back to School with the History Makers.
5. Houston, TX: North Houston Astronomy Club – March 22, 2013 – Invited Talk – Numerical Cosmology
6. Austin, TX: National Society of Black Physicists – September 24, 2011 – Invited Talk – Spectral Methods in General Relativistic MHD Simulations
7. Houston, TX: Houston Astronomical Society – September 2, 2011 – Invited Talk – Gravitational Radiation from the Early Universe

8. Houston, TX: United Space School – July 26, 2011 – Invited talk about the Physics Program at UHCL
9. Pittsburgh, PA: Carnegie Mellon University – April 15, 2011 – Invited talk on Numerical Simulations of Gravitational Waves from Primordial Turbulence
10. Houston, TX: Johnson Space Center – February 16, 2011 – Invited talk on African-American Scientists and Engineers: Standing on the Shoulders of Giants
11. Houston, TX: Foundation for International Space Education – July 27, 2010 – Invited talk about the Physics Program at UHCL
12. Houston, TX: JSC Astronomical Society – November 13, 2009 – Invited talk - Gravitational Wave Astronomy 101
13. Houston, TX: Annual Banquet of the Houston Astronomical Society – October 10, 2009 – Keynote Address – Gravitational Wave Astronomy 101
14. Tampa, FL: University of South Florida – September 26, 2008 – Invited talk on Numerical Cosmology – Building a Dynamical Universe
15. Washington, DC: National Society of Black Physicists – February 22, 2008 – Invited talk on Gravitational Waves and the Evolution of the Universe
16. Houston, TX: University of Houston Clear Lake – November 29, 2007 – Invited talk - Numerical Cosmology for Poets
17. Houston, TX: University of Houston – October 9, 2007 – Invited talk on Cosmic Structure Formation via Gravitational Radiation
18. Eugene, OR: University of Oregon – May 11, 2006 – Invited talk on Cosmic Structure Formation via Gravitational Radiation
19. Orlando, FL: National Society of Black Physicists – February 19, 2005 – Invited talk on Computational Electromagnetism
20. Grinnell, IA: Grinnell College – May 4, 2004 – Invited talk on Gravitational Wave Physics.
21. Atlanta, GA: National Society of Black Physicists – February 13, 2003– Invited talk on Gravitational Wave Physics.

2.2.3 Proposals and Funding

I have submitted numerous proposals for internal and external funding. I have been awarded a total of $810,023 as a PI or Co-PI since my appointment to UHCL. I believe that this is competitive given that I am a theorist and have little need to purchase expensive equipment. I received no startup funds when I joined the faculty at UHCL. Below is a summary of these proposals.

	Project Description	Status	Amount
1	FRSF - Startup Research in Computational Physics Later partially funded with help from Dean McKay and Provost Hayes	Not Funded	$1,615
2	FDF – Participation in Texas APS Meeting	Funded	$535
3	FRSF – Numerical Cosmology	Funded	$1,435
4	FDF – Participation in 2003 NSBP Meeting I later was invited to give a talk at this conference	Not Funded	

5	FDF – Participation in Tenth Marcel Grossman Meeting	Funded	$1,500
6	APS – Travel Grant for Marcel Grossman Meeting	Funded	$1,000
7	FDF – Participation in 2004 NSBP Meeting	Funded	$1,299
8	CGS/Sloan – Professional Science MS planning grant	Funded	$6,000
9	ASEE/NASA – Faculty Fellowship Program	Funded	$12,000
10	NAVY – Joint proposal with Tai-Yang Research	Not Funded	
11	ISSO - Post-Doctoral Aerospace Fellowship Projects	Funded	$20,000
12	FDF – Participation in CGS Workshop Later paid for using the CGS/Sloan Grant	Not Funded	
13	NASA – Faculty Fellowship Minigrant	Not Funded	
14	ISSO – Post-Doctoral Grant matching funds from ASPL	Funded	$30,000
15	Co-I on NFS proposal “Theoretical and Computational Studies of Large-Dimensional Homogeneous Dynamical Systems”	Not Funded	$1,045,086
16	Research Corp Grant – “Cosmic Structure Formation from Gravitational Radiation”	Not Funded	$40,236
17	CGS/Sloan – Professional Science MS implementation grant	Funded	$25,000
18	FRSF – Cosmic Structure Formation Research	Funded	$2,406
19	ISSO – Cosmic Structure Formation Research	Funded	$6,666
20	FDF – Participation in 2005 NSBP Meeting	Funded	$1,210
21	FDF- Participation in 2006 NSBP Meeting	Funded	$1,741
22	NSF – “Origin of Structure in the Early Universe”	Not Funded	$291,861
23	Research Corporation – “Cosmic Structure Formation from Gravitational Radiation”	Not Funded	$53,684
24	Co-I on FRSF Grant – “Lepton Scatterings and Leptogenesis in the Early Universe”	Funded	$4,000
25	ISSO – “Origin of Structure in the Early Universe from Gravitational Radiation”	Funded	$7,077
26	FDF – Participation in 2006 April APS Meeting	Funded	$680
27	FDF – Participation in 2007 NSBP Meeting	Funded	$1,741
28	FRSF – Cosmic Structure Formation Research	Funded	$5,460
29	NASA - The Effect of Gravitational Radiation on Structure Formation	Not Funded	$810,146
30	NASA - The Effect of Gravitational Radiation on Structure Formation	Not Funded	$403,428
31	NFS - The Effect of Gravitational Radiation on Structure Formation	Not Funded	$403,428
32	FDF – Participation in 2008 NSBP Meeting	Funded	$1,500
33	NASA - The Effect of Gravitational Radiation on Structure Formation	Not Funded	$358,374
34	FDF – Participation in 2009 NSBP Meeting	Funded	$1,512
35	Teragrid – Supercomputer Access	Funded	200,000 units
36	Norman Hackerman grant	Not Funded	$100,000
37	FDF – Participation in 2010 April APS Meeting	Funding	$1,195

38	NSF – Computing Research Infrastructure	Not Funded	$371,991
39	FAA – Center for Commercial Space Transportation	Not Funded	$20,000,000
40	FDF – Participation in 2011 April APS Meeting	Funded	$2,000
41	ISSO – Postdoc and Minigrant	Funded	$66,800
42	Teragrid - Supercomputer Access	Funded	200,000 units
43	FRSF – startup for Dr. Withey	Funded	$5,000
44	FDF – Participation in 2011 NSBP Meeting	Funded	$300
45	FDF – Participation in 2012 April APS Meeting	Funded	$1,300
46	FRSF – Develop Mini Computing Cluster	Not Funded	$5,023
47	NSF REU – Physics REU Site proposal 2012	Not Funded	$305,037
48	NSF S-STEM –Natural Science Scholar Program	Funded	$592,468
49	NSF EIGER – MHD Turbulence Simulations	Not Funded	$144,700
50	FDF – 2013 April APS Meeting	Funded	$1,600
51	NSF WIDER – Implement Evidence based STEM teaching reforms	Not Funded	$1,100,410
52	NSF REU – resubmission of 2012 Physics REU Site proposal	Not Funded	$319,068
53	FDF – CHAOS 2014	Funded	$1,600
54	FRSF- Advanced Investigation of the Gravitational Wave Spectrum Produced by Primordial Plasma Turbulence	Funded	$5000
55	FDF- TSAPS at TAMU	Funded	$600
56	FDF- NSBP in Baltimore, MD	Funded	$1000
57	NSF REU – Physics REU Site proposal	Not Funded	$269,910
58	NSF RUI - Numerical Simulations of Cosmological Gravitational Waves from MHD Turbulence	Not Funded	$252,568
59	NSF - Strategies: Transformative Learning: STEM Simulations (STEMsims)	Not Funded	$1,168,998
60	NSF RUI – Numerical Simulations of Cosmological Gravitational Waves from MHD Turbulence (Resubmission)	Not Funded	$259,919
61	FDF – GR21	Funded	$1,800
62	FDF – CHAOS 2017	Funded	$2,000

2.2.4 Other Scholarly Activities

I regularly attend meetings related to my research interests. Since coming to UHCL, I attended the Texas Section of the American Physical Society (APS) and American Association of Physics Teachers (AAPT) joint meetings in Brownsville TX, Houston TX and College Station. I attended the National Society of Black Physicists (NSBP) and National Society of Hispanic Physicists (NSHP) joint meetings in Washington D.C., Atlanta GA, Orlando FL, San Jose CA, Boston MA, Nashville TN, Austin TX and Baltimore, MD. I attended the April APS meetings in Dallas TX, Anaheim CA, Atlanta GA and Washington, DC. I attended several Council of Graduate School (CGS)

Meetings in Tuscan AZ, Washington DC and San Juan PR. I attended the Chaotic Modeling and Simulation International Meeting (CHAOS) in Lisbon, Portugal and Barcelona, Spain. I attended the Tenth Marcel Grossman Meeting on Gravitational Physics (MG X) in Rio de Janeiro, Brazil. I also attended the Twenty-first General Relativity International Conference (GR21) in New York, NY. In December of 2016, I attended a Sustainable Horizons Institute meeting at Lawrence Berkley National Laboratory where I presented my work of Gravitational Waves Induced by MHD Turbulence. In addition, I regularly participated in a weekly telephone conference on numerical relativity hosted by Penn State and co-founded a weekly Astrophysics Colloquium and Physics Journal Club at UHCL.

I have also given several presentations on campus through the Astrophysics Colloquium, Journal Club, Physics Club meetings and Space Science Seminar series in order to foster graduate student enthusiasm towards physics research. I hosted several public lectures as part of our Spring Seminar Series, Distinguished lecture series and as co-host for the Space Center Lecture series. I appeared on an episode of “The Universe” on the History Channel, was interviewed for the Houston Chronicle’s blog “Meet a Scientist Monday #12” and gave interviews on Fox 26 news and Radio One. In addition, I helped community members and other faculty members whenever an expert in Physics was needed. For example, I helped Keith Parsons when he needed opinions on his book about the philosophy of science. I also helped Jay Wright, from JSC, when he needed load calculations for his KC-135 experiment and helped the Yale Drop Team prepare their experiment for a flight in the KC-135 (vomit comet).

2.2.5 Honors

During my time at UHCL I received several honors. I was honored at the Compact for Faculty Diversity’s ninth annual Institute on Teaching and Mentoring with a plaque commemorating me as a Sloan Scholar. I was also named a NASA Faculty Fellow. My high school, Fort Zumwalt North, honored me in their inaugural “Hall of Fame”. In addition, I received public recognition in both the UH System’s Success Stories and the Egret Magazine. In 2012, I was chosen for inclusion in the HistoryMakers oral history archive.

2.2.6 Research Development

Much of my work focused on developing the capacity for Physics research on the UHCL campus. This involved the development of the Astrophysics Colloquium Series, the Fall and Spring Physics & Space Science Seminar series, the MOU with JSC’s ARES, the Joint UH/UHCL Physics Journal Club, the development the computational physics and plasma science labs and our special guest lecture series. These events not only improved our research capacity but also helped to increase enrollment by publicizing the Physics program. The development of the new Physics curriculum and my Summer Faculty Fellowship research with the VASIMR project also contributed to this effort. My goal is to bring UHCL students into physics research that will be of mutual benefit to the students, UHCL and the JSC community.

In 2004, I chaired an informal faculty task force whose mission was to evaluate the computational needs and resources of SCE. This led to UHCL joining the Texas Educational Grid Project and accepting a donation of a 48 node Beowulf Cluster from Conoco Phillips. In addition to the cluster, I also built and maintained a computational physics lab in Bayou 3104 until I was fortunate enough to move my work into Bayou 3324. I am currently working with several students to build a 5 node computational mini cluster for student training and small research projects.

During this time I was active in learning everything I could about pursuing external grants. I helped plan and participate in a visit from the Research Corporation. I attended a grant-writing workshop at the University of Texas in Dallas that was sponsored by the National Science Foundation. I also attended a grant writer's workshop at UH. In addition I initiated agreements with two scientists, Dr.'s Tafa and Tarditi to volunteer their time as Visiting Research Scholars so that we may collaborate more freely on research projects of mutual interest. In 2007, I began to work with faculty from UH on the development of a Space Research Cluster. That year I also attended Helen Lane's talk on possible research collaborations with JSC before preparing my NASA ROSES grant proposal.

I participated in the planning for several major grants such as the NASA ISS National Lab, NASA JSC Internship CAN, NSF S-STEM, a $1,000,000 funded MRI grant with UH and the Ron McNair foundation grant. I was also PI on our largest grant attempt, a center for commercial space transportation through the FAA. The grant involved over 125 participants from UHCL, UH and Rice and was worth $10,000,000 from the FAA with an additional $10,000,000 match from local industry. I was able to assemble a team to produce this proposal in less than one month.

2.3 PROFESSIONAL ACTIVITIES AND SERVICES

2.3.1 Service to the Profession

In an effort to develop myself professionally, I have continued to be involved in several organizations outside of the university. These professional organizations and societies keep me up to date on advances in the field, provide me with opportunities to present my research and help me to maintain contacts with other physicists. Because I was the only full-time physicist for my first several years at UHCL, contact with other physicists through these organizations has been especially valuable.

In addition to my memberships in professional societies I have been involved in several other professional service activities. In 2005, I was invited to chair a session at the April Meeting of the American Physical Society, but was unable to attend because of lack of funding. I often peer-review grants and articles. I also Peer-reviewed other Physics Departments for the U.S. News & World Report's America's Best Graduate Schools issue. In 2006, I was interviewed for Project Crossover, a study about how people transition from students to scientists. In 2012, I meet with faculty from several other physics programs (Texas and Nation wide) to address the enrollment issues in the field.

2.1.4.3 Membership

1. American Physical Society (APS) – This is the largest national organization for Physicists. It does more to promote physics research than any other organization.
2. American Association of Physics Teachers (AAPT) – The primary function of this organization is to promote physics education and physics education research. Members are K-12 teachers as well as University Faculty.
3. National Society of Black Physicists (NSBP) – I have attended every annual meeting since 1997. The NSBP has done more to increase the representation of people of color in Physics than any other organization. It is my most important source of professional advice and mentoring.
4. Council of Graduate Schools (CGS) – Although I am not a member as an individual (the University is the member) I have attended annual meetings since being awarded the CGS/Sloan PSM Grant. This organization is active in national policy-making particularly as it applies to the issue of national competitiveness in the sciences.
5. Physics Teacher Education Coalition (PhysTec) – I joined this program on behalf of the physics program. The goal of this organization is to improve Physics Teacher education and the quality of Physics instruction in High Schools.
6. APS Bridge Program – I joined this program on behalf of the physics program. This program focuses on increasing the number of underrepresented minority students in Physics PhD programs by helping them better prepare for the rigors of graduate school. We are currently working to become a funded Bridge Program Site.

2.3.2 Service to the University

My service to the University has been both official and unofficial. By this I mean that I have served on both organized and informal committees in an effort to make the university a better place. Below is a list of many of the positions and committees that I have served on at UHCL. This is probably not a complete list because it is difficult to remember all of them.

2.1.4.3 University Level

1. UHCL Presidential Search Committee – I was chosen by Chancellor Khator to represent the UHCL faculty on the committee.
2. Faculty Senate – I was elected to serve on the Faculty Senate's Research committee beginning in the fall of 2007 and was elected chair in 2008.
3. Faculty Senate President – 2012-13, served as FS President Elect. 2013-14 and 2015-16, served as FS President. 2014-15, served as FS Past President.
4. Faculty Senate Executive Committee – 2008-2009, 2012-2016.
5. University Council – 2008-2009, 2012-2016.
6. Academic Council - 2008-2009, 2012-2016.
7. University Planning and Budget Committee – 2007-2009.
8. Convocation Committee – I served on both the 2005 and 2006 Convocation Committees. In 2006, I chaired a session on Academic New Initiatives that lead to many positive reviews from all those who attended.
9. Faculty Senate Research Task Force – I helped Dr. Sanchez by developing an online survey of the faculty about their research needs and how they are being supported.
10. Black History Month Faculty Panel – Participated on two Black History Month Panels (one in 2004 and the other in 2007). Both panels focused on education and career opportunities for black students.
11. Participated in the development of an educational game for K-12 students. This also served to promote the university.
12. Worked with the University Advancement office on projects, such as the Wine under the Stars event and the Gates public lecture.
13. Planned and hosted a visit and public lecture by Professor James Gates, Jr. and used the proceeds to fund our search for a Visiting Assistant Professor of Physics. About 200 people attended the lecture.
14. Planned and hosted a visit and public lecture by Dr. Neal Lane. About 200 people attended the lecture.
15. Planned and hosted a visit and public lecture by Professor John Hawley. About 400 people attended the lecture.
16. Planned and hosted a visit and public lecture by Dr. Joseph Romm. About 75 people attended the lecture.
17. Planned and hosted a visit and public lecture by President Allen Sessoms. About 75 people attended the lecture.
18. Served as the UHCL Goldwater Scholarship Faculty Representative.
19. Served on the New Student Orientation – Spring 2007 and Fall 2008 Faculty Panel – answered questions from new students to help them adjust to life at UHCL.

20. Arranged a tour and visit to JSC for the Provost and several UHCL faculty in order to promote closer relations between the two institutions.
21. Arranged a tour and visit to Ad Astra Rocket Company for Dean Davari and Provost Stockton.
22. Served on the Management of Technology review committee.
23. Participated in Rice's SpaceCity 2020 event on the future of NASA JSC.
24. Meet with LPI to develop a research and education collaboration.
25. Faculty presenter for the Film and History Club's movie Mindwalk.
26. Served on the Computer Services Advisory Committee (CSAC).
27. I am serving on the Provost's Task Force to develop a new Faculty Center at UHCL.
28. Helped organize the Fall 2014 Faculty Retreat at San Jacinto College.
29. Co-founded UHCL's Center for Faculty Development.

2.1.4.3 School Level

1. Director of Graduate Programs – I oversee all aspects of our 13 graduate programs. Some projects which have worked on are: a revised Assistantship Policy, streamlining admissions processes, working with admissions to recruit more domestic graduate students and planning an Advising & Registration Event for new graduate students.
2. Curriculum Committee – I have served on the SCE Curriculum Committee since coming to the University in 2002. In 2006, I was elected chair which I served as until 2008.
3. Professional Physics MS Development Chair – In connection with the CGS/Sloan PSM grant, I was charged with developing the Physics Professional Science Master's program in Technical Management.
4. Proposed MOU with JSC ARES – I worked with Steven Hawley, John Shebalin and several SCE Faculty and Administrators in an attempt to develop a Memorandum of Understanding with NASA JSC in order to increase our access to JSC's research facilities. There was already a similar agreement in place between JSC and UH Central. This eventually resulted in a Space Act Agreement between JSC and UHCL.
5. Student Affairs Committee – Reviewed scholarship applications for all SCE scholarships.
6. SCE Library, Research & Computing Committee – I served on the committee for two years but it never met.
7. Served as the UHCL representative to the Texas Educational Grid Project.
8. Interviewed, hired and helped supervise a web content editor for the SCE website.
9. Served on the SCE Dean Search committee.
10. Served on the SCE Policy and Advisory committee.
11. Served as an Alternate on the SCE Faculty Development committee.
12. Served on Post-Tenure Review Committee.

2.1.4.3 Division Level

1. Chair of Physics – Founded, promoted and developed the UHCL Physics program. I managed as many as 10 adjunct faculty on a given semester and oversaw the educational needs of over 250 undergraduate and graduate students. My duties include biennial planning, creating a strategic plan for the physics program, preparing class schedules, hiring and supervising adjunct faculty, promoting the physics program, managing the physics program's resources and assessing the physics program.
2. Chair of the Physical Sciences – In addition to chairing the Physics program, I also chaired the Physical Sciences program until the programs split in 2005. My duties included biennial planning, creating a strategic plan for the program, preparing class schedules, hiring and supervising adjunct faculty, promoting the program, managing the program's resources and assessing the physical sciences program.
3. Physics Program Development Chair – Chaired an unofficial task force to study the feasibility of developing a physics program at UHCL, wrote the program proposal and oversaw its approval.
4. Physical Sciences Program Review committee – Supplied information to the Program Review Chair, for the review.
5. Aerospace Engineering Task Force – Served as a member of the task force to determine the feasibility of an Aerospace Engineering program at UHCL.
6. Successfully developed an IPA agreement with NASA JSC in order to hire a visiting professor of Physics at no cost to the university.
7. Served as Chair of the Physics Visiting Assistant Professor search committee
8. Served on the Geology Assistant Professor search committee.
9. Participated in the planning of the 2007 AAAS SWARM meeting.
10. Helped organize the UH/UHCL Joint Physics Journal Club
11. Granted a Joint Faculty Appointment with the University of Houston Physics Department.
12. Served as the Chair of the Physics Assistant Professor search committee that hired Dr. Masood.
13. Served as the Chair of the Physics Assistant/Associate Professor search committee that hired Dr. Withey.
14. Served as the Chair of the Physics Assistant Professor search committee that hired Dr. Mayes.
15. Served as the Chair of the Physics Lecturer search committee that hired Mr. Thompson.
16. Served as the Chair of the Physics Program Review committee.

2.1.4.3 Student Advising

1. Physics Club Advisor – Worked to develop a Physics Club at UHCL. Unfortunately the club could not be sustained initially but has since been re-funded.
2. Total Success Mentor – Mentored UHCL students outside of Physics.
3. Black Student Association Advisor – Attended meetings and helped students plan for events such as the Black History Month Celebration Events held at UHCL.

2.3.3 Service to the Community

My service to the community has been incredibly diverse and far-reaching.

1. Participation in the Bay Area Houston Science Teacher Institute Partnership proposal team
2. Ethnic College Counseling Center Counselor – Flew to Florida to help the Ethnic College Counseling Center's HBCU/Black History Tour for K-12 students.
3. 2003 & 2007 Science Engineering Fair of Houston – Judge
4. 2003 -2008 Celebrating Our Elders Essay Scholarship Competition – Judge
5. 2004 -2006 Science Olympiad – Judged the Bridge Building Competition
6. Helped to ship surplus UHCL library books to Nigeria.
7. Stepping Up Speaker - talked to a group of high-risk high school kids from underrepresented backgrounds about careers in Science and Technology.
8. Reviewed Keith Parson's book on the Philosophy of Science for scientific accuracy.
9. NSBE-HSC-Boeing Engineer for a day – Gave talks in 2005, 2006 and 2008 about careers in Science and Technology for a group of elementary and middle school children.
10. Attempted to develop a Physics section for the Kid's U summer program.
11. Gave talks before two groups of high school students on pursuing careers in science and engineering in collaboration with the UHCL admissions office.
12. Gave a talk at the International Space School (hosted by UHCL) about the UHCL Physics program and its Space related research
13. Attended the Boeing Black Employees Association appreciation luncheon
14. Attended the National Society of Black Engineer's Annual Martin Luther King Luncheon as their honored guest
15. Hosted a visit with Congressman Nick Lampson and the Science Faculty to discuss Science Education
16. NSBE – SPRC Meeting – Participated in the Martin Luther King discussion table on how to get more underrepresented minorities interested in careers in science and engineering.
17. Gave a talk in conjunction with the Film and History Club's movie "Mindwalk"
18. Attended the Boeing Black Employee Association (BBEA) Black Heritage Lunch.
19. Gave two talks at San Jacinto College about the Physics Program.
20. Promoted the Engineering Physics sub-plan at the San Jacinto College Engineering Fair.
21. Helped Space Center Houston plan their Physics Day.
22. Helped LPI with their Family Space Day.
23. Served on Space Center Houston's Advisory Board.
24. Gave the Keynote Lecture at the NASA MLK event in 2011.
25. Greeted the graduates on behalf of the faculty at the December 2012 Commencement ceremony.
26. Served on the Science of Science Fiction Panel at Galacticon III, 2013

27. Served on the Educational Advisory Board for Space Center Houston
28. Served on the Advisory Board for Latin Deaf Services, Inc.
29. Served on the Investment Board for AUM Clean Energy Group.
30. Peer-reviewed several articles for publication.
31. Peer-reviewed several grants for funding

3 CURRICULUM VITAE

David Garrison

Web: http//sce.uhcl.edu/garrison

Education

Ph.D. Physics, Pennsylvania State University
Department of Physics, 1997-2002
Dissertation: "Testing Binary Black Hole Codes in Strong Field Regimes"
Dissertation Committee: Jorge Pullin, Pablo Laguna, Abhay Ashtekar, Steinn Sigurdsson.

B.S. Physics, Massachusetts Institute of Technology
Undergraduate studies, 1993-1997
Major in Physics, Minor in Earth Atmospheric & Planetary Science, and Concentration in Political Science.
Undergraduate Thesis: Gravitational Lensing of Extended Radio Sources

Notable Achievements

1. Founded the Physics program at UHCL (BS, MS, Collaborative PhD)
2. Developed the Collaborative UHCL-UH Physics PhD Program through agreement with the UH Physics Department
3. Established the UHCL Physics guest lecture series and Distinguished lecture series
4. Developed the Professional Science Masters of Physics: Technical Management Sub-Plan
5. Developed the undergraduate Engineering Physics sub-plan
6. Developed an advisory board for the UHCL Physics program
7. Helped develop the UHCL Computational Physics Laboratory, Physics Teaching Laboratory and Plasma Physics Laboratory
8. PI of a multi-university unfunded FAA Center of Excellence in Commercial Space Transportation. The proposal involved 125 participants and was completed in less than one month.
9. Co-founded UHCL's Center for Faculty Development
10. Appeared on an episode of "The Universe" on the History Channel.
11. Interviewed several times on Television, Radio and the World Wide Web.
12. Interviewed for HistoryMakers - ScienceMakers series

Honors, Grants and Fellowships

UHCL Faculty Development Fund Award Total, $22,913
UHCL Faculty Research Support Fund Awards Total, $24,916
NSF SSTEM Co-I, 2013, $592,468
HistoryMakers – ScienceMaker, 2012
Institute for Space Systems Operations Grant, 2010, $66,800
Fort Zumwalt North Hall of Fame Inductee, 2009
Institute for Space Systems Operations Mini-Grant, 2006, $7,077
Institute for Space Systems Operations Mini-Grant, 2005, $6,666
Council of Graduate Schools PSM implementation grant, 2005-2007, $25,000
NASA Faculty Fellowship Program at JSC, 2004, $12,000
Institute for Space Systems Operations Post-Doctoral Aerospace Grant, 2004, $20,000
Council of Graduate Schools Professional Science M.S. planning grant, 2004, $6,000
NASA GSRP Fellowship, 2001-2002, $27,000
Academic Computing Fellowship, 2001-2002, $15,000
Sloan Scholar, 1998-2002
Bayer Fellowship, 1997-1998, $3,000
Minority Scholars Award, 1997-1998

Class of 1961 Clarke E. Swannack Scholarship Recipient, 1995-1997
University Club Scholarship Recipient, 1993-1997
National Merit Scholarship Commended Student, 1993

Teaching/Adminstrative Experience

Director of Graduate Programs for the School of Science and Computer Engineering & Associate Professor of Physics, University of Houston-Clear Lake (Joint Faculty appointment with the University of Houston as Associate Professor of Physics)- 2014-Present

The Graduate Program Director serves as the administrator reporting to the academic dean for the school and assists the dean and associate dean in planning, executing, and monitoring the school's activities. In coordination with the division heads, program chairs, and where appropriate, others at the School, the Graduate Program Director coordinates all activities related to graduate programs and processes through the several primary responsibilities. I also developed a Recruitment Plan in order to increase domestic graduate student enrollment in the college and I am currently running a targeted marketing program.

Department Chair & Associate Professor of Physics, University of Houston-Clear Lake (Joint Faculty appointment with the University of Houston as Associate Professor of Physics) –2008-2015

Founded and developed the UHCL Physics program (BS, MS, Collaborative PhD, PSM Physics sub-plan in Technical Management and the BS Engineering Physics sub-plan). Presently teaching undergraduate and graduate level physics and astronomy courses. Classical Mechanics, Electrodynamics, Fundamentals of Spacetime, General Relativity, Modern Physics Research, Methods in Computational Physics, Research Project and Seminar, Mathematica for Physics and Mathematical Methods in Physics I & II. Other duties include: advising and mentoring students, community outreach, running the UHCL Physics seminar series, promoting the physics and space science programs, managing adjunct faculty, developing the school's undergraduate and graduate physics curriculum, managing a research program in theoretical and computational physics and developing the educational and research relationships between UHCL, UH and the Johnson Space Center.

Department Chair & Assistant Professor of Physics, University of Houston-Clear Lake –2003-2008

Some duties included biennial planning, creating a strategic plan for the physics program, preparing class schedules, service on the school curriculum committee, hiring and supervising roughly four to seven adjunct professors per semester, promoting the physics program and managing the physics program's resources.

Visiting Assistant Professor and Interim Chair of Physical Sciences, University of Houston-Clear Lake – 2002-2003

Taught graduate and undergraduate level physics courses. Classical Mechanics, Electrodynamics, Special Relativity, Research Methods in Space Science, Research Project & Seminar and Mathematical Methods in Physics I & II. Other duties included: advising and mentoring students, community outreach, promoting the physics and space science programs, managing adjunct faculty, developing the school's physics curriculum, developing a Master's degree in physics program, starting a physics research program and improving the relationship between UHCL and the Johnson Space Center.

Teaching Assistant, Pennsylvania State University --1998-2000

Taught recitations and labs for several introductory level physics classes. Courses include virtually every course in Penn State's Algebra and Calculus based Physics Curriculum. Examples include: Physics 202 - Calculus based physics for engineers focusing on electrostatics taught using traditional recitations and lectures; Physics 203 - Calculus based physics for engineers focusing on thermodynamics and modern physics taught using traditional recitations and lectures; Physics 212 - Calculus based physics for engineers focusing on electrostatics taught using dynamic physics, a combination of group learning in recitations and labs as well as traditional lectures; Physics 215 - Algebra based physics for pre-med students focusing on classical mechanics and thermodynamics taught using traditional recitations and lectures.

Writer, Thinkwell --2001

Helped develop interactive Physics CD's that included video lectures and tests. I wrote practice tests and answer keys for each unit.

Instructor, Kaplan --1999-2001

Prepared Students for the Physics section of the MCAT Medical School Admissions exam using a series of lectures. Each lecture lasted for three hours; the first was on classical mechanics, the second was on electrostatics and thermodynamics and the last was on magnetism and modern physics. These lectures focused on reviewing the material as well as test taking techniques and confidence building.

Teaching Assistant, Washington University --1994

Assisted Prof. Ogilvie of Washington University in developing and preparing the curriculum for Computational Physics for Washington University Juniors, Seniors and first year Graduate Students. My work included setting up computers, installing software and networking, developing and testing homework projects and writing elements of the curriculum. Matlab, Fortran and Maple where used.

Physics Tutor, --1994-2002

Individually tutored several students in basic and advanced undergraduate level math and physics courses. Examples include: 8.01 and 8.02 at MIT; Physics 201, Physics 202, Physics 203, Physics 204, Physics 211, Physics 212, Physics 213, Physics 214, Physics 215, Physics 237, Physics 265, Physics 400 and Physics 419 at Penn State.

Research Experience

Associate Professor, University of Houston-Clear Lake –2008-Present

Various research projects both independently and in collaboration with NASA JSC. Research topics include numerical relativity, cosmology, computational physics and plasma physics. My focus is on studying the early universe using numerical simulations.

Assistant Professor, University of Houston-Clear Lake –2003-2008

Various research projects both independently and in collaboration with NASA JSC. Some research topics include numerical relativity and cosmology as well as collaboration with the Advanced Space Propulsion Laboratory's VASMIR project for the development of a Plasma rocket engine.

Visiting Assistant Professor, University of Houston-Clear Lake –2002-2003

Various research projects both independently and in collaboration with NASA JSC. Work included numerical relativity and cosmology as well as collaboration with the Advanced Space Propulsion Laboratory's VASMIR project for the development of a Plasma rocket engine.

Research Assistant, Pennsylvania State University --1998-2002

Working with Prof. Jorge Pullin and Prof. Pablo Laguna on several projects in an effort to develop numerical codes to solve the problem of the 3D spiraling coalescence of two black holes. This project is done in Penn State's Center for Gravitational Physics and Geometry in order to realize the top candidate for a gravitational wave source that may be detected by LIGO. Most of my work is based on developing a method of testing the stability of the numerical codes using periodic cosmological systems, which lack singularities. Using these modes I induced constraint violating and gauge modes in unstable codes and identified early clues to their instability. Additional projects included a study of gravitational gradient noise in gravity wave detectors, applying causal differencing to our evolution methods and the development of black hole spectroscopy, a method of using data from gravitational wave detectors to determine the mass and angular momentum of a black hole.

B.S. Physics Thesis Project, Massachusetts Institute of Technology -- 1996-1997

Worked with Prof. Jacqueline Hewitt simulating the gravitational lensing of observed images to determine the conditions under which a gravitational lens is detectable. I used Monte Carlo techniques and an unlensed radio image of Cygnus-A to generate statistical data on the luminosity ratios of lensed radio lobes. Next I compared the results to the natural range of luminosity ratios of unlensed radio lobes caused by varying the orientation of the radio lobes with respect to the observer. I then attempted to show whether or not gravitational lenses could be detected by simply looking at the luminosity ratios of the radio lobes. This knowledge could lead to new techniques in the detection of dark matter.

Research Assistant, Washington University --1995

Worked with Prof. Ogilvie and Prof. Will of Washington University on several projects in theoretical Physics such as variable calculations and computer simulations, which provided me with an introduction to General Relativity and gauge theory. Many of the simulations used Unix based visualization packages although some of the work was based on using symbolic manipulators to plot analytic functions.

Research Assistant, Massachusetts Institute of Technology --1995

Worked with Prof. David Pritchard on a project to measure the mass of ions more precisely than ever before. The data gained from this experiment will be used to develop a new atomic standard for the kilogram, and is accurate enough to find the “rest mass” of both gamma waves and atomic bonds. Much of my work included building electronics and analyzing data.

Research Assistant, Massachusetts Institute of Technology -- 1994

Worked in the Undergraduate Research Opportunity Program (UROP) with Prof. John King to develop an ultrasonic whistle capable of producing high frequency sounds (25 kHz) at 145 dB of intensity. Based on a Hartman Whistle, I machined several models myself using a metal lathe and brass stock and tested them using high frequency microphones.

Selected Publications

1. Relativistic Magnetohydrodynamic Turbulence in the Early Universe by David Garrison, to appear in the Proceedings of the 10th Chaotic Modeling and Simulation International Conference.
2. Extracting Gravitational Waves Induced by Plasma Turbulence in the Early Universe through an Averaging Process by David Garrison and Christopher Rameriz, arXiv:1503.04764, Classical and Quantum Gravity 34, 145008 (2017).
3. Using Gravitational Waves to put limits on Primordial Magnetic Fields by David Garrison, arXiv: 1608.01005, *GJSFR-A Volume 17, Issue 1 (2017)*
4. Invariants in Relativistic MHD Turbulence by David Garrison and Phu Nguyen, *Journal of Modern Physics*, **7**, 281-289. doi: 10.4236/jmp.2016.73028, arXiv:1501.06068
5. Gauge Field Turbulence as a Cause of Inflation in Chern-Simons Modified Gravity by David Garrison, to appear in the Proceedings of the 7th Chaotic Modeling and Simulation International Conference
6. Numerical Relativity as a tool for studying the Early Universe by David Garrison, Journal of

Gravity, vol. 2014, Article ID 407197, 11 pages, 2014. doi:10.1155/2014/407197, gr-qc/1207.7097

7. A Numerical Simulation of Chern-Simons Inflation by David Garrison and Christopher Underwood, Advances in Astronomy, Volume 2013, 207218, hep-th/1208.2660
8. What Every Successful Physics Graduate Student Should Know by David Garrison, Smashwords, 2013
9. TESTING BINARY BLACK HOLE CODES IN STRONG FIELD REGIMES: UNDERSTANDING NUMERICAL INSTABILITIES THROUGH COMPUTATIONAL EXPERIMENTS by David Garrison, LAP Lambert Academic Publishing, 2011
10. Numerical Cosmology: Building a dynamical universe by David Garrison, AIP Conf. Proc., 2010 -- Volume 1280, pp. 65-69.
11. Gravitational Waves and the Evolution of the Universe by David Garrison, AIP Conf. Proc., 2009 -- Volume 1140, pp. 42-45.
12. Did Gravitational Waves Affect the Evolution of the Universe? by David Garrison, gr-qc/808.1764.
13. Numerical analysis of simplified Relic-Birefringent gravitational waves by David Garrison and Rafael de la Torre, Classical and Quantum Gravity 24 (2007) 5889
14. Serving Nontraditional Graduate Students by David Garrison, Physics Today, January 2007
15. Development of a Comprehensive Physics Program at a non-traditional upper-level undergraduate and graduate small university by David Garrison, APS Forum On Education Spring 2006 Newsletter
16. Testing Binary Black Hole codes with Cosmological Spacetimes by David Garrison, Proceedings of the Tenth Marcel Grossman Meeting on General Relativity, 2006
17. Gravity Gradients in LIGO: a proposal for Data Analysis by David Garrison and Gabriela Gonzalez, Proceedings of the Tenth Marcel Grossman Meeting on General Relativity, 2006
18. Black Hole Spectroscopy: testing general relativity through gravitational-wave observations by Olaf Dreyer, Lee Finn, Ramon Lopez-Aleman, Badri Krishnan, Bernard J. Kelly, David Garrison, Classical and Quantum Gravity 21 (2004) 787-803
19. Causal Differencing in ADM and Conformal ADM Formulations: A Comparison in Spherical Symmetry. by Luis Lehner, Mijan Huq, David Garrison. 2000. Physical Review D. Volume 62, 084016
20. Notes on causal differencing in ADM/CADM formulations: a 1D comparison by Luis Lehner, Mijan Huq, David Garrison, gr-qc/0004065

Selected Presentations and Posters

1. Barcelona, Spain: 10th Chaotic Modeling and Simulation International Conference – May 31, 2017 - Relativistic Magnetohydrodynamic Turbulence in the Early Universe
2. Berkley, CA: Sustainable Pathways Workshop – December 7, 2016 – Poster on Gravitational Waves induced by Plasma Turbulence in the Early Universe
3. New York, NY: GR21 – July 11, 2016 – Poster on Numerical Simulations of Cosmological Gravitational Waves from MHD Turbulence.
4. Commerce, TX – March 26, 2015 – Invited talk on Characterization of Gravitational Waves from Primordial Relativistic Turbulence.
5. Lisbon, Portugal: CHAOS 2014 – June 7, 2014 – Gauge Field Turbulence as a Cause of Inflation in Chern-Simons Modified Gravity.
6. Houston, TX: University of Houston – April 4, 2014 - Invited talk on Numerical Relativity as a tool for studying the Early Universe.

7. Houston, TX: Rice University – October 23, 2013 – Invited talk on Numerical Relativity as a tool for studying the Early Universe.
8. Houston, TX: WALIPP TSU Preparatory Academy – September 27, 2013 – Back to School with the History Makers.
9. Houston, TX: North Houston Astronomy Club – March 22, 2013 – Invited talk on Numerical Cosmology
10. Austin, TX: National Society of Black Physicists – September 24, 2011 – Invited Talk – Spectral Methods in General Relativistic MHD Simulations
11. Houston, TX: Houston Astronomical Society – September 2, 2011 – Invited Talk – Gravitational Radiation from the Early Universe
12. Houston, TX: United Space School – July 26, 2011 – Invited talk about the Physics Program at UHCL
13. Pittsburgh, PA: Carnegie Mellon University – April 15, 2011 – Invited talk on Numerical Simulations of Gravitational Waves from Primordial Turbulence
14. Houston, TX: Johnson Space Center – February 16, 2011 – Invited talk on African-American Scientists and Engineers: Standing on the Shoulders of Giants
15. Houston, TX: Foundation for International Space Education – July 27, 2010 – Invited talk about the Physics Program at UHCL
16. Houston, TX: JSC Astronomical Society – November 13, 2009 – Invited talk - Gravitational Wave Astronomy 101
17. Houston, TX: Annual Banquet of the Houston Astronomical Society – October 10, 2009 – Keynote Address – Gravitational Wave Astronomy 101
18. Tampa, FL: University of South Florida – September 26, 2008 – Invited talk on Numerical Cosmology – Building a Dynamical Universe
19. Washington, DC: National Society of Black Physicists – February 22, 2008 – Invited talk on Gravitational Waves and the Evolution of the Universe
20. Houston, TX: University of Houston Clear Lake – November 29, 2007 – Invited talk on Numerical Cosmology for Poets
21. Houston, TX: University of Houston – October 9, 2007 – Invited talk on Cosmic Structure Formation via Gravitational Radiation
22. Eugene, OR: University of Oregon – May 11, 2006 – Invited talk on Cosmic Structure Formation via Gravitational Radiation
23. Orlando, FL: National Society of Black Physicists – February 19, 2005 – Invited talk on Computational Electromagnetism
24. Grinnell, IA: Grinnell College – May 4, 2004 – Invited talk on Gravitational Wave Physics.
25. Rio de Janeiro, Brazil: Tenth Marcel Grossmann Meeting on General Relativity – July 21, 2003 – Talk on Testing Binary Black Hole Codes with Cosmological Spacetimes, July 25, 2003 – Talk on Gravitational Gradient Noise.
26. Atlanta, GA: National Society of Black Physicists – February 13, 2003– Invited talk on Gravitational Wave Physics.
27. Paris, France: UNESCO - July 22, 2002 - Poster on Testing Numerical Relativity Codes in Strong Field Regimes.
28. Houston, TX: Texas Southern University – February 11, 2002 – Invited talk on Gravitational Wave Research.

Skills

Experience with: Macintosh, UNIX, LINUX, Windows, and DOS operating systems; Networking systems including Internet Web Servers; Mathematics software such as Maple, Matlab, and Mathematica; R, C, C++, Visual Basic, Perl, HTML, Java, JSP, ASP, SQL, and Fortran programming languages.

Activities & Organizations

NPSMA Advisory Board – 2017-Present
AUM Clean Energy Group, Investment Board – 2013-2014
Space Center Houston, Educational Advisory Board Member – 2012-Present
Latin Deaf Services, Inc., Advisory Board Member – 2011-Present
UHCL Faculty Senate – 2007-2009, 2012-2015
UHCL Faculty Senate Executive Committee - 2008-2009, 2012-2015
UHCL Faculty Senate President Elect, President and Past President – 2012-2015
UHCL Faculty Senate President – 2015-2016
UHCL University Council – 2008-2009, 2012-2015
UHCL Academic Council – 2008-2009, 2012-2015
UHCL Faculty Senate Research Committee – 2007-2009 – Chair -- 2008-2009
UHCL Planning and Budget Committee – 2007-2009
UHCL Black Students Association – Advisor – 2005-2007
Organized UHCL Physics and Space Science Guest Lecture Series – 2003-Present
UHCL Physics Club – Co-advisor – 2002-Present
American Association of Physics Teachers -- 2002-2003
National Society of Black Physicists -- 2002-Present
American Physical Society -- 1994-Present
Kappa Sigma Fraternity –1993-Present -- Social Chair – 1995-1996
MIT Varsity Football Team -- 1993, 1994 & 1996
National Society of Black Engineers --1993-1997
Black Student Union, Society of Physics Students --1993-1997
Helped organize 1997 National Conference for Black Physics Students -- 1997
National Honor Society -- 1989-1993
Jazz Band improvisational soloist --1989-1993

4 ANNUAL REPORTS

4.1 2002 Annual Report

4.2 2003 Annual Report

4.3 2004 Annual Report

4.4 2005 Annual Report

4.5 2006 Annual Report

4.6 2007 Annual Report

4.7 2008 Annual Report

4.8 2009 Annual Report

4.9 2010 Annual Report

4.10 2011 Annual Report

4.11 2012 Annual Report

4.12 2013 Annual Report

4.13 2014 Annual Report

4.14 2015 Annual Report

4.15 2016 Annual Report

FACULTY ANNUAL REPORT

David Garrison, Visiting Assistant Professor of Physical Science
August 19, 2002 through December 31, 2002

TEACHING AND EDUCATIONAL ACTIVITIES

During the Fall 2002 semester I taught two classes and advised an independent study student who was finishing his degree. Below are details of all teaching activities:

1) PHYS 5931 Section 02 – Research Topics in Physics: Classical Mechanics

   This was a graduate level class contained a total of four graduate students and one undergraduate student. One of the graduate students is a Ph.D. Physics student at the University of Houston who wanted to take the class at UHCL and transfer credit to UH. Student comments on the class were good. They seemed to like the pace of the class and liked the organization and overall quality of the course. Most of the evaluation categories had a mean of 4.0 or greater. Based on their comments, the students liked the way I answered questions and explained concepts but would like me to provide copies of the lecture notes and homework solutions.

2) PHYS 4331 Section 01 – Principles of Electromagnetism

   This was an undergraduate class which was taught in conjunction with a section of PHYS 5931. The class contained eight students only four of whom took the class for credit. Based on the student's comments, many of them seemed to like the pace of the class as well as its overall quality and my teaching capability. All of the evaluation categories (except for the pace of the course) had a mean of 4.25 or greater. The students written comments seemed to suggest that they liked the way I explained the math solutions in compliment to the textbook.

3) ASTR 6838 Research Project and Seminar

   This was an individual instruction capstone course for the Space Science concentration of the Physical Science master's degree program. I advised one student within the course who successfully completed his master's degree at the end of the fall semester.

COURSE AND PROGRAM DEVELOPMENT

During the fall of 2002, I began work on the development of a master's degree of physics program at UHCL. This process began with an online survey of the JSC/Contractor community. I developed the software to conduct the survey on my own. I then used the electronic newsletter "JSC Today" as well as contacts in many of the contractor's human resources departments to distribute it to the local community. I received 233 responses over the next two months. I then developed a website called Physics Program Notes to answer questions and keep the community informed of any advances made to the program's development. The interest that I generated lead to the development of a Physics Club at UHCL and support from several high level people at the University of Houston's Physics Department, JSC, USA and Lockheed.

RESEARCH, SCHOLARLY AND ARTISTIC ACTIVITIES
I received a Faculty Development Fund award to attend the Texas Section of the APS meeting in Brownsville Texas between October 11th and 13th. While there I gave a talk on methods of testing the stability of binary black hole codes using cosmological spacetimes.

I attended the SREB conference on Teaching and mentoring in Washington, DC from October 25th through October 27th.

In November, I received a Faculty Research and Support Fund award for a project titled "Numerical Cosmology". The purpose of this project is to develop a computer code to perform numerical tests of various cosmological theories. Since receiving the award, I have been actively collaborating with a group at JSC. To further stimulate this research I began a weekly Astrophysics Seminar series focusing on cosmology.

During the fall, I also submitted a paper for publication in the Physical Review D and to the Proceedings for the 2002 meeting of the National Society of Black Physicists.

HONORS
On October 25th, I received an award from the Sloan Foundation for completing their fellowship program.

PROFESSIONAL ACTIVITES AND SERVICE
Last year, I managed to attend all but one of the monthly faculty meetings of the School of Science and Computer Engineering. In addition to serving on the admissions and administrative committees for the Physical Science program, I also served on the School of Science and Computer Engineering's Curriculum Committee and as Advisor to the Physics Club.

WEB LINKS
The Physics Program Notes website is located at:
http://sce.cl.uh.edu/physicalscience/PhysicsProNotes.html
The Physics Program Survey of interest is located at:
http://nas.cl.uh.edu/garrison/survey/
The latest results of the Physics Program Survey are located at:
http://nas.cl.uh.edu/garrison/survey/results.asp

FACULTY ANNUAL REPORT

David Garrison, Faculty Chair and Assistant Professor of Physics
January 1, 2003 through December 31, 2003

TEACHING AND EDUCATIONAL ACTIVITIES

My students find me to be challenging and demanding but fair. Virtually all the students who filled out teaching evaluations enjoyed my courses and feel that they have learned a lot from me. My colleagues tend to agree.

Classroom Instruction:

Spring 2003:

- Special Relativity – 5 graduate students
- Research Methods in Space Science – 1 graduate student
- Research Project and Seminar – 5 graduate students
- Mathematical Methods in Physics 1 – 9 graduate students

Summer 2003:

- Mathematical Methods in Physics 2 – 7 graduate students

Fall 2003:

- Mathematical Methods in Physics 1 – 6 graduate students
- Classical Mechanics – 12 graduate students
- Spacetime Physics – 3 graduate students for credit, 1 for no credit

Individual Instruction and Advisement (other than organized classes)

- Advised all undergraduate and graduate physical science students (about 50 total)
- Supervised 5 research projects

Organized Mentoring

- Multicultural & International Student Services (MISS) Office' Total Success Mentoring Program – Mentored one student who was in the process of finishing her degree in MIS. The goal of this program was to help her finish her degree and decide what to do after graduation.
- Independent Study Mentorship (ISM) Program with Clear Lake Independent School District – As a result of this program I introduced this student to relativity and he completed two projects (one on special relativity the other on GPS and cosmology) and presented a final report on these topics.

COURSE AND PROGRAM DEVELOPMENT

- Oversaw the approval of the new Undergraduate Physical Science Program focusing on teacher certification
- Developed and oversaw the approval of a new Graduate Physics Program
- Developed a proposal for a Professional Science Master's Degree Program with the Council of Graduate Schools and the Sloan Foundation
- Worked with the Bay Area Houston Science Teacher Institute Partnership on an NSF proposal to enhance K-12 science education

- Developed three completely new courses, Special Relativity and Tensors (later renamed Fundamentals of Spacetime), Mathematical Methods in Physics 1 and Mathematical Methods in Physics 2
- Attended 5 academic and training fairs to promote the Physics and Physical Science programs
- Attended all UHCL undergraduate and graduate open houses

DEVELOPMENT OF EDUCATIONAL MATERIALS

- Began development of Web Enhanced versions of the core Graduate Physics courses – Completed the online notes for Mathematical Methods in Physics 1

RESEARCH, SCHOLARLY AND ARTISTIC ACTIVITIES

- Conducted a weekly Astrophysics Seminar series between JSC and UHCL
- Attended a weekly telephone conference on numerical relativity hosted by Penn State's Center for Gravitational Physics and Geometry

PUBLICATIONS

- Black Hole Spectroscopy: testing general relativity through gravitational-wave observations, Olaf Dreyer, Lee Finn, Ramon Lopez-Aleman, Badri Krishnan, Bernard J. Kelly, David Garrison, Classical and Quantum Gravity 21 {2004) 787-803

PAPERS PRESENTATIONS, ABSTRACTS AND POSTER SESSIONS

- Gave an invited talk at the 2003 NSBP meeting in Atlanta, "Introduction to Gravitational Wave Physics"
- Gave two talks at the Tenth Marcel Grossman Meeting on Gravitational Physics (MGX) in Rio de Janeiro, "Testing Binary Black Hole Codes using Cosmological Spacetimes" and "Gravity Gradients in LIGO: A Proposal for Data Analysis"

HONORS and AWARDS

- FDF Award: $1500, $1299
- Received a travel grant to attend the MGX Meeting: $1000

PROFESSIONAL ACTIVITES AND SERVICE

- Served as Program Chair of Physics and Physical Sciences
- Served on the SCE curriculum committee
- Served as advisor to the Physics Club
- Served as a judge for the 2003 Science and Engineering Fair of Houston
- Served on the Office of University Advancement's Inclusion Committee
- Served as a judge for the Celebrating our Elder's Scholarship Competition
- Worked on developing a Memorandum of Understanding between the Physics Program and the Johnson Spaceflight Center (JSC)
- Featured on NASA's African-Americans in Space Science Poster

WEB LINKS

The Physics Program Informational website is located at:

- http://sce.cl.uh.edu/physicalscience/PhysicsProNotes.html

The latest results of the Physics Program Survey are located at:

- http://nas.cl.uh.edu/garrison/survey/results.asp

The follow-up survey results are located at:

- http://nas.cl.uh.edu/garrison/survey2/results.asp

FACULTY ANNUAL REPORT

David Garrison, Faculty Chair and Assistant Professor of Physics and Physical Sciences
January 1, 2004 through December 31, 2004

TEACHING AND EDUCATIONAL ACTIVITIES

My students find me to be challenging and demanding but fair. Virtually all the students who filled out teaching evaluations enjoyed my courses and feel that they have learned a lot from me. My colleagues tend to agree.

Classroom Instruction:

<u>Spring 2004:</u>

- PHYS 5331 Electrodynamics – 11 graduate students. I introduced this course to the UHCL curriculum during the fall of 2002 as an expansion of the electromagnetism survey course. Since then, it has become part of our graduate core curriculum.
- ASTR 6230 / 6838 Research Project and Seminar / Research Methods in Space Science – 3 graduate students. These are the capstone courses for students completing the Masters of Physical Science degree. I modified this course to be centered on teaching student's communications skills as well as research. Students complete research projects and then present research papers both orally and in written form. The seminar portion of this course has become very popular in the local community.

<u>Summer 2004:</u>

- PHYS 5931 Using Mathematica to Solve Physics Problems – 8 graduate students. This was a new course (first time preparation), which I developed to teach students to use the Mathematica computer program to solve advanced physics problems. We covered a variety of subjects during the summer but the main purpose of the class was to introduce a new tool to the students for use in other physics courses and research.

<u>Fall 2004:</u>

- PHYS 5531 Mathematical Methods in Physics 1 - 14 graduate students. This was a class, which I originally introduced in the spring of 2003. During the fall of 2004, I web enhanced the course in order to make it more flexible for students who work full-time. The course covers 8 topics of advanced mathematics which include: Ordinary Differential Equations, Infinite Series, Integration Techniques, Fourier Series and Transforms, Complex Variables, Linear Algebra, Partial Differential Equations and Probability & Statistics. Students consider this to be the most intense of the core physics courses and the most essential to further success in physics. Those who survive the course tend to do very well in the other physics classes.
- PHYS 5431 Classical Mechanics – 9 graduate students. I originally developed this course in the fall of 2002. It is based on a similar course given at Penn State

and is easily the equivalent of a Ph.D. level classical mechanics class. It teaches Newtonian mechanics through Hamiltonian formulations.

- PHYS 6131 Fundamentals of Spacetime – 4 graduate students. This was my absolute favorite course to teach. I originally developed this class in the spring of 2003 and I can honestly say that it is unique among physics curricula anywhere. I created the class as a way of preparing students to take general relativity at the graduate level. Students are taught about special relativity and tensors from a graphical rather than purely mathematical approach. Special relativity is derived from first principles and towards the end of the class, Maxwell's equations of electrodynamics are derived.

Course evaluations:

Course Title	Pace	Overall Quality	Subject Knowledge	Overall Teaching	Stimulate & Challeng Students	Encourage Class Participation	Helping Students Understand
PHYS 5331	3.00	5.00	5.00	5.00	5.00	5.00	5.00
ASTR 6838	4.13	3.63	3.50	3.75	4.00	4.50	4.13
PHYS 5431	4.00	3.78	4.22	3.78	3.67	4.22	3.78
PHYS 5931	N/A	N/A	N/A	N/A	N/A	N/A	N/A
PHYS 5431	4.00	3.78	4.22	3.78	3.67	4.22	3.78
PHYS 5531	4.30	3.80	4.30	3.80	3.70	3.90	4.00
PHYS 6131	4.00	4.50	5.00	4.25	4.75	4.50	5.00

Selected Comments:

PHYS 5331 Electrodynamics:

"Enthusiastic and enjoys his work. He is friendly and always willing to try and help"

"Hire more physics teachers to help even the load. Dr. Garrison is good but he cannot do everything."

"Excellent coverage of much material to an audience of mostly full-time employees. I learned quite a bit in this class."

PHYS 5431 Classical Mechanics:

"Well prepared notes for class: explains steps missing in book explains subject matter well."

"Good coverage, kept compatibility with scope at other university mechanics courses."

"Concise and follows text & schedule. Thorough treatment of material and coverage of difficult textbook."

"The course covered a lot of material. By the end I feel I have a good understanding of a complex subject. Topics were tied together very well."
"Enjoyed the course."
"Very knowledgeable about the material. Can answer questions about the lecture content readily."
"Part of the problem may be that Dr. Garrison teaches an awful lot of classes, making it difficult to prepare. He needs more professors."

PHYS 5531 Mathematical Methods:

"Thorough & knowledgeable. Moves fast & covers lots of material."
"Very prepared and approachable. Covered large amount of material in a short time in a way that made sense."
"Dr. Garrison could probably use some more faculty so that he has more time to prepare for class and fix these problems."
"He will become an outstanding professor!"

PHYS 6131 Fundamentals of Spacetime:

"-knows the subject well
-good presence and presentation
-good sense of humor"
"Dr. G is destined to be a really great professor."
"Dr. Garrison is well prepared for this class. He enjoys the subject and strives to ensure that students are grasping the concepts."
"I enjoyed this class, the lectures and problems sets. I learned several new concepts."
"He knows the subject material extremely well and is able to clearly communicate the core ideas."
"He is very encouraging of students to think and ask questions."
"The instructor was very knowledgeable about the material. A complex subject was presented in a way that was relatively easy to understand."

Individual Instruction and Advisement (other than organized classes)

- Advised all undergraduate and graduate physics and physical science students (about 50 students total)
- Supervised 3 final research projects – "Detection and Methods for Accessing the Potential Near and Deep Martian Subsurface Water", "Detection of Transiting Earth-Sized Extra-Solar Planets of Nearby Stars Using the Kepler Photometer" and "Continuous Thrust Transfer Orbits and Launch Window Determination for Earth-Deimos Travel"
- Supervised 1 Thesis Student – He was working on a method of developing a battery on the moon as part of the new vision of NASA. Unfortunately, he did not receive enough founding from NASA to continue the project.
- Taught 5 independent studies – General Relativity, Quantum Mechanics, Doubly Special Relativity, Lunar Battery Feasibility (thesis proposal preparation) and Theoretical Physics involving a new theory of electron-positron pair creation

Organized Mentoring

- Multicultural & International Student Services (MISS) Office' Total Success Mentoring Program – Mentored one student who was in the process of finishing her degree in MIS. The goal of this program was to help her finish her degree and decide what to do after graduation.
- Ethnic College Counseling Center Counselor – In the spring of 2004, I flew to Florida at my own expense to server as a counselor for this program designed to introduce underrepresented minority students to the higher educational system.

COURSE AND PROGRAM DEVELOPMENT

- Developed a proposal for a Professional Physics Master's Degree Program with the Council of Graduate Schools (CGS) and the Sloan Foundation – I was given a grant by CGS/Sloan to study the feasibility of a professional physics degree focusing on training project managers. My activities included chairing a committee consisting of faculty from Physics, Chemistry, Systems Engineering, MBA and Marketing. I prepared a survey of local industrial leaders and presented a proposal for the project management program to the University's Development and Advisory Council. This talk later sparked the desire in local industry to develop an Engineering Management degree at UHCL. Other activities included developing a second survey, attending the CGS summer workshop in San Juan, PR, hiring and working closely with a consultant to conduct a focus group, working with President Staples in order to obtain feed-back on the program with local industry, producing a video CD containing information of the program and writing an implementation grant proposal for the program. The program, which I developed, will increase enrollment in Physics by at least 10 students per year, without adding sections or classes to the UHCL course inventory.
- Received final approval and implemented the Master's degree in Physics - After much work writing the proposal, conducting surveys and attending academic fairs, the Master's of Physics Program was approved by the THECB. I then had the task of phasing out the Physical Science Program and moving students into the Physics Program. As sole faculty advisor for the program, I also had to deal with a backlog of students who have been taking classes in the program but were not listed as either Physics or Physical Science majors.
- Attended 6 academic and training fairs to promote the Physics and Physical Science programs – JSC Academic Fair, UHCL-Community College Luncheon, Engineering Career Expo, JSC Young Professionals Workshop, the United Space Alliance Educational Fair and the National Society of Black Engineers Professional Development Conference. My efforts in promoting the physics program led to a milestone as all core graduate level physics courses made for the first time before the end of early registration in fall of 2004.
- I worked with Pam Christol and Anne Coppenhaver from SOE on developing a summer physics program for teacher enhancement and K-12 students. This program's plan was based on the Modeling program developed at the University of Arizona by Jane Jackson. Our goal was to initiate the program during the first year as a continuing education program for existing teachers and bring in students the following year.

- Member of the SCE Aerospace Engineering Task Force - My job was to research other Aerospace Engineering programs and present this information to the rest of the committee in a reasonable way.

DEVELOPMENT OF EDUCATIONAL MATERIALS

- Attended the University of Houston's Campus Online Workshop (COW) and developed a Web Enhanced version of Mathematical Methods in Physics 1. This course provided the additional challenge of putting mathematics online. I soon began working with the COW staff on a committee to develop Math COW; a workshop specifically aimed at teaching mathematics related subjects online.

RESEARCH, SCHOLARLY AND ARTISTIC ACTIVITIES

- Conducted a weekly Astrophysics Seminar series between JSC and UHCL – the purpose of this seminar is to increase research collaboration between JSC and UHCL as well as to stimulate student interest in research collaborations with JSC
- Attended a weekly telephone conference on numerical relativity hosted by Penn State's Center for Gravitational Physics and Geometry
- Developed a weekly Spring Seminar Series to stimulate interest in Space Science and Physics and to directly involve JSC researchers in activities at UHCL. I assembled a group of twelve speakers and advertised the talks through the Physics Program Notes website, Physics Program website, fliers on campus and using my email distribution list. In addition, I worked with the UHCL communications office to publicize the series through the local newspapers. This seminar was given in conjunction with the Research Project and Seminar class and included a growing audience of about 25 people. For the 2005 seminar series, I added a course PHYS 5033 Modern Physics Research and allowed for continuing education credits through the school of education.
- Attended the VASIMR workshop at the Advanced Space Propulsion Lab at JSC
- Attended and presented at the ASPL Theory and Computation Meeting at JSC
- Chaired a committee to evaluate the computational needs and resources of SCE
- Developed a partnership with ManSat Limited and Tai-Yang Research on an grant proposal to test synthetic diamonds for use in the VASIMR engine
- Developed a partnership with Jay Wright's group at JSC to test a new propulsion system on the KC-135 and air tables. I performed all the load calculations for the experiment.

PUBLICATIONS

- Testing Binary Black Hole codes with Cosmological Spacetimes by David Garrison (published in the proceedings for the Tenth Marcel Grossman Meeting on General Relativity, 2003)
- Gravity Gradients in LIGO: a proposal for Data Analysis by David Garrison, Gabriela Gonzalez (published in the proceedings for the Tenth Marcel Grossman Meeting on General Relativity, 2003)
- NASA internal report following the ASEE-NASA summer faculty fellowship "Computer Simulation of the VASIMR Engine"

- My 2003 paper "Black Hole Spectroscopy: testing general relativity through gravitational-wave observations" was cited 6 times in 2004.

PAPERS PRESENTATIONS, ABSTRACTS AND POSTER SESSIONS

- Gave an invited talk at Grinnell College in Iowa, "Introduction to Gravitational Wave Physics"
- Gave a talk at the National Society of Black Physics joint meeting with the National Society of Hispanic Physicists on "Quantum Mechanics and Doubly Special Relativity"
- Gave a talk at the ASPL Theory – Computation Meeting on "The Cactus Code"
- Gave an exit talk after the NASA Summer Faculty Fellowship program on the feasibility of using Cactus for Magneto-hydrodynamic Simulations of the VASIMR engine

HONORS AND AWARDS

- FDF Award: $1299 – to attend the 2004 meeting of the National Society of Black Physicists meeting in Washington, DC
- ASEE-NASA Summer Faculty Fellowship: $12,000 – Awarded to promote my research collaboration with ASPL involving the combination of my experience using the Cactus framework of numerical relativity with the magneto-hydrodynamic work needed for VASIMR
- CGS/Sloan PSM Award: $6,000 – Planning grant for the Professional Physics Program
- ISSO Postdoc Award: $50,000 per year for up to three years - $20,000 from ISSO and $30,000 from ASPL to sponsor a postdoc to aid in my research efforts with ASPL's VASIMR project
- I was featured and on the cover of the Spring 2004 issue of the Egret
- I was featured in the UH system's Success Stories

PROFESSIONAL ACTIVITES AND SERVICE

- Served as Program Chair of Physics and Physical Sciences – My duties included biennial planning, creating a strategic plan for the physics program, preparing class schedules, hiring and supervising roughly eight adjunct professor per semester, promoting the physics and physical science programs and managing the physics programs resources. During 2004, I increased the visibility of the physics program by adding a poster board near the Math Lab, rewrote the graduate and undergraduate program brochures, developed a physics program website and a physics recruitment poster which was distributed to over 50 different schools and organizations. Also during 2004, I purchased a new system to provide computer-based physics and astronomy simulations for our undergraduate and graduate courses. As part of my biennial planning efforts, I conducted a study comparing the Physics program at UHCL to others nationwide. I found that we have the largest graduate enrollment of any program in our class. Our typical graduate enrollment is about three and a half times that of the average terminal MS in

Physics program. This also led to the realization that our student to FTE faculty ratio is about 15 times that of other programs.

- Served on the SCE curriculum committee – I reviewed curriculum changes, program reviews and all new program development issues related to SCE.
- Served on the Black History Month Faculty Panel
- Participated in the development of an educational game for K-12 students
- Served as advisor to the Physics Club
- Developed an online survey for the Faculty Senate's Research Task Force
- Served as a Judge for the 2004 Science Olympiad – Bridge Building Competition
- Served on the 2005 UHCL Convocation Committee
- Served as a Judge for the Celebrating our Elder's Scholarship Competition
- Served on the Student Affairs Committee
- I worked with the UHCL Library to send several hundred pounds of old books to Nigeria and personally delivered them to the post office. Shipping at my own expense.
- Proof read Keith Parson's new book on the Philosophy of Science for scientific accuracy
- Co-advisor for the Black Student Association
- Gave a talk for "Stepping up" a group of group of high risk high school children from underrepresented backgrounds
- Attended the Alumni Association's Wine under the Stars even to promote the physics program

WEB LINKS

The new Physics Program website is located at:

- http://sce.cl.uh.edu/Physics

The Physics Program Informational website is located at:

- http://sce.cl.uh.edu/physicalscience/PhysicsProNotes.html

The latest results of the Physics Program Survey are located at:

- http://sce.cl.uh.edu/garrison/survey/results.asp

The latest results of the follow-up Physics Program Survey are located at:

- http://sce.cl.uh.edu/garrison/survey2/results.asp

The latest results of the first Professional Physics Program Survey are located at:

- http://sce.cl.uh.edu/garrison/survey3/results.asp

The latest results of the second Professional Physics Program Survey are located at:

- http://sce.cl.uh.edu/garrison/survey4/results.asp

The latest results of Faculty Senate Research Task Force Survey are located at:

- http://sce.cl.uh.edu/garrison/survey5/results.asp

FACULTY ANNUAL REPORT

David Garrison, Faculty Chair and Assistant Professor of Physics
January 1, 2005 through December 31, 2005

TEACHING AND EDUCATIONAL ACTIVITIES

Virtually all the students who filled out teaching evaluations enjoyed my courses and feel that they have learned a lot from me. My colleagues tend to agree.
Classroom Instruction:

Spring 2005:

- PHYS 5331 Electrodynamics – 9 graduate students. I introduced this course to the UHCL curriculum during the fall of 2002 as an expansion of the electromagnetism survey course. Since then, it has become part of our graduate core curriculum.
- ASTR 6838 Research Project and Seminar – 2 graduate students. This is the capstone course for students completing the Masters of Physical Sciences degree. I modified this course to focus on teaching communication skills as well as research. Students complete research projects and then present research papers both orally and in written form. The seminar portion of this course has become very popular in the local community.
- PHYS 5033 / 6838 Modern Physics Research / Research Project and Seminar – 5 graduate students. Physics 5033 is a new course developed to expose non-physics majors to current topics of interest using our physics guest lecture series. PHYS 6838 is the capstone course for students completing the Masters of Physics degree. Like ASTR 6838, this course focuses on teaching communication skills as well as research. Students complete research projects and then present research papers both orally and in written form. The seminar portion of this course has become very popular in the local community.
- PHYS 6132 General Relativity – 4 graduate students. This was a new course developed to prepare students for advanced research in general relativity. Every student enrolled in this course later completed a capstone research project in General Relativity and two are currently working on a peer reviewed journal article based on their work.

Summer 2005:

- PHYS 5533 Numerical Methods in Physics – 9 graduate students. This was a new course developed to teach students the fundamentals of scientific programming for physics. Students learned about different numerical techniques and wrote programs to implement them.

Fall 2005:

- PHYS 5531 Mathematical Methods in Physics 1 - 18 graduate students. This was a class, which I originally introduced in the spring of 2003. During the fall of 2004, I web enhanced the course in order to make it more flexible for students who work full-time. The course covers 8 topics of advanced mathematics which include: Ordinary Differential Equations, Infinite Series, Integration Techniques, Fourier Series and Transforms, Complex Variables, Linear Algebra, Partial

Differential Equations and Probability & Statistics. Students consider this to be the most intense of the core physics courses and the most essential to further success in physics. Those who survive the course tend to do very well in the other physics classes.

- PHYS 5431 Classical Mechanics – 11 graduate students. I originally developed this course in the fall of 2002. It is based on a similar course given at Penn State and is easily the equivalent of a Ph.D. level classical mechanics class. It teaches Newtonian mechanics through Hamiltonian formulations.
- PHYS 6838 Research Project and Seminar – 4 graduate students. This is the capstone course for students completing the Masters of Physics degree. This course focuses on teaching communication skills as well as research. Students complete research projects and then present research papers both orally and in written form. In fall of 2005, I modified the writing requirement so students now write articles for submission to peer reviewed journals instead of term papers. I taught this course as an overflow although I was granted a course release.

Course evaluations:

Course Title	Pace	Overall Quality	Subject Knowledge	Overall Teaching	Stimulate & Challeng Students	Encourage Class Participation	Helping Students Understand
ASTR 6838	N/A	N/A	N/A	N/A	N/A	N/A	N/A
PHYS 5033	3.00	5.00	5.00	4.50	4.50	4.00	4.00
PHYS 5331	3.25	3.86	4.13	3.75	4.00	4.38	4.25
PHYS 6132	4.00	4.50	5.00	4.75	4.75	4.75	4.50
PHYS 6838	N/A	N/A	N/A	N/A	N/A	N/A	N/A
PHYS 5533	N/A	N/A	N/A	N/A	N/A	N/A	N/A
PHYS 5431	3.43	3.43	3.43	3.43	3.57	4.14	4.00
PHYS 5531	3.75	3.58	3.50	3.25	3.50	4.25	4.50
PHYS 6838	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Selected Comments:

PHYS 5331 Electrodynamics:

“Great instructor and great subject”

“Knows how to solve problems & explain enough detail to allow student to grasp solutions.”

“very strong mathematical understanding”

PHYS 5531 Mathematical Methods:

“Likes topic, cares about students”

“Dr. Garrison was very knowledgeable about all the different subjects & very organized in how he presents them.

"Instructor cared about students"
"Great knowledge -> Easy to communicate material"
"Very helpful & interested in helping us learn."

PHYS 5533 Numerical Methods in Physics:

"Dr. Garrison is well-acquainted with the methods taught in his course and more importantly, the application of them."
"The instructor is very knowledgeable about physics and computer science."
"Knowledgeable and concise."
"Dr. Garrison is well prepared for the lectures and is well versed in using the various compilers."

PHYS 6132 General Relativity:

"Expert in subject material, truly cares about the subject."
"The instructor is very knowledgeable and excited about the course material. I learned very much about difficult material. Lecture notes were provided after students struggled to keep up with note taking."
"-Tremendously knowledgeable"
"-very good nature – likes seeing students learn"
"-interested in his field"

Individual Instruction and Advisement (other than organized classes)

- Advised almost all undergraduate and graduate physics and physical science students both formally and informally (about 50 students total).
- Supervised 8 independent study research projects – "Space Radiation Research", "Field Relationships", "Magnetohydrodynamics", "Theory of Pair Production", "Initial Conditions for GRMHD", "Optimization of GRMHD Code", "Data Analysis for GRMHD Code" and "Visualization of GRMHD Data".
- In 2005, I graduated a total of 7 Physics and 2 Physical Science graduate students that I advised.

COURSE AND PROGRAM DEVELOPMENT

- Won an implementation grant for the Professional Physics Master's Degree Program from the Council of Graduate Schools (CGS) and the Sloan Foundation – In 2004, I was given a grant by CGS/Sloan to study the feasibility of a professional physics degree focusing on training project managers. My activities included chairing a committee consisting of faculty from Physics, Chemistry, Systems Engineering, MBA and Marketing. I prepared a survey of local industrial leaders and presented a proposal for the project management program to the University's Development and Advisory Council. This talk later sparked the desire in local industry to develop an Engineering Management degree at UHCL. Other development activities included developing a second survey, attending the CGS summer workshop in San Juan, PR, hiring and working closely with a consultant to conduct a focus group, working with President Staples in order to obtain feed-back on the program with local industry, producing a video CD containing information of the program and writing an implementation grant proposal for the program. The program, which I developed, will increase enrollment in Physics by at least 10 students per year, without adding sections or classes to the UHCL course inventory. The UHCL curriculum committee approved this program in late 2004.

- Served as the UHCL Physics PSM director to manage, promote, assess and fine-tune the Physics PSM concentration.
- Attended a PSM Physics conference in Tuscan Arizona to meet with other Physics PSM program directors.
- Attended a PSM Meeting in Washington DC hosted by CGS. As a result of this meeting new legislation was introduced in congress making over $20M per year available to PSM programs such as ours.
- Promoted the traditional Physics and PSM Physics programs at the 2005 NSBP conference in Orlando Florida.
- Member of the SCE Aerospace Engineering Task Force - My job was to research other Aerospace Engineering programs and present this information to the rest of the committee in a reasonable way. Our goal was to determine the feasibility of and develop an implementation plan for an Aerospace Engineering degree at UHCL.
- Gave a talk, introducing the Physics Program, at the Spring 2005 UHCL Open House.
- Signed up to give a lab tour at the Fall 2005 UHCL Open House.
- Represented UHCL Physics at a meeting on San Jacinto Community College's new Associates of Arts in Teaching. I helped define the new curriculum as it applies the UHCL's Physical Sciences teacher preparation program.
- Built the UHCL Physics Teaching Laboratory. This new lab utilizes several new features including computer-based and computer-enhanced experiments as well as wireless networking.
- Worked on developing the curriculum for an interdisciplinary Scientific Computing undergraduate and graduate program.
- Worked on developing a Physics Track within our undergraduate Physical Sciences program in order to provide students with more preparation before entering the Physics M.S. program.
- Helped plan for the development of an Astronomy Teaching Observatory for UHCL. I worked with Dr. Talent and reviewed several options including the development of a remote observatory near the George Observatory. This would be useful for both undergraduate and graduate research and teaching.
- Began talks on future educational and research collaborations with the new Physics Department chair of Texas Southern University.

DEVELOPMENT OF EDUCATIONAL MATERIALS

- Helped plan and attended the University of Houston's Math Campus Online Workshop (MathCOW)
- Proposed the development of an online version of our popular Modern Astronomy course. In fall of 2005, enrollment in the course reached over 180 students although no full-time faculty are involved in the class. I worked with adjuncts to

research and choose a new textbook as well as to implement new technology in the class.

- Enhanced the graduate capstone courses for Physics and Physical Sciences to teach students how to publish research papers.

RESEARCH, SCHOLARLY AND ARTISTIC ACTIVITIES

- Conducted a weekly Astrophysics Seminar series between JSC and UHCL – the purpose of this seminar is to increase research collaboration between JSC and UHCL as well as to stimulate student interest in research collaborations with JSC.
- Attended a weekly telephone conference on numerical relativity hosted by Penn State's Center for Gravitational Physics and Geometry.
- Organized and hosted a weekly Spring Seminar Series to stimulate interest in Space Science and Physics and to directly involve JSC researchers in activities at UHCL. I assembled a group of twelve speakers and advertised the talks through the Physics Program website, fliers on campus and using my email distribution list. In addition, I worked with the UHCL communications office to publicize the series through the local newspapers. This seminar was given in conjunction with the Research Project and Seminar class and included a growing audience of about 30 people per week. For the 2005 seminar series, I added a course PHYS 5033 Modern Physics Research and allowed for continuing education credits through the school of education. Also for 2005, the World Year of Physics, I gave a special lecture that brought 70 new guests to campus on the Saturday night before the fall classes began. I estimate that this seminar series brought a total of 300 new visitors to campus during 2005.
- Attended the VASIMR workshop at the Lunar and Planetary Institute.
- Wrote a General Relativistic Magneto hydrodynamics (GRMHD) computer code for cosmological simulations. This is one of the few know GRMHD codes and will be used for a new numerical cosmology research project.
- Built a computational physics lab using retired campus computers. The lab featured 3 PCs to which I installed Linux, 6 iMacs running Mac OS X Tiger, 1 dual processor Macintosh running Mac OS X Tiger Server and a 12 node Beowulf built by a student. I networked and administrated all the computers myself.
- Worked with the Texas Educational Grid Computing Project to acquire a 48-node Beowulf supercomputer for our campus computational infrastructure. I attended several meetings with TXGrid and Conoco Phillips and worked with an outside moving company in order to move the machine to UHCL. I then worked with other UHCL faculty and staff to set-up the computer. I also did an interview for The Uhclidian on the new supercomputer.
- Helped to plan and participate in a visit from the Research Corporation. I invited several students to attend and gave the Research Corporation representative a tour of the new computational physics lab.
- Attended the University of Texas Dallas meeting on NSF grant proposals, sponsored by the National Science Foundation.
- Helped organize and attend several meetings of SCE faculty on Grid Computing.

PUBLICATIONS

- Submitted a paper titled "Development of a Comprehensive Physics Program at a non-traditional upper-level undergraduate and graduate small university" to a peer-reviewed journal, the European Journal of Physics.
- My 2003 paper "Black Hole Spectroscopy: testing general relativity through gravitational-wave observations" was cited 3 times in 2005.
- Submitted 2 articles to the proceedings of the NSBP conference, "Computational Electrodynamics" and "Computer Simulation of the VASIMR Engine".

PAPERS PRESENTATIONS, ABSTRACTS AND POSTER SESSIONS

- Gave an invited talk at the National Society of Black Physics joint meeting with the National Society of Hispanic Physicists on "Computational Electrodynamics" Later submitted to the conference proceedings.
- Gave a contributed talk at the National Society of Black Physics joint meeting with the National Society of Hispanic Physicists on "Computer Simulation of the VASIMR Engine". Later submitted to the conference proceedings.
- Gave a talk for the World Year of Physics 2005 on the UHCL campus titled "World Year of Physics: A Brief Look Back", 70 people attended.

HONORS AND AWARDS

- Co-PI on an NSF proposal for their Focused Research Groups in the Mathematical Sciences Program. The title of our proposal was "Theoretical and Computational Studies of Large-Dimensional Homogeneous Dynamical Systems" the total amount of the proposal was $1,045,086.
- PI on a Research Corporation proposal titled "Cosmic Structure Formation from Gravitational Radiation" the total amount of the proposal was $40,236 including a $6,000 match from the provost's office.
- Won a CGS / Sloan PSM Implementation grant $25,000.
- Won a Faculty Research and Support Grant of $2,406 for my numerical cosmology project.
- Won an Institute for Space Systems Operations mini-grant for $6,666.
- Won an Faculty Development Fund Award: $1210 – to attend the 2005 meeting of the National Society of Black Physicists meeting in Orlando, FL
- PI on a Faculty Development Fund proposal to attend the 2006 NSBP meeting in San Jose California; $1,741.

PROFESSIONAL ACTIVITES AND SERVICE

- Served as Program Chair of both the Physics and Physical Sciences programs through Spring of 2005 when Dr. Mills took over as chair of the Physical Sciences program – My duties included biennial planning, creating a strategic plan for the physics program, preparing class schedules, hiring and supervising roughly ten adjunct professors per semester, promoting the physics and physical science programs and managing the physics program's resources. As part of my biennial planning efforts in 2004, I conducted a study comparing the Physics program at UHCL to others nationwide. I found that we have the largest graduate enrollment of any program in our class.

- Served on the Physical Sciences program review committee.
- Served on the SCE curriculum committee – I reviewed curriculum changes, program reviews and all new program development issues related to SCE.
- Served on the 2006 UHCL Convocation Committee – I volunteered to organize and facilitate a session on academic new initiatives.
- 2005 Science Olympiad Judge for the Bridge Building competition.
- Served as a Judge for the Celebrating our Elder's Scholarship Competition
- Served on the Student Affairs Committee – reviewed scholarship applications for SCE students seeking financial aid.
- Served on the SCE Library, Research & Computing Committee.
- Co-advisor for the Black Student Association.
- Gave a talk for the NSBE-HSC-Boeing Engineer for a day event before a group of elementary and middle school children.
- Attempted to develop a Physics section for the Kid's U summer program.
- Gave talks before two groups of high school students on pursuing careers in science and engineering in collaboration with the UHCL admissions office.
- Helped to successfully develop an IPA agreement with NASA JSC in order to hire a visiting professor for the Physics program at no cost to the university.
- Attended the 2005 National Society of Black Physicists joint meeting with the National Society of Hispanic Physicists in Orlando Florida.
- I was invited to chair a session of the April Meeting of the American Physical Society but was unable to attend because UHCL has no funds for this type of activity.
- Attended the Texas Section of the American Physical Society (TSAPS) Meeting at the University of Houston central campus and acted as the NSBP representative to have special sections added to the conference.
- Attended the 2005 UHCL Spring Graduation.
- Peer viewed other Physics Departments for the U.S. News & World Report's America's Best Graduate Schools issue.

WEB LINKS

The Texas Educational Grid Project website is located at:

- http://www.txgrid.org

The Physics Program website is located at:

- http://sce.cl.uh.edu/Physics

The Physics Program Informational website is located at:

- http://sce.cl.uh.edu/physicalscience/PhysicsProNotes.html

The latest results of the Physics Program Survey are located at:

- http://sce.cl.uh.edu/garrison/survey/results.asp

The latest results of the follow-up Physics Program Survey are located at:

- http://sce.cl.uh.edu/garrison/survey2/results.asp

The latest results of the first Professional Physics Program Survey are located at:

- http://sce.cl.uh.edu/garrison/survey3/results.asp

The latest results of the second Professional Physics Program Survey are located at:

- http://sce.cl.uh.edu/garrison/survey4/results.asp

FACULTY ANNUAL REPORT

David Garrison, Faculty Chair and Assistant Professor of Physics
January 1, 2006 through December 31, 2006

TEACHING AND EDUCATIONAL ACTIVITIES

Virtually all the students who filled out teaching evaluations enjoyed my courses and feel that they have learned a lot from me. My colleagues tend to agree.
Classroom Instruction:

Spring 2006:

- PHYS 5331 Electrodynamics – 9 graduate students. I introduced this course to the UHCL curriculum during the fall of 2002 as an expansion of the electromagnetism survey course. Since then, it has become part of our graduate core curriculum.
- ASTR 6838 Research Project and Seminar – 3 graduate students. This is the capstone course for students completing the Masters of Physical Sciences degree. I modified this course to focus on teaching communication skills as well as research. Students complete research projects and then present research papers both orally and in written form. The seminar portion of this course has become very popular in the local community.
- PHYS 5033 / 6838 Modern Physics Research / Research Project and Seminar – 2 undergraduate students and 4 graduate students. Physics 5033 is a new course developed to expose non-physics majors to current topics of interest using our physics guest lecture series. PHYS 6838 is the capstone course for students completing the Masters of Physics degree. Like ASTR 6838, this course focuses on teaching communication skills as well as research. Students complete research projects and then present research papers both orally and in written form. The seminar portion of this course has become very popular in the local community.

Fall 2006:

- PHYS 5531 Mathematical Methods in Physics 1 - 9 graduate students. This was a class, which I originally introduced in the spring of 2003. During the fall of 2004, I web enhanced the course in order to make it more flexible for students who work full-time. The course covers 8 topics of advanced mathematics which include: Ordinary Differential Equations, Infinite Series, Integration Techniques, Fourier Series and Transforms, Complex Variables, Linear Algebra, Partial Differential Equations and Probability & Statistics. Students consider this to be the most intense of the core physics courses and the most essential to further success in physics. Those who survive the course tend to do very well in the other physics classes.
- PHYS 6131 Fundamentals of Spacetime – 6 graduate students. This was one of my absolute favorite courses to teach. I originally developed this class in the spring of 2003 and I can honestly say that it is unique among physics curricula anywhere. I created the class as a way of preparing students to take general relativity at the graduate level. Students are taught about special relativity and

tensors from a graphical rather than purely mathematical approach. Special relativity is derived from first principles and towards the end of the class, Maxwell's equations of electrodynamics are derived.

Course evaluations:

PHYS 5033:
- Pace: 3.0
- Overall Quality: 4.5
- Subject Knowledge: 4.5
- Overall Teaching: 4.0
- Stimulate & Challenge Students: 3.5
- Encourage Class Participation: 4.5
- Helping Students Understand: 3.5

PHYS 5331:
- Pace: 4.0
- Overall Quality: 4.25
- Subject Knowledge: 4.75
- Overall Teaching: 4.5
- Stimulate & Challenge Students: 4.5
- Encourage Class Participation: 4.75
- Helping Students Understand: 4.75

PHYS 5531:
- Pace: 3.6
- Overall Quality: 3.6
- Subject Knowledge: 4.2
- Overall Teaching: 4.0
- Stimulate & Challenge Students: 4.2
- Encourage Class Participation: 4.2
- Helping Students Understand: 4.4

PHYS 6131:
- Pace: 3.8
- Overall Quality: 3.2
- Subject Knowledge: 4.2
- Overall Teaching: 3.4
- Stimulate & Challenge Students: 3.6
- Encourage Class Participation: 3.8
- Helping Students Understand: 3.8

Selected Comments:

"I was really excited to be involved in this course, because that helped to have better understanding about my major and possible future explorations. Now I know why people should appreciate science."

Individual Instruction and Advisement (other than organized classes)

- Advised almost all undergraduate and graduate physics and physical science students both formally and informally (about 50 students total).
- Supervised 4 independent study research projects – topics included: Plasma Physics, Data Visualization, Early Universe Gravitational Wave production, Cosmology and Computational Physics.
- In 2006, I graduated a total of 4 Physics and 3 Physical Science graduate students.
- Mentored one high school and one freshman student during the summer on computational physics.

COURSE AND PROGRAM DEVELOPMENT

- Managed an implementation grant for the Professional Physics Master's Degree Program from the Council of Graduate Schools (CGS) and the Sloan Foundation – In 2004, I was given a grant by CGS/Sloan to study the feasibility of a professional physics degree focusing on training technical managers. My activities included chairing a committee consisting of faculty from Physics, Chemistry, Systems Engineering, MBA and Marketing. I prepared a survey of local industrial leaders and presented a proposal for the project management program to the University's Development and Advisory Council. This talk later sparked the desire in local industry to develop an Engineering Management degree at UHCL. Other development activities included developing a second survey, attending the CGS summer workshop in San Juan, PR, hiring and working closely with a consultant to conduct a focus group, working with President Staples in order to obtain feed-back on the program with local industry, producing a video CD containing information of the program and writing an implementation grant proposal for the program. The program, which I developed, should increase enrollment in Physics by about least 10 students per year, without adding sections or classes to the UHCL course inventory. The UHCL curriculum committee approved this program in late 2004 and added it to the university catalog in Fall 2006.
- Served as the UHCL Physics PSM director to manage, promote, assess and fine-tune the Physics PSM concentration.
- Attended a PSM Meeting in Washington DC hosted by CGS. As a result of this meeting new legislation was introduced in congress making over $20M per year available to PSM programs such as ours.
- Promoted the traditional Physics and PSM Physics programs at the 2006 NSBP conference in San Jose, California.
- Worked on developing a Physics Track within our undergraduate Physical Sciences program in order to provide students with more preparation before entering the Physics M.S. program.
- Helped develop a new brochure for the Physics Program with MMI.
- Participated in the design and planning for the new Physics and Astronomy teaching lab.

- Helped select and order equipment for the new Physics and Astronomy teaching lab.
- Attended a meeting with Noel-Levitz on improving enrollment at UHCL.
- Developed and distributed a survey to determine the local community's need for a Physics PhD program.
- Used the data from the above survey to develop an agreement with the UH Physics Department to establish a joint PhD program. Worked with Dean Davari and the UH Physics Chair Dr. Pinsky to get this agreement approved by both the UH and UHCL Science Schools. This is the first program of its kind anywhere in the US as it allows students to complete their MS and PhD in Physics on a part-time basis. It may also set a standard for other joint programs between SCE and the UH School of Science.
- Met with MEI Technologies CEO and HR to determine their educational needs.
- Met with GHG CEO to help develop a partnership (and equipment donation) for our Computer Science Program.
- Helped Dr. Masood develop a new Physics Education research and training proposal.
- Attended the Office of Admissions, HR Breakfast.

DEVELOPMENT OF EDUCATIONAL MATERIALS

- Helped establish the new Physics and Astronomy teaching lab.

RESEARCH, SCHOLARLY AND ARTISTIC ACTIVITIES

- Conducted a weekly Astrophysics Seminar series between JSC and UHCL personal – the purpose of this seminar is to increase research collaboration between JSC and UHCL as well as to stimulate student interest in research collaborations with JSC.
- Organized and hosted a weekly Spring Seminar Series to stimulate interest in Space Science and Physics and to directly involve JSC researchers in activities at UHCL. I assembled a group of twelve speakers and advertised the talks through the Physics Program website, fliers on campus and using my email distribution list. In addition, I worked with the UHCL communications office to publicize the series through the local newspapers. This seminar was given in conjunction with the Research Project and Seminar class and included a growing audience of about 30 people per week. For the 2006 seminar series, I added a course PHYS 5033 Modern Physics Research Seminar and allowed for continuing education credits through the school of education.
- Organized and hosted a new monthly Fall Physics seminar series.
- Hosted a visit and public lecture by Professor Sylvester James Gates, Jr. the James S. Toll Professor of Physics at the University of Maryland's Physics Department. I worked with the Office of University Advancement to gain external funding and used the proceeds to fund our search for a Visiting Assistant Professor of Physics. About 200 people attended the lecture and over $3,000 was raised.

- Wrote a General Relativistic Magneto hydrodynamics (GRMHD) computer code for cosmological simulations. This is one of the few know GRMHD codes and will be used for a new numerical cosmology research project.
- Worked with the Texas Educational Grid Computing Project to acquire a 48-node Beowulf supercomputer for our campus computational infrastructure. I attended several meetings with TXGrid and Conoco Phillips. I also worked with other UHCL faculty and staff to set-up and maintain the computer.
- Helped develop a new computational Physics Lab in Bayou 3324 with 30 dual-boot Windows / Linux Workstations and a small Beowulf cluster.
- Wrote an article for the APS Forum on Education Newsletter on non-traditional graduate physics education.
- Wrote a letter for Physics Today on Serving Nontraditional Graduate Students.
- Attended the UH Grant Writing workshop.
- I initiated agreements with two Scientists, Dr.'s Tafa and Tarditi to work as Visiting Research Scholars. They provide additional research opportunities to students at no cost to the university.

PUBLICATIONS

- My 2003 paper "Black Hole Spectroscopy: testing general relativity through gravitational-wave observations" was cited 8 times in 2006.
- Gravity Gradients in LIGO: a proposal for Data Analysis by David Garrison and Gabriela Gonzalez, Proceedings of the Tenth Marcel Grossman Meeting on General Relativity, 2006.
- Testing Binary Black Hole codes with Cosmological Spacetimes by David Garrison, Proceedings of the Tenth Marcel Grossman Meeting on General Relativity, 2006.
- Development of a Comprehensive Physics Program at a non-traditonal upper-level undergraduate and graduate small university by David Garrison, APS Forum On Education Spring 2006 Newsletter.
- Serving Nontraditional Graduate Students by David Garrison, Physics Today, January 2007.

PAPERS PRESENTATIONS, ABSTRACTS AND POSTER SESSIONS

- Gave a contributed talk at the National Society of Black Physics joint meeting with the National Society of Hispanic Physicists on "Cosmic Structure Formation in the Early Universe ".
- Gave a contributed talk at the April APS Meeting on "Initial Conditions for Cosmic Evolution Using GRMHD Equations".
- Gave an invited talk at the University of Oregon on "Cosmic Structure Formation via Gravitational Radiation".

HONORS AND AWARDS

- PI on submitted NSF Grant proposal titled "Origin of Structure in the Early Universe from Gravitational Radiation" the total amount of the proposal is $291,861.
- PI on a resubmitted Research Corporation proposal titled "Cosmic Structure Formation from Gravitational Radiation" the total amount of the proposal is $53,684 including a $15,000 match from the provost's office.
- Co-PI on an FRSR Grant with Dr. Masood titled "Lepton Scatterings and Leptogenesis in the Early Universe" funded for $4,000.
- PI on an Institute for Space Systems Operations mini-grant titled "Origin of Structure in the Early Universe from Gravitational Radiation" funded for $7,077.
- PI on a funded Faculty Development Fund proposal to attend the 2006 NSBP meeting in San Jose California; $1,741.
- PI on a funded Faculty Development Fund proposal to attend the 2006 April APS meeting in Dallas Texas; $680.

PROFESSIONAL ACTIVITES AND SERVICE

- Served as Program Chair of Physics – My duties included biennial planning, creating a strategic plan for the physics program, preparing class schedules, hiring and supervising roughly ten adjunct professors per semester, promoting the physics program and managing the physics program's resources. As part of my biennial planning efforts in 2004 and 2006, I conducted a study comparing the Physics program at UHCL to others nationwide. I found that we have the largest graduate enrollment of any program in our class.
- Served on the Physical Sciences program review committee.
- Served as Chair of the Physics Visiting Assistant Professor search committee.
- Served on the Geology Search Committee.
- Served as Chair of the SCE curriculum committee – I reviewed curriculum changes, program reviews and all new program development issues related to SCE.
- Served on the 2006 UHCL Convocation Committee – I volunteered to organize and facilitate a session on academic new initiatives which received high ratings from attendants.
- Hosted a visit and public lecture by Professor James Gates, Jr. and used the proceeds to fund our search for a Visiting Assistant Professor of Physics. About 200 people attended the lecture.
- 2006 Science Olympiad Judge for the Bridge Building competition.
- Served as a Judge for the Celebrating our Elder's Scholarship Competition
- Served on the Student Affairs Committee – reviewed scholarship applications for SCE students seeking financial aid.
- Served on the SCE Library, Research & Computing Committee.
- Co-advisor for the Black Student Association – helped plan the 2006 and 2007 Black History Month program.
- Gave a talk at the International Space School hosted by UHCL.
- Gave a talk for the NSBE-HSC-Boeing Engineer for a day event before a group of elementary and middle school children.

- Interviewed for Project Crossover, a study about how people transition from students to Scientists.
- Attended the 2006 National Society of Black Physicists joint meeting with the National Society of Hispanic Physicists in San Jose California.
- Attended the April APS Meeting in Dallas Texas.
- Attended the Boeing Black Employees Association appreciation luncheon.
- Attended the National Society of Black Engineer's Annual Martin Luther King Luncheon as their honored guest.
- Nominated as the UHCL Goldwater Scholarship Faculty Representative.
- Hosted a visit with Congressman Nick Lampson and the Science Faculty.

WEB LINKS

The Texas Educational Grid Project website is located at:

- http://www.txgrid.org

The Physics Program website is located at:

- http://sce.cl.uh.edu/Physics

The Physics Program Informational website is located at:

- http://sce.cl.uh.edu/physicalscience/PhysicsProNotes.html

The latest results of the Physics Program Survey are located at:

- http://sce.cl.uh.edu/garrison/survey/results.asp

The latest results of the follow-up Physics Program Survey are located at:

- http://sce.cl.uh.edu/garrison/survey2/results.asp

The latest results of the first Professional Physics Program Survey are located at:

- http://sce.cl.uh.edu/garrison/survey3/results.asp

The latest results of the second Professional Physics Program Survey are located at:

- http://sce.cl.uh.edu/garrison/survey4/results.asp

The latest results of the Physics Ph.D. Program Survey are located at:

- http://sce.cl.uh.edu/garrison/survey6/results.asp

FACULTY ANNUAL REPORT

David Garrison, Faculty Chair and Assistant Professor of Physics
January 1, 2007 through December 31, 2007

TEACHING AND EDUCATIONAL ACTIVITIES

Virtually all the students who filled out teaching evaluations enjoyed my courses and feel that they have learned a lot from me. My colleagues tend to agree.
Classroom Instruction:

Spring 2007:

- PHYS 6132 General Relativity – 5 graduate students. This is an extremely advanced course designed to introduce students to General Relativity so that they may do research in the area. In the future this course may count towards the PhD at UH through our Collaborative Program.
- ASTR 6838 Research Project and Seminar – 1 graduate student. This is the capstone course for students completing the Masters of Physical Sciences degree. I modified this course to focus on teaching communication skills as well as research. Students complete research projects and then present research papers both orally and in written form. The seminar portion of this course has become very popular in the local community.
- PHYS 4732 / 6838 Modern Physics Research / Research Project and Seminar – 2 undergraduate students and 2 graduate students. Physics 4732 is a new course developed to expose undergraduates to current topics of interest using our physics guest lecture series. This has since become a capstone course for our undergraduate Physical Science Degree. PHYS 6838 is the capstone course for students completing the Masters of Physics degree. Like ASTR 6838, this course focuses on teaching communication skills as well as research. Students complete research projects and then present research papers both orally and in written form. The seminar portion of this course has become very popular in the local community.

Fall 2007:

- PHYS 5331 Electrodynamics – 6 graduate students and 2 undergraduates (one signed up through PHYS 4839 independent study). This was meant to be the last time I taught Electrodynamics at the Graduate Level using the textbook by Griffiths. In the future this class will become Principles of Electromagnetism (PHYS 4331) and PHYS 5331 will become a more advanced class using the standard PhD level text written by J. D. Jackson.
- PHYS 5531 Mathematical Methods in Physics 1 - 15 graduate students. This was a class, which I originally introduced in the spring of 2003. During the fall of 2004, I web enhanced the course in order to make it more flexible for students who work full-time. The course covers 9 topics of advanced mathematics which include: Ordinary Differential Equations, Infinite Series, Integration Techniques, Fourier Series and Transforms, Complex Variables, Linear Algebra, Tensors, Partial Differential Equations and Probability & Statistics. Students consider this

to be the most intense of the core physics courses and the most essential to further success in physics. Those who survive the course tend to do very well in the other physics classes.

Course evaluations:

PHYS 5331:
Pace: 3.80
Overall Quality: 3.20
Subject Knowledge: 3.80
Overall Teaching: 3.00
Stimulate & Challenge Students: 3.80
Encourage Class Participation: 4.00
Helping Students Understand: 3.60

PHYS 5531:
Pace: 4.83
Overall Quality: 3.17
Subject Knowledge: 3.67
Overall Teaching: 3.00
Stimulate & Challenge Students: 2.67
Encourage Class Participation: 3.50
Helping Students Understand: 3.67

PHYS 6132:
Pace: 3.75
Overall Quality: 4.00
Subject Knowledge: 4.25
Overall Teaching: 3.50
Stimulate & Challenge Students: 3.75
Encourage Class Participation: 4.25
Helping Students Understand: 4.25

Selected Comments:
"Very organized, can get the point across effectively"
"… willing to work with student"
"Willing to focus on problem areas of course material"
"Prepared, knowledgeable, and runs thru lecture material quickly."

Individual Instruction and Advisement (other than organized classes)
- Advised almost all graduate physics students both formally and informally (about 40 students total).
- Supervised 1 capstone research project, which lead to a publication with a student.
- Taught 2 independent studies.
- In 2007, I graduated a total of 4 Physics and 1 Physical Science graduate students.

COURSE AND PROGRAM DEVELOPMENT

- Managed an implementation grant for the Professional Physics Master's Degree Program from the Council of Graduate Schools (CGS) and the Sloan Foundation – In 2004, I was given a grant by CGS/Sloan to study the feasibility of a professional physics degree focusing on training technical managers. My activities included chairing a committee consisting of faculty from Physics, Chemistry, Systems Engineering, MBA and Marketing. I prepared a survey of local industrial leaders and presented a proposal for the project management program to the University's Development and Advisory Council. This talk later sparked the desire in local industry to develop an Engineering Management degree at UHCL. Other development activities included developing a second survey, attending the CGS summer workshop in San Juan, PR, hiring and working closely with a consultant to conduct a focus group, working with President Staples in order to obtain feed-back on the program with local industry, producing a video CD containing information of the program and writing an implementation grant proposal for the program. The program, which I developed, should increase enrollment in Physics by about least 10 students per year, without adding sections or classes to the UHCL course inventory. The UHCL curriculum committee approved this program in late 2004 and added it to the university catalog in Fall 2006. This implementation grant closed out at the end of 2007.
- Served as the UHCL Physics PSM director to manage, promote, assess and fine-tune the Physics PSM concentration.
- Attended a PSM Meeting in Washington DC hosted by CGS.
- Promoted the traditional Physics and PSM Physics programs at the 2007 NSBP conference in Boston, MA.
- Helped develop a new booklet for the Physics Program with MMI.
- Participated in the development of the new Physics and Astronomy teaching lab.
- Helped select and order equipment for the new Physics and Astronomy teaching lab.
- Used the data from a survey of the local community to develop an agreement with the UH Physics Department to establish a Collaborative Physics PhD program. Worked with Dean Davari and the UH Physics Chair Dr. Pinsky to get this agreement approved by both the UH and UHCL Science Schools. Worked with David Bell (from UH) and the UHCL Provost's office to get final approval for the program. This is the first program of its kind anywhere in the US as it allows students to complete their MS and PhD in Physics on a part-time basis. It may also set a standard for other joint programs between SCE and the UH School of Science.
- Helped Dr. Masood develop a new Physics Education research and training proposal.
- I got the UHCL Physics program officially recognized by the American Institute of Physics, therefore making it easier for us to recruit graduate students through undergraduate physics programs.

RESEARCH, SCHOLARLY AND ARTISTIC ACTIVITIES

- Organized and hosted a weekly Spring Seminar Series to stimulate interest in Space Science and Physics and to directly involve JSC researchers in activities at UHCL. I assembled a group of twelve speakers and advertised the talks through the Physics Program website, fliers on campus and using my email distribution list. In addition, I worked with the UHCL communications office to publicize the series through the local newspapers. This seminar was given in conjunction with the Research Project and Seminar class and PHYS 4732. We had an audience of about 30 people per week.
- Hosted a dinner and public lecture by Dr. Neal Lane Former Director of the National Science Foundation and Whitehouse Science Advisor. I worked with the Office of University Advancement to gain external funding. About 200 people attended the lecture and $2,000 in external money was raised. Before the lecture, I hosted a dinner in the faculty lounge for Dr. Lane, faculty and administrators at UHCL, and people from JSC and local industry to discuss the future of science in our community.
- Continued development of a General Relativistic Magneto hydrodynamics (GRMHD) computer code for cosmological simulations. This is one of the few know GRMHD codes and will be used for a new numerical cosmology research project. In 2007, I successfully tested the code and began to produce publishable results.
- Worked with the Texas Educational Grid Computing Project to upgrade our Beowulf supercomputer. I attended several meetings with TXGrid and Conoco Phillips. I also worked with other UHCL faculty and staff to set-up and maintain the computer.
- Published an article in Classical and Quantum Gravity with a student.
- I worked with Dr. Tarditi to develop a plasma physics lab on our campus using surplus equipment from JSC and funds from my Sloan Grant.
- Joined the Space and Complex Systems Research Cluster at UH.
- Attended a talk by Dr. Helen Lane on research opportunities at JSC.
- Helped establish the UH-UHCL Physics Journal Club and gave a talk on Deformed Special Relativity.
- Helped develop a UHCL Physics Research website.
- Worked with SOE on a Greater Texas Foundation Grant proposal.

PUBLICATIONS

- My 2003 paper “Black Hole Spectroscopy: testing general relativity through gravitational-wave observations” was cited 6 times in 2007.
- Published a paper, Numerical analysis of simplified Relic-Birefringent gravitational waves by David Garrison and Rafael de la Torre, Classical and Quantum Gravity 24 (2007) 5889

PAPERS PRESENTATIONS, ABSTRACTS AND POSTER SESSIONS

- Gave a contributed talk at the 2007 National Society of Black Physics joint meeting with the National Society of Hispanic Physicists.
- Helped organize and gave a contributed talk at the 2007 AAAS SWARM meeting at UHCL.
- Gave a talk for the UHCL Natural Science Seminar Series.
- Gave a talk for the Provost's Scholarly Research Lecture Seminar Series.
- Gave an invited talk at UH as part of our Collaborative Physics Program. This was my interview talk for my joint faculty appointment with UH.

HONORS AND AWARDS

- PI on an unfunded (currently in review) NASA Grant, the total amount of the proposal is $810,146.
- PI on a resubmitted (unfunded) Research Corporation proposal titled "Cosmic Structure Formation from Gravitational Radiation" the total amount of the proposal is $53,684 including a $15,000 match from the provost's office.
- PI on a funded Faculty Development Fund proposal to attend the 2007 NSBP meeting in Boston, MA; $1,741.
- PI on a funded Faculty Research and Support Fund proposal; $5460.

PROFESSIONAL ACTIVITES AND SERVICE

- Served as Program Chair of Physics – My duties included biennial planning, creating a strategic plan for the physics program, preparing class schedules, hiring and supervising roughly ten adjunct professors per semester, promoting the physics program and managing the physics program's resources. As part of my biennial planning efforts in 2004 and 2006, I conducted a study comparing the Physics program at UHCL to others nationwide. I found that we have the largest graduate enrollment of any program in our class.
- Served on the Physical Sciences program review committee.
- Served on the Geology Search Committee.
- Served as Chair of the SCE curriculum committee – I reviewed curriculum changes, program reviews and all new program development issues related to SCE.
- Served on the Faculty Senate Research Committee.
- Served on the University Planning & Budget Committee.
- Hosted a visit and public lecture by Dr. Neal Lane. About 200 people attended the lecture.
- Organized a visit to JSC for the new Provost and several UHCL faculty in order to promote closer relations between the two institutions.
- Met with the administration of LPI and UHCL in order to develop a research and educational collaboration.
- Granted a Joint Faculty Appointment with the Physics Department at the University of Houston.
- 2007 Houston Science and Engineering Fair Judge.
- Served as a Judge for the Celebrating our Elder's Scholarship Competition

- Served on the Student Affairs Committee – reviewed scholarship applications for SCE students seeking financial aid.
- Served on the SCE Library, Research & Computing Committee.
- Co-advisor for the Black Student Association – helped plan the 2006 and 2007 Black History Month program. Served on a Faculty Panel for the 2007 Black History Month.
- Gave a talk at the International Space School hosted by UHCL.
- Attended the 2007 National Society of Black Physicists joint meeting with the National Society of Hispanic Physicists in Boston, MA where I promoted our Physics program.
- Attended the Boeing Black Employees Association Black Heritage Lunch.
- Attended the National Society of Black Engineer's Annual Martin Luther King Lunch and Strategic Planning Research Conference meeting.
- Attended the Ad Astra Rocket Company's Space Act agreement signing ceremony.
- Served as the UHCL Goldwater Scholarship Faculty Representative.
- Served on the New Student Orientation- faculty panel twice (Spring and Fall Semesters).
- Served as a mentor for the ISS office's Total Success Mentor Program.
- I was a faculty presenter for the Film and History Club's movie Mindwalk.
- Interviewed, hired and helped supervise a web content editor for the SCE website.

WEB LINKS

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FACULTY ANNUAL REPORT

David Garrison, Faculty Chair and Associate Professor of Physics

January 1, 2008 through December 31, 2008

TEACHING AND EDUCATIONAL ACTIVITIES

Virtually all the students who filled out teaching evaluations enjoyed my courses and feel that they have learned a lot from me. My colleagues tend to agree. Also, notice that my evaluations where much better when I wasn't in a faculty senate leadership position.

Classroom Instruction:

Spring 2008:

- PHYS 5332 Electrodynamics II – 8 graduate students. This is the equivalent of the standard PhD level Electrodynamics course taught using the textbook by J. D. Jackson. This course counts towards PhD candidacy through our Collaborative PhD program.
- PHYS 4839 / 6838 Modern Physics Research / Research Project and Seminar – 1 undergraduate student and 4 graduate students. Physics 4839 was PHYS 4732 taught as an independent study course. This was a course developed to expose undergraduates to current topics of interest using our physics guest lecture series. This has since become a capstone course for our undergraduate Physical Science Degree. PHYS 6838 is the capstone course for students completing the Masters of Physics degree. This course focuses on teaching communication skills as well as research. Students complete research projects and then present research papers both orally and in written form. The seminar portion of this course has become very popular in the local community.

Summer 2008:

- PHYS 5533 Methods in Computational Physics – 5 graduate students. I developed this course to train students how to perform research in computational physics. This was only the second time this hands-on course was taught.
- PHYS 6838 Research Project and Seminar – 1 graduate student. I taught this course for one student who needed to complete her degree in the summer because of a situation at work.

Fall 2008:

- PHYS 4331 Principles of Electromagnetism – 7 graduate and undergraduate students. This was the undergraduate version of PHYS 5331 taught using the textbook by Griffiths.
- PHYS 5531 Mathematical Methods in Physics 1 and PHYS 5919 Recitation for Mathematical Methods in Physics 1 – 15/17 graduate students. This was a class, which I originally introduced in the spring of 2003. The course covers 9 topics of advanced mathematics which include: Ordinary Differential Equations, Infinite Series, Integration Techniques, Fourier Series and Transforms, Complex Variables, Linear Algebra, Tensors, Partial Differential Equations and Probability

& Statistics. Students consider this to be the most intense of the core physics courses and the most essential to further success in physics. Those who survive the course tend to do very well in the other physics classes.

- PHYS 6838 Research Project and Seminar – 1 graduate student. I taught this course for one student who needed to complete her degree in the fall because of a situation at work.

Course evaluations:

PHYS 4331:
Pace: 4.0
Overall Quality: 3.4
Subject Knowledge: 4.8
Overall Teaching: 3.6
Stimulate & Challenge Students: 4.2
Encourage Class Participation: 4.0
Helping Students Understand: 4.4

PHYS 5332:
Pace: 3.75
Overall Quality: 3.75
Subject Knowledge: 4.0
Overall Teaching: 4.25
Stimulate & Challenge Students: 4.5
Encourage Class Participation: 4.5
Helping Students Understand: 4.5

PHYS 5531:
Pace: 3.64
Overall Quality: 2.82
Subject Knowledge: 3.4
Overall Teaching: 2.82
Stimulate & Challenge Students: 3.3
Encourage Class Participation: 3.55
Helping Students Understand: 3.36

PHYS 5533:
Pace: 3.5
Overall Quality: 4.25
Subject Knowledge: 4.75
Overall Teaching: 4.75
Stimulate & Challenge Students: 4.75
Encourage Class Participation: 4.75
Helping Students Understand: 5.0

Selected Comments:

> "Very prompt in answering questions, knowledge in subject, accommodating to student's needs"
>
> "Makes topic interesting, relates material to other aspects of physics curriculum"
>
> "Appreciate breath of coverage, recitation class was very helpful"
>
> "He understands the students and is willing to take time out to discuss some of the more difficult subjects"

Individual Instruction and Advisement (other than organized classes)

- Advised about 30 master's level physics students both formally and informally.
- Taught 1 independent study.
- In 2008, I graduated a total of 5 Physics graduate students.
- Chaired a PhD Thesis Committee through the Collaborative Physics PhD Program.
- Attended the 2008 Institute on Teaching and Mentoring in Tampa Florida.

COURSE AND PROGRAM DEVELOPMENT

- Served as the UHCL Physics PSM director to manage, promote, assess and fine-tune the Physics Technical Management Sub-Plan.
- Promoted the Collaborative PhD, Traditional Physics MS and PSM Physics programs at the 2008 NSBP conference in Washington, DC.
- Mailed Physics Program booklets and posters to all the undergraduate physics departments in Texas and Louisiana in order to increase enrollment.
- Developed and submitted a proposal for the development of a BS in Physics at UHCL.
- Developed recitation sections for the six core courses needed for PhD candidacy through the Collaborative Physics PhD Program.
- Developed the Physics Candidacy Certificate.
- Served on the Faculty Senate's "Going 4 years" taskforce.
- Participated in the development of a Space Act Agreement with JSC.
- Gave a talk at Jacobs to promote the Physics Program.
- Gave two talks at BAHEP (the Aerospace Advisory Committee and Education and Training Committee) to promote the Physics Program.
- Developed an agreement with LPI where several of there research staff would be appointed as Visiting Assistant Professors and team-teach a course on Solar System Evolution.
- Worked to develop the use of Internet video conferencing to teach distance learning courses.

RESEARCH, SCHOLARLY AND ARTISTIC ACTIVITIES

- Helped the Yale Drop Team test their experiment for NASA's Zero-G plane.
- Organized and hosted a weekly Spring Seminar Series to stimulate interest in Space Science and Physics and to directly involve JSC researchers in activities at UHCL. I assembled a group of twelve speakers and advertised the talks through the Physics Program website, fliers on campus and using my email distribution list. In addition, I worked with the UHCL communications office to publicize the series through the local newspapers. This seminar was given in conjunction with the Research Project and Seminar class and PHYS 4732. We had an audience of about 30 people per week.
- Hosted our first American Astronomical Society Shapley Lecture by Professor Wendy Bauer.
- Planned a visit, dinner and public lecture by University of Virginia Astronomy Professor John Hawley. The event occurred on January 23, 2009 and about 400 people attended.
- Continued development of a General Relativistic Magnetohydrodynamics (GRMHD) computer code for cosmological simulations. This is one of the few know GRMHD codes and will be used for a new numerical cosmology research project. In 2007, I successfully tested the code and began to produce publishable results. Submitted a paper based on these results for publication during the summer of 2008. I rewrote and resubmitted this paper in January of 2009.
- Worked with the Texas Educational Grid Computing Project to upgrade our Beowulf supercomputer. I attended several meetings with TXGrid and Conoco Phillips. I also worked with other UHCL faculty and staff to set-up and maintain the computer.
- Member of the Space and Complex Systems Research Cluster at UH.
- Helped establish the UH-UHCL Physics Journal Club.
- Worked with SOE on a Greater Texas Foundation Grant proposal.

PUBLICATIONS

- My 2003 paper "Black Hole Spectroscopy: testing general relativity through gravitational-wave observations" was cited 4 times in 2008, bringing the total to 30 citations.
- My 2007 paper, "Numerical analysis of simplified Relic-Birefringent gravitational waves" was cited 1 time in 2008.
- Submitted a paper for the proceedings of the 2008 NSBP conference.
- Did Gravitational Waves Affect the Evolution of the Universe by David Garrison (Preprint gr-qc/0808.1764) submitted for publication in Classical and Quantum Gravity

PAPERS PRESENTATIONS, ABSTRACTS AND POSTER SESSIONS

- Appeared on an episode of "The Universe" on the History Channel.
- Gave an Invited Talk on the Affect of Gravitational Waves on the Evolution of the Universe at the 2008 NSBP meeting.

- Gave an Invited Talk on my theory of cosmic structure formation at the University of South Florida.

HONORS AND AWARDS

- Awarded a Joint Faculty Appointment with the Physics Department at UH through the Collaborative Physics PhD Program.
- PI on an unfunded NASA Grant, the total amount of the proposal is $403,428.
- PI on an under-review NFS Grant, the total amount of the proposal is $403,428.
- PI on a funded Faculty Development Fund proposal to attend the 2008 NSBP meeting in Washington, DC; $1,500.

PROFESSIONAL ACTIVITES AND SERVICE

- Served as Program Chair of Physics – My duties included biennial planning, creating a strategic plan for the physics program, preparing class schedules, hiring and supervising roughly six to ten adjunct professors per semester, promoting the physics program and managing the physics program's resources. As part of my biennial planning efforts in 2004, 2006 and 2008, I conducted a study comparing the Physics program at UHCL to others nationwide. I found that we have one of the largest graduate enrollments of any program in our class and the highest major to full-time faculty ratio in Texas.
- Served on the Physical Sciences program review committee.
- Served on the SCE Dean Search Committee.
- Chaired the Physics Assistant Professor Search Committee.
- Served as Chair of the SCE curriculum committee – I reviewed curriculum changes, program reviews and all new program development issues related to SCE.
- Served on the SCE Policy committee.
- Served on the Faculty Senate Research Committee and was elected chair starting Fall 2008.
- As FS Research Chair I worked to develop a university Research Website and evaluate course capture software.
- Served on the University Planning & Budget Committee.
- Served on the Faculty Senate Executive Committee.
- Served on Academic Council.
- Served on University Council.
- Granted a Joint Faculty Appointment with the Physics Department at the University of Houston.
- Served as a Judge for the Celebrating our Elder's Scholarship Competition
- Served on the Student Affairs Committee – reviewed scholarship applications for SCE students seeking financial aid.
- Co-advisor for the Black Student Association – gave a talk on African American's in Physics

- Attended the 2008 National Society of Black Physicists joint meeting with the National Society of Hispanic Physicists in Washington, DC where I promoted our Physics program.
- Attended the National Society of Black Engineer's (NSBE) Annual Martin Luther King Lunch and Strategic Planning Research Conference meeting.
- Attended NSBE's Engineer for a Day to encourage kids to pursue careers in science and engineering.
- Organized a tour and visit with the management of Ad Astra Rocket Company, Dean Davari and Provost Stockton.
- Served as the UHCL Goldwater Scholarship Faculty Representative.
- Served on the New Student Orientation- faculty panel twice (Spring and Fall Semesters).

WEB LINKS

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The latest results of the Physics Ph.D. Program Survey are located at:

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FACULTY ANNUAL REPORT

David Garrison, Faculty Chair and Associate Professor of Physics
January 1, 2009 through December 31, 2009

TEACHING AND EDUCATIONAL ACTIVITIES

Virtually all the students who filled out teaching evaluations enjoyed my courses and felt that they have learned a lot from me. My colleagues tend to agree. In Spring 2009, I taught four courses while maintaining an extremely heavy service load. In Fall 2009, I was on faculty development leave.

Classroom Instruction:

Spring 2009:

- PHYS 5311 Electrodynamics I – 8 graduate students (after drop date). This is the recitation for Physics 5331. Each week I would work out example problems with students in order to prepare them for the Ph.D. Candidacy Exam.
- PHYS 5331 Electrodynamics I – 10 graduate students (after drop date). This is the standard PhD level Electrodynamics course taught using the textbook by J. D. Jackson. This course counts towards PhD candidacy through our Collaborative PhD program.
- PHYS 6132 / 7397 General Relativity - 1 graduate student at UHCL and 3 graduate students at UH (after drop date). This is an extremely advanced course designed to introduce students to General Relativity so that they may do research in the area. This course counts towards the PhD at UH through our Collaborative Program and was taught at both UHCL and UH using video conferencing software.
- PHYS 4732 / 6838 Modern Physics Research / Research Project and Seminar – 2 undergraduate student and 2 graduate students. PHYS 4732 is a course developed to expose undergraduates to current topics of interest using our physics guest lecture series. This has since become a capstone course for our undergraduate Physics and Physical Sciences Degrees. PHYS 6838 is the capstone course for students completing the Masters of Physics degree. This course focuses on teaching communication skills as well as research. Students complete research projects and then present research papers both orally and in written form. The seminar portion of this course has become very popular in the local community.

Summer 2009:

- No Teaching

Fall 2009:

- Faculty Development Leave

Course evaluations:

PHYS 5311 / 5331:

Pace: 3.86
Overall Quality: 4.0
Subject Knowledge: 4.17
Overall Teaching: 4.17
Stimulate & Challenge Students: 4.33
Encourage Class Participation: 4.67
Helping Students Understand: 4.57

PHYS 6132 / 7397:
Pace: 3.0
Overall Quality: 5.0
Subject Knowledge: 5.0
Overall Teaching: 5.0
Stimulate & Challenge Students: 5.0
Encourage Class Participation: 5.0
Helping Students Understand: 5.0

PHYS 4732 / 6838:
Pace: 3.0
Overall Quality: 5.0
Subject Knowledge: 5.0
Overall Teaching: 5.0
Stimulate & Challenge Students: 5.0
Encourage Class Participation: 5.0
Helping Students Understand: 5.0

Selected Comments:
"Knowledge of the Subject and was well-prepared with practice questions."
"Good at expressing what is expected of the student in the course"
"Very knowledgeable of the subject and was consistent with his help and support with problems/concerns."
"The instructor in this course was very helpful and very knowledgeable of the subject being taught."
"I think this course is very well taught and I would not recommend any changes."
"The recitations are good. Prof. Garrison knows what he is doing. Smart guy."
"Very knowledgeable and well prepared. Articulates effectively."

Individual Instruction and Advisement (other than organized classes)

- Advised about 30 master's level physics students both formally and informally.
- Taught 2 independent studies.
- In 2009, we graduated a total of 9 Physics graduate students.
- Chaired a PhD Thesis Committee through the Collaborative Physics PhD Program.

COURSE AND PROGRAM DEVELOPMENT

- Served as the UHCL Physics PSM director to manage, promote, assess and fine-tune the Physics Technical Management Sub-Plan.
- Promoted the Collaborative PhD, Traditional Physics MS and PSM Physics programs at the 2009 NSBP conference in Nashville, TN.
- Mailed Physics Program booklets and posters to all the undergraduate physics departments in Texas and Louisiana in order to promote our physics program.
- Continued work on a proposal for a BS in Physics at UHCL that was approved in November 2009 after a 20 month approval process.
- Continued development of recitation sections for the six core courses needed for PhD candidacy through the Collaborative Physics PhD Program.
- Worked with UH and UHCL faculty to evaluate and improve the Collaborative Physics PhD Program.
- Served on the Faculty Senate's "Going 4 years" taskforce.
- Conducted a bi-yearly needs assessment survey of the Physics Program
- Worked to develop the use of Internet video conferencing to teach distance learning courses (with Wimba, Adobe Connect Pro, etc..) such as my Spring 2009 General Relativity course.
- Gave a presentation at TLEC about using Video Conferencing software for distance education.
- Developed a Facebook page to promote the Physics Program.
- Wrote a "Guide to Graduate Physics" to improve student understanding of the graduate physics process.
- Continued to maintain all the Physics teaching lab computers.

RESEARCH, SCHOLARLY AND ARTISTIC ACTIVITIES

- Organized and hosted a weekly Spring Seminar Series to stimulate interest in Space Science and Physics and to directly involve JSC researchers in activities at UHCL. I assembled a group of thirteen speakers and advertised the talks through the Physics Program website, fliers on campus and using my email distribution list. In addition, I worked with the UHCL development and communications offices to publicize the series through the local newspapers. This seminar was given in conjunction with the Research Project and Seminar class and PHYS 4732. We had an audience of about 30 people per week.
- Hosted our second American Astronomical Society Shapley Lecture by Professor Robert Rood from the University of Virginia.
- Planned a visit, dinner and public lecture by University of Virginia Astronomy Professor John Hawley. The event occurred on January 23, 2009 and about 400 people attended.
- Planned a visit, dinner and public lecture by Joseph Romm of the Center for Energy and Climate Solutions.
- Continued development of a General Relativistic Magnetohydrodynamics (GRMHD) computer code for cosmological simulations. This is one of the few know GRMHD codes and will be used for a new numerical cosmology research project. In 2007, I successfully tested the code and began to produce publishable

results. Submitted a paper based on these results for publication during the summer of 2008. I rewrote and resubmitted this paper in January of 2009.
- Went on Faculty Development Leave in Fall 2009 in order to write a more robust GRMHD code.
- Worked with the Texas Educational Grid Computing Project to enhance our on-campus Beowulf supercomputer faculty. I attended several meetings with TXGrid and Conoco Phillips. I also worked with other UHCL faculty and staff to set-up and maintain the computer.
- Member of the Space and Complex Systems Research Cluster at UH.
- Was invited to submit a proposal for the THECB's Norman Hackerman grant program (submitted January 2010).
- Developed a collaboration with Dr. Ricardo Vilalta of the UH Computer Science program to use an AI to analyze the results of my cosmological code.
- Co-hosted the Space Center Lecture Series at UHCL.

PUBLICATIONS
- My 2003 paper "Black Hole Spectroscopy: testing general relativity through gravitational-wave observations" was cited 6 times in 2009, bringing the total to 36 citations.
- Submitted a paper for the proceedings of the 2009 NSBP conference.
- Gravitational Waves And The Evolution Of The Universe by David Garrison PROCEEDINGS OF THE NATIONAL SOCIETY OF BLACK PHYSICISTS: 35th Annual Day of Scientific Lectures & 31st Annual Meeting, 2008 Joint Annual Conference of The National Society of Black Physicists and The National Society of Hispanic Physicists

PAPERS PRESENTATIONS, ABSTRACTS AND POSTER SESSIONS
- Was the keynote speaker at the Houston Astronomical Society's Annual Banquet.
- Gave an Invited talk at a JSC Astronomical Society meeting.
- Gave a contributed talk at the 2009 NSBP meeting.

HONORS AND AWARDS
- Inducted into the first Fort Zumwalt North High School's Hall of Fame.
- PI on an unfunded NASA Grant, the total amount of the proposal is $358,374.
- PI on a funded Faculty Development Fund proposal to attend the 2009 NSBP meeting in Nashville, TN; $1,512.
- Awarded 200,000 units on the University of Texas' Supercomputer Ranger through the Teragrid

PROFESSIONAL ACTIVITES AND SERVICE
- Served as Program Chair of Physics – My duties included biennial planning, creating a strategic plan for the physics program, preparing class schedules, hiring and supervising roughly six to ten adjunct professors per semester, promoting the physics program and managing the physics program's resources. As part of my biennial planning efforts in 2004, 2006 and 2008, I conducted a study comparing

the Physics program at UHCL to others nationwide. I found that we have one of the largest graduate enrollments of any program in our class and the highest major to full-time faculty ratio in Texas.

- Chaired the Physics program review committee and submitted the review to the SCE curriculum committee in Fall 2009.
- Served on the Physical Sciences program review committee.
- Served on the SCE Dean Search Committee.
- Chaired the Physics Assistant Professor Search Committee.
- Served as Chair of the SCE curriculum committee until March 2009 – I reviewed curriculum changes, program reviews and all new program development issues related to SCE.
- Served on the SCE Policy and Advisory committee.
- Served on the Faculty Senate Research Committee and served as chair from Fall 2008 through Spring 2009.
- As FS Research Chair I worked to develop a University Research Website and evaluate course capture software leading to the university's purchase of Wimba.
- Served on the University's Planning & Budget Committee.
- Served on the Faculty Senate Executive Committee.
- Served on Academic Council.
- Served on University Council.
- Co-advisor for the Black Student Association – served on the Black History Month Faculty Panel
- Attended the 2009 National Society of Black Physicists joint meeting with the National Society of Hispanic Physicists in Nashville, TN where I promoted our Physics program.
- Organized a tour and visit with the management of Ad Astra Rocket Company, Dean Davari and Provost Stockton in order to stimulate future collaborations.
- Served as the UHCL Goldwater Scholarship Faculty Representative.

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- http://sce.uhcl.edu/garrison/survey4/results.asp

The latest results of the Physics Ph.D. Program Survey are located at:

- http://sce.uhcl.edu/garrison/survey6/results.asp

The last Physics Needs Assessment Survey is located at:

- http://www.surveymonkey.com/s/XH58M76

FACULTY ANNUAL REPORT

David Garrison, Associate Professor and Chair of Physics
January 1, 2010 through December 31, 2010

TEACHING AND EDUCATIONAL ACTIVITIES

Virtually all the students who filled out teaching evaluations enjoyed my courses and felt that they have learned a lot from me. My colleagues tend to agree. I also maintain a roughly 50% pass rate on Ph.D. candidacy exams which is about as good as any faculty in a typical Physics Ph.D. program.

Classroom Instruction:

Spring 2010:

- PHYS 5311 Recitation for Electrodynamics I – 5 graduate students (after drop date). This is the recitation for Physics 5331. Each week I would work out example problems with students in order to prepare them for the Ph.D. Candidacy Exam.
- PHYS 5331 Electrodynamics I – 11 graduate students (after drop date). This is the standard PhD level Electrodynamics course taught using the textbook by J. D. Jackson. This course counts towards PhD candidacy through our Collaborative PhD program.
- PHYS 4732 / 6838 Modern Physics Research / Research Project and Seminar – 2 undergraduate student and 7 graduate students. PHYS 4732 is a course developed to expose undergraduates to current topics of interest using our physics guest lecture series. This has since become a capstone course for our undergraduate Physics and Physical Sciences Degrees. PHYS 6838 is the capstone course for students completing the Masters of Physics degree. This course focuses on teaching communication skills as well as research. Students complete research projects and then present research papers both orally and in written form. The seminar portion of this course has become very popular in the local community.

Summer 2010:

- No Teaching

Fall 2010:

- PHYS 4331 Principles of Electromagnetism – 4 undergraduate students (after drop date). This was the undergraduate version of PHYS 5331 taught using the textbook by Griffiths.
- PHYS 5511 Recitation for Mathematical Methods 1 – 4 graduate students (after drop date). This is the recitation for Physics 5531. Each week I would work out example problems with students in order to prepare them for the Ph.D. Candidacy Exam.
- PHYS 5531 Mathematical Methods in Physics 1 – 8 graduate students (after drop date). This was a class, which I originally introduced in the spring of 2003. The course covers 10 topics of advanced mathematics which include: Ordinary

Differential Equations, Infinite Series, Integration Techniques, Fourier Series and Transforms, Complex Variables, Linear Algebra, Tensors, Partial Differential Equations, Special Functions and Probability & Statistics. Students consider this to be an intense core physics course and the most essential to further success in physics. Those who survive the course tend to do very well in the other physics classes.

Course evaluations:

PHYS 4331:
- Pace: 3.75
- Overall Quality: 4.25
- Subject Knowledge: 4.75
- Overall Teaching: 4.25
- Stimulate & Challenge Students: 4.5
- Encourage Class Participation: 4.5
- Helping Students Understand: 4.5

PHYS 5311 / 5331:
- Pace: 4.33
- Overall Quality: 3.0
- Subject Knowledge: 3.56
- Overall Teaching: 3.22
- Stimulate & Challenge Students: 3.33
- Encourage Class Participation: 3.56
- Helping Students Understand: 3.33

PHYS 5511 / 5531:
- Pace: 4.5
- Overall Quality: 4.8
- Subject Knowledge: 5.0
- Overall Teaching: 4.4
- Stimulate & Challenge Students: 4.6
- Encourage Class Participation: 5.0
- Helping Students Understand: 4.8

PHYS 4732 / 6838:
- Pace: N/A
- Overall Quality: N/A
- Subject Knowledge: N/A
- Overall Teaching: N/A
- Stimulate & Challenge Students: N/A
- Encourage Class Participation: N/A
- Helping Students Understand: N/A

Selected Comments:

"Available additional office hours upon request"
"Very knowledgeable. Used real-world examples"
"Knowledgeable, prepared organized"
"There was a lot of material"
"He used good practical examples to explain difficult topics. This was helpful to engage me."

Individual Instruction and Advisement (other than organized classes)

- Advised about 15 master's level physics students both formally and informally.
- Taught 5 independent studies.
- In 2010, we graduated a total of 9 Physics graduate students and 1 Physics undergrad student making us the second largest producers of Physics Master's degrees in the state of Texas.

COURSE AND PROGRAM DEVELOPMENT

- Served as the UHCL Physics PSM director to manage, promote, assess and fine-tune the Physics Technical Management Sub-Plan.
- Promoted the Collaborative PhD, Traditional Physics MS, PSM and BS Physics programs at the 2010 April APS conference in Washington DC.
- Implemented a new BS in Physics at UHCL that was approved in November 2009 after a 20-month approval process.
- Continued development of recitation sections for the six core courses needed for PhD candidacy through the Collaborative Physics PhD Program.
- Worked with UH and UHCL faculty to evaluate and improve the Collaborative Physics PhD Program in a 3rd year review of the program.
- Maintained a Facebook page to promote the Physics Program.
- Continued to maintain all the Physics teaching lab computers.
- Developed an Advisory Board for the UHCL Physics Program, which held it's first meeting in Fall 2010.
- Gave feedback to UHCL's "Going 4 year" Planning process.
- Joined PhysTec to get the UHCL Physics program involved in teacher training.
- Completed the 2009-2010 Program Review for Physics.
- Chaired a search committee, which lead to the successful hire of a new Associate Professor of Physics.
- Chaired a third year review committee for Dr. Samina Masood.

RESEARCH, SCHOLARLY AND ARTISTIC ACTIVITIES

- Organized and hosted a weekly Spring Seminar Series to stimulate interest in Space Science and Physics and to directly involve JSC researchers in activities at UHCL. I assembled a group of eleven speakers and advertised the talks through the Physics Program website, fliers on campus and using my email distribution list. In addition, I worked with the UHCL development and communications offices to publicize the series through the local newspapers. This seminar was given in conjunction with the Research Project and Seminar class and PHYS 4732. We had an audience of about 30 people per week.

- Hosted our third American Astronomical Society Shapley Lecture by Professor Eric Linder from the Berkeley Center for Cosmological Physics.
- Planned and implemented a visit, dinner and public lecture by President Allen Sessoms of the University of the District of Columbia.
- Planned and implemented a visit, dinner and public lecture by Joseph Romm of the Center for Energy and Climate Solutions.
- Continued development of a General Relativistic Magnetohydrodynamics (GRMHD) computer code for cosmological simulations. This is being used for a numerical cosmology research project. In 2010, I Submitted a paper describing the code to Classical and Quantum Gravity (still pending review).
- Worked with the Texas Educational Grid Computing Project to enhance our on-campus Beowulf supercomputer faculty. This resulted in an upgrade to Athena with several dozen dual-processor Itanium 2 nodes.
- Member of the Space and Complex Systems Research Cluster at UH.
- Co-hosted the Space Center Lecture Series at UHCL.
- PI on a Norman Hackerman grant proposal to the THECB $100,000 (unfunded).
- PI on a NSF CRI grant to enhance our supercomputing infrastructure $371,991 (unfunded).
- PI on a 3-university (UHCL, UH and Rice) FAA grant to establish a new center for Commercial Space Transportation $10,000,000 in FAA funding plus $10,000,000 in matching funds (unfunded).
- PI on a successful ISSO mini and postdoc grant $66,800 (funded).
- Submitted a paper on the "Modification of Einstein's equations by a spacetime strain" with a former student to Classical and Quantum Gravity.
- Wrote a pre-proposal letter for a PhysTec grant (not invited to apply for full proposal).
- Wrote a pre-proposal for the Clare Boothe Luce foundation fellowship (not invited to apply for full proposal).

PUBLICATIONS

- My 2003 paper "Black Hole Spectroscopy: testing general relativity through gravitational-wave observations" is still gaining citations. It was cited 6 times in 2010, bringing the total to 42 citations.
- Submitted "Modification of Einstein's equations by a spacetime strain" to Classical and Quantum Gravity (rewrite needed).
- Submitted "Numerical Relativity as a tool for studying the Early Universe" to Classical and Quantum Gravity (pending).

PAPERS PRESENTATIONS, ABSTRACTS AND POSTER SESSIONS

- Gave a contributed talk at the 2010 April APS meeting "Numerical Cosmology: Building a Dynamical Universe".
- Gave an invited talk at the 2010 United Space School about the UHCL Physics Program.

HONORS AND AWARDS

- Awarded 200,000 units on the supercomputers Ranger and Queenbee by the Teragrid Organization.
- Awarded $66,800 from ISSO for startup and Postdoc to conduct a "Theoretical and Numerical Study of Plasma Electromagnetic Interference (EMI) due to Plasma Turbulence in the VASIMR Exhaust Plume". This funding was used to hire 3 graduate students during the summer of 2010 and a new Research Assistant Professor starting Fall 2010.

PROFESSIONAL ACTIVITES AND SERVICE

- Served as Program Chair of Physics – My duties included biennial planning, creating a strategic plan for the physics program, preparing class schedules, hiring and supervising roughly four to seven adjunct professors per semester, promoting the physics program and managing the physics program's resources. As part of my biennial planning efforts in 2004, 2006 and 2008, I conducted a study comparing the Physics program at UHCL to others nationwide. I found that we have one of the largest graduate enrollments of any program in our class and the highest major to full-time faculty ratio in Texas.
- Chaired the Physics program review committee and completed the review process in the Spring of 2010.
- Served on the Physical Sciences program review committee.
- Chaired the Physics Assistant/Associate Professor Search Committee, we finally completed the search after reviewing roughly 170 applicants over the course of 14 months.
- Served on the SCE Policy and Advisory committee.
- Served and an Alternate on the SCE Faculty Development Committee.
- Served on the Management of Technology review committee.
- Served as the UHCL Goldwater Scholarship Faculty Representative.

WEB LINKS

The Texas Educational Grid Project website is located at:

- http://www.txgrid.org

The Physics Program website is located at:

- http://sce.uhcl.edu/Physics

The Physics Program Informational website is located at:

- http://sce.uhcl.edu/physicalscience/PhysicsProNotes.html

The latest results of the Physics Program Survey are located at:

- http://sce.uhcl.edu/garrison/survey/results.asp

The latest results of the follow-up Physics Program Survey are located at:

- http://sce.uhcl.edu/garrison/survey2/results.asp

The latest results of the first Professional Physics Program Survey are located at:

- http://sce.uhcl.edu/garrison/survey3/results.asp

The latest results of the second Professional Physics Program Survey are located at:

- http://sce.uhcl.edu/garrison/survey4/results.asp

The latest results of the Physics Ph.D. Program Survey are located at:

- http://sce.uhcl.edu/garrison/survey6/results.asp

The last Physics Needs Assessment Survey is located at:

- http://www.surveymonkey.com/s/XH58M76

FACULTY ANNUAL REPORT

David Garrison, Associate Professor and Chair of Physics
January 1, 2011 through December 31, 2011

TEACHING AND EDUCATIONAL ACTIVITIES

Virtually all the students who filled out teaching evaluations enjoyed my courses and felt that they have learned a lot from me. My colleagues tend to agree. I also maintain a roughly 50% pass rate on Ph.D. candidacy exams which is about as good as any faculty in a typical Physics Ph.D. program.

Classroom Instruction:

<u>Spring 2011:</u>

- PHYS 5311 Recitation for Electrodynamics I – 4 graduate students (after drop date). This is the recitation for Physics 5331. Each week I would work out example problems with students in order to prepare them for the Ph.D. Candidacy Exam.
- PHYS 5331 Electrodynamics I – 5 graduate students (after drop date). This is the standard PhD level Electrodynamics course taught using the textbook by J. D. Jackson. This course counts towards PhD candidacy through our Collaborative PhD program.
- PHYS 4732 / 6838 Modern Physics Research / Research Project and Seminar – 2 undergraduate student and 5 graduate students. PHYS 4732 is a course developed to expose undergraduates to current topics of interest using our physics guest lecture series. This has since become a capstone course for our undergraduate Physics and Physical Sciences Degrees. PHYS 6838 is the capstone course for students completing the Masters of Physics degree. This course focuses on teaching communication skills as well as research. Students complete research projects and then present research papers both orally and in written form. The seminar portion of this course has become very popular in the local community.

<u>Summer 2011:</u>

- PHYS 6132 General Relativity - 5 graduate student at UHCL. This is an extremely advanced course designed to introduce students to General Relativity so that they may do research in the area. This course counts towards the PhD at UH through our Collaborative Program and has been taught at both UHCL and UH using video conferencing software.

<u>Fall 2011:</u>

- PHYS 4331 Principles of Electromagnetism – 8 undergraduate students (after drop date). This was the undergraduate version of PHYS 5331 taught using the textbook by Griffiths.
- PHYS 5511 Recitation for Mathematical Methods 1 – 6 graduate students (after drop date). This is the recitation for Physics 5531. Each week I would work out

example problems with students in order to prepare them for the Ph.D. Candidacy Exam.

- PHYS 5531 Mathematical Methods in Physics 1 – 7 graduate students (after drop date). This was a class, which I originally introduced in the spring of 2003. The course covers 10 topics of advanced mathematics which include: Ordinary Differential Equations, Infinite Series, Integration Techniques, Fourier Series and Transforms, Complex Variables, Linear Algebra, Tensors, Partial Differential Equations, Special Functions and Probability & Statistics. Students consider this to be an intense core physics course and the most essential to further success in physics. Those who survive the course tend to do very well in the other physics classes.

Course evaluations:

PHYS 4331:
- Pace: 4.8
- Overall Quality: 4.2
- Subject Knowledge: 4.8
- Overall Teaching: 4.4
- Stimulate & Challenge Students: 4.6
- Encourage Class Participation: 4.8
- Helping Students Understand: 4.6

PHYS 5311 / 5331:
- Pace: 4.0/4.33
- Overall Quality: 4.33/4.67
- Subject Knowledge: 5.0/5.0
- Overall Teaching: 4.67/4.67
- Stimulate & Challenge Students: 5.0/5.0
- Encourage Class Participation: 5.0/4.67
- Helping Students Understand: 5.0/5.0

PHYS 6132:
- Pace: N/A
- Overall Quality: N/A
- Subject Knowledge: N/A
- Overall Teaching: N/A
- Stimulate & Challenge Students: N/A
- Encourage Class Participation: N/A
- Helping Students Understand: N/A

PHYS 5511 / 5531:
- Pace: 3.8/4.0
- Overall Quality: 3.6/3.6
- Subject Knowledge: 4.6/4.8
- Overall Teaching: 4.0/3.4

Stimulate & Challenge Students: 4.2/4.0
Encourage Class Participation: 4.2/4.2
Helping Students Understand: 4.4/4.4

PHYS 4732 / 6838:
Pace: 3.0
Overall Quality: 4.75
Subject Knowledge: 4.75
Overall Teaching: 4.75
Stimulate & Challenge Students: 4.5
Encourage Class Participation: 4.75
Helping Students Understand: 4.75

Selected Comments:
"He knows the material well – a lot of material, and can cover them in a short amount of time, i.e. we covered tensor calculus in 3 hours."
"Good examples given in class"
"knows his stuff"
"Fills in gaps from text derivations"

Individual Instruction and Advisement (other than organized classes)

- Advised about 20 undergraduate and graduate physics students both formally and informally.
- Advised one PhD student through our Collaborative Physics PhD program.
- Served on one PhD thesis committee through our Collaborative Physics PhD program.
- Taught 1 independent studies.
- In 2011, we graduated a total of 6 Physics graduate students but no Physics undergrad students which still makes us one of the largest producers of Physics Master's degrees in the state of Texas.

COURSE AND PROGRAM DEVELOPMENT

- Served as the UHCL Physics PSM director to manage, promote, assess and fine-tune the Physics Technical Management Sub-Plan.
- Promoted the Collaborative PhD, Traditional Physics MS, PSM and BS Physics programs at the 2011 April APS conference in Anaheim, CA.
- Developed and implemented a sub-plan in Engineering Physics under our new Physics BS program.
- Continued the development of recitation sections for the six core courses needed for PhD candidacy through the Collaborative Physics PhD Program, making them mandatory for all students.
- Maintained a Facebook page to promote the Physics Program.
- Continued to maintain all the Physics teaching lab computers until all Mac's where replaced with PC's.

- Worked with our Advisory Board for the UHCL Physics Program, which met once each long semester.
- Gave feedback to UHCL's downward expansion planning process.
- Chaired a search committee, which lead to the successful hire of a new Associate Professor of Physics, Dr. Paul Withey.
- Chaired a tenure year review committee for Dr. Samina Masood.
- Gave talks at San Jacinto Central Campus and attended Engineering Education Fairs to promote our Undergrad Physics Program.
- Participated in an external review of San Jacinto College's Physics and Astronomy curriculum.

RESEARCH, SCHOLARLY AND ARTISTIC ACTIVITIES

- Organized and hosted a weekly Spring Seminar Series to stimulate interest in Space Science and Physics and to directly involve JSC researchers in activities at UHCL. I assembled a group of eleven speakers and advertised the talks through the Physics Program website, fliers on campus and using my email distribution list. In addition, I worked with the UHCL development and communications offices to publicize the series through the local newspapers. This seminar was given in conjunction with the Research Project and Seminar class and PHYS 4732. We had an audience of about 30 people per week.
- Hosted our fourth American Astronomical Society Shapley Lecture by Professor Edward Kolb the Arthur Holly Compton Distinguished Service Professor of Astronomy & Astrophysics and the College and Chair of the Department of Astronomy and Astrophysics at the University of Chicago.
- Hosted a talk by author Jeffery Bennett.
- Continued development of a General Relativistic Magnetohydrodynamics (GRMHD) computer code for cosmological simulations. This is being used for a numerical cosmology research project. In 2011, I developed what is probably the only Cactus based multiprocessor spectral differencing code in existence.
- Traveled to Carnegie Mellon University to meet with potential collaborators.
- Developed a collaboration with Haverford College and Princeton University on numerical simulations of pre-inflationary cosmology.
- Advised a PhD student through our Collaborative Physics PhD program.
- Served on a Thesis committee for another student through our Collaborative Physics PhD program.
- Submitted an unsuccessful proposal to the NASA ROSES program on predicting the spectrum of gravitational waves from primordial turbulence.
- Submitted a still pending proposal to NSF's Gravity Theory program on predicting the spectrum of gravitational waves from primordial turbulence.
- Participated in the planning for a NASA ISS National Lab Proposal.
- Participated in the planning for a NASA JSC Internship CAN Proposal.
- Participated in an S-STEM grant.
- Participated in SCE's strategic planning for future research.
- Member of the Space and Complex Systems Research Cluster at UH.

- Co-hosted the Space Center Lecture Series at UHCL.
- Wrote a pre-proposal letter for a PhysTec grant (not invited to apply for full proposal).
- Interviewed for the Houston Chronicle's "Meet a Scientist Monday #12" April 24th 2011 - http://blogs.chron.com/proteinwrangler/

PUBLICATIONS

- Published the book: TESTING BINARY BLACK HOLE CODES IN STRONG FIELD REGIMES: UNDERSTANDING NUMERICAL INSTABILITIES THROUGH COMPUTATIONAL EXPERIMENTS by David Garrison, LAP Lambert Academic Publishing, 2011

PAPERS PRESENTATIONS, ABSTRACTS AND POSTER SESSIONS

- Gave a contributed talk at the 2011 April APS in Anaheim, CA.
- Gave an invited talk at the 2011 NSBP Meeting in Austin, TX.
- Gave an invited talk at a Houston Astronomical Society Meeting.
- Gave an invited talk at the 2011 United Space School about the UHCL Physics Program.
- Gave an invited talk at Carnegie Mellon on simulating primordial gravitational waves.
- Gave an invited talk for JSC's Black History Month event.

HONORS AND AWARDS

- Awarded $5,000 with Dr. Withey to help him start his research at UHCL.

PROFESSIONAL ACTIVITES AND SERVICE

- Served as Program Chair of Physics – My duties included biennial planning, creating a strategic plan for the physics program, preparing class schedules, hiring and supervising roughly four to seven adjunct professors per semester, promoting the physics program and managing the physics program's resources. As part of my biennial planning efforts in 2004, 2006 and 2008, I conducted a study comparing the Physics program at UHCL to others nationwide. I found that we have one of the largest graduate enrollments of any program in our class and the highest major to full-time faculty ratio in Texas.
- Served on the Physical Sciences program review committee.
- Chaired the Physics Assistant/Associate Professor Search Committee, we finally completed the search after reviewing roughly 170 applicants over the course of 14 months.
- Served on the SCE Policy and Advisory committee.
- Served and an Alternate on the SCE Faculty Development Committee.
- Served as the UHCL Goldwater Scholarship Faculty Representative.
- Served on the ISSO Grant Proposal Review Panel.
- Helped Space Center Houston with their Physics Day.
- Helped LPI with their Family Space Day.

- Accepted an invitation to serve on Space Center Houston's Advisory Board.
- Participated in Rice's SpaceCity2020 event on the future of NASA JSC.
- Meet with Professor Cheng the new Vice Chair of the Texas Section of the APS about the THECB's closing of several public physics programs.

WEB LINKS

The Texas Educational Grid Project website is located at:

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- http://www.surveymonkey.com/s/XH58M76

FACULTY ANNUAL REPORT

David Garrison, Associate Professor and Chair of Physics
January 1, 2012 through December 31, 2012

TEACHING AND EDUCATIONAL ACTIVITIES

Virtually all the students who filled out teaching evaluations enjoyed my courses and felt that they have learned a lot from me. My colleagues tend to agree. I also maintain a roughly 50% pass rate on Ph.D. candidacy exams which is about as good as any faculty in a typical Physics Ph.D. program.

Classroom Instruction:

Spring 2012:

- PHYS 5311 Recitation for Electrodynamics I – 5 graduate students. This is the recitation for Physics 5331. Each week I would work out example problems with students in order to prepare them for the Ph.D. Candidacy Exam.
- PHYS 5331 Electrodynamics I – 4 graduate students. This is the standard PhD level Electrodynamics course taught using the textbook by J. D. Jackson. This course counts towards PhD candidacy through our Collaborative PhD program.
- PHYS 4732 / 6838 Modern Physics Research / Research Project and Seminar – 4 undergraduate student and 1 graduate students. PHYS 4732 is a course developed to expose undergraduates to current topics of interest using our physics guest lecture series. This has since become a capstone course for our undergraduate Physics and Physical Sciences Degrees. PHYS 6838 is the capstone course for students completing the Masters of Physics degree. This course focuses on teaching communication skills as well as research. Students complete research projects and then present research papers both orally and in written form. The seminar portion of this course has become very popular in the local community.

Summer 2012:

- PHYS 4333/5931 Special Relativity - 2 undergraduate student and 3 graduate students. This was one of my absolute favorite courses to teach. I originally developed this class in the spring of 2003 and I can honestly say that it is unique among physics curricula anywhere. I created the class as a way of preparing students to take general relativity at the graduate level. Students are taught about special relativity and tensors from a graphical rather than purely mathematical approach. Special relativity is derived from first principles and towards the end of the class Maxwell's equations of electrodynamics are derived.

Fall 2012:

- PHYS 5511 Recitation for Mathematical Methods 1 – 7 graduate students. This is the recitation for Physics 5531. Each week I would work out example problems with students in order to prepare them for the Ph.D. Candidacy Exam.
- PHYS 5531 Mathematical Methods in Physics 1 – 6 graduate students. This was a class, which I originally introduced in the spring of 2003. The course covers 10

topics of advanced mathematics which include: Ordinary Differential Equations, Infinite Series, Integration Techniques, Fourier Series and Transforms, Complex Variables, Linear Algebra, Tensors, Partial Differential Equations, Special Functions and Probability & Statistics. Students consider this to be an intense core physics course and the most essential to further success in physics. Those who survive the course tend to do very well in the other physics classes.

Course evaluations:

PHYS 5311 / 5331:
- Pace: 3.5/4.0
- Overall Quality: 3.5/3.0
- Subject Knowledge: 4.5/4.0
- Overall Teaching: 4.0/3.5
- Stimulate & Challenge Students: 4.0/4.0
- Encourage Class Participation: 4.5/5.0
- Helping Students Understand: 4.5/4.0

PHYS 4333/5931:
- Pace: N/A
- Overall Quality: N/A
- Subject Knowledge: N/A
- Overall Teaching: N/A
- Stimulate & Challenge Students: N/A
- Encourage Class Participation: N/A
- Helping Students Understand: N/A

PHYS 5511 / 5531:
- Pace: 3.0/3.75
- Overall Quality: 3.25/3.75
- Subject Knowledge: 4.25/3.75
- Overall Teaching: 3.5/3.25
- Stimulate & Challenge Students: 3.75/4.0
- Encourage Class Participation: 3.75/4.0
- Helping Students Understand: 4.25/4.25

PHYS 4732 / 6838:
- Pace: 3.67
- Overall Quality: 5.0
- Subject Knowledge: 5.0
- Overall Teaching: 5.0
- Stimulate & Challenge Students: 5.0
- Encourage Class Participation: 5.0
- Helping Students Understand: 5.0

Selected Comments:

"He is extremely knowledgeable on the course material"
"good communication, knowledgeable, very friendly, professional!!"
"Knows the extremely difficult & complex material well, which is very impressive. Gives nice physical examples to arcane mathematical formulations of electrodynamics."
"This particular topic & textbook is known to be among the hardest in physics graduate school. The course provided a nice overview of the textbook and allowed me to work through ample problems in detail."

Individual Instruction and Advisement (other than organized classes)

- Advised about 20 undergraduate and graduate physics students both formally and informally.
- Served as Chair of 2 Masters Thesis Committees.
- Advised 2 independent studies.
- In 2012, we graduated a total of 2 Physics graduate students and 2 Physics undergrad students.

COURSE AND PROGRAM DEVELOPMENT

- Developed a THECB planning authority proposal and needs assessment survey to upgrade our Cooperative Physics PhD program into a full Joint Physics PhD program after meeting with the Deans at UHCL and UH as well as several physics faculty in both programs.
- Attended 3 meetings, which focused on improving our enrollment and the quality of our physics programs. 1) Texas Spin-Up Meeting in Austin, 2) National Physics Chair's Meeting in Washington, DC and 3) Physics Enrollment Workshop in Washington, DC. This lead to several ideas that we are implementing (or have implemented) in order to improve the UHCL Physics program and prepare for downward expansion.
- Attempted to work with the School of Education and the Math Department to develop a Physics Teacher Education Certificate program.
- Served as the UHCL Physics PSM director to manage, promote, assess and fine-tune the Physics Technical Management Sub-Plan.
- Promoted the Collaborative PhD, Traditional Physics MS, PSM and BS Physics programs at the 2012 April APS conference in Atlanta, GA.
- Continued to promote and implement a new sub-plan in Engineering Physics under our new Physics BS program.
- Maintained a Facebook page to promote the Physics Program.
- Worked with our Advisory Board for the UHCL Physics Program, which met once each long semester.
- Gave feedback to UHCL's downward expansion planning process.

RESEARCH, SCHOLARLY AND ARTISTIC ACTIVITIES

- Organized and hosted a weekly Spring Seminar Series to stimulate interest in Space Science and Physics and to directly involve JSC researchers in activities at UHCL. I assembled a group of twelve speakers and advertised the talks through the Physics Program website, fliers on campus and using my email distribution list. In addition, I worked with the UHCL development and communications offices to publicize the series through the local newspapers. This seminar was given in conjunction with the Research Project and Seminar class and PHYS 4732. We had an audience of about 30 people per week.

- Continued development of a General Relativistic Magnetohydrodynamics (GRMHD) computer code for cosmological simulations. This is being used for a numerical cosmology research project. Paper submitted for publication in 2012.
- Developed collaboration with Haverford College and Princeton University on numerical simulations of pre-inflationary cosmology. Paper submitted in 2012.
- Chaired 2 MS Thesis committees in 2012.
- Submitted a pending proposal to NSF's Gravity Theory program (through the NSF EAGER program) on simulating relativistic turbulence.
- Submitted a pending NSF REU site grant program.
- Submitted an unfunded FRSF proposal.
- Participated in an S-STEM grant proposal.
- Participated in a McNair grant proposal.
- Participated in a NAIC Phase 1 Step A proposal.
- Member of the Space and Complex Systems Research Cluster at UH.

PUBLICATIONS

- Published the book: "What Every Successful Physics Graduate Student Should Know" by David Garrison, iTunes Book Store, 2012
- A Numerical Simulation of Chern-Simons Inflation by Annie Preston, David Garrison and Stephon Alexander, hep-th/1208.2660 submitted to the Journal of Cosmology and Astroparticle Physics
- Numerical Relativity as a tool for studying the Early Universe by David Garrison, gr-qc/1207.7097 submitted to Classical and Quantum Gravity

PAPERS PRESENTATIONS, ABSTRACTS AND POSTER SESSIONS

- Gave a contributed talk and poster at the 2012 April APS in Atlanta, GA.
- Greeted the graduates on behalf of the faculty at the December 2012 Commencement ceremony.

HONORS AND AWARDS

- Chosen and interviewed as part of the HistoryMakers (ScienceMakers) oral history archive project.

PROFESSIONAL ACTIVITES AND SERVICE

- Served as Program Chair of Physics – My duties included biennial planning, creating a strategic plan for the physics program, preparing class schedules, hiring and supervising roughly four to seven adjunct professors per semester, promoting the physics program and managing the physics program's resources. As part of my biennial planning efforts in 2004, 2006 and 2008, I conducted a study comparing the Physics program at UHCL to others nationwide. I found that we have one of the largest graduate enrollments of any program in our class and the highest major to full-time faculty ratio in Texas.

- Elected President of the UHCL Faculty Senate. In 2012 I served as President-Elect and therefore a member of the Faculty Senate Executive Committee, Academic Council, University Council, Texas Council of Faculty Senates and University Faculty Executive Council.
- Served on the Physical Sciences program review committee.
- Served on the SCE Policy and Advisory committee.
- Served as the UHCL Goldwater Scholarship Faculty Representative.
- Served on the Space Center Houston's Educational Advisory Board.
- Served on CSAC.
- Attended the SCE/Community College breakfast.

WEB LINKS

The Texas Educational Grid Project website is located at:

- http://www.txgrid.org

The Physics Program website is located at:

- http://sce.uhcl.edu/Physics

The Physics Program Informational website is located at:

- http://sce.uhcl.edu/physicalscience/PhysicsProNotes.html

The latest results of the Physics Program Survey are located at:

- http://sce.uhcl.edu/garrison/survey/results.asp

The latest results of the follow-up Physics Program Survey are located at:

- http://sce.uhcl.edu/garrison/survey2/results.asp

The latest results of the first Professional Physics Program Survey are located at:

- http://sce.uhcl.edu/garrison/survey3/results.asp

The latest results of the second Professional Physics Program Survey are located at:

- http://sce.uhcl.edu/garrison/survey4/results.asp

The latest results of the Physics Ph.D. Program Survey are located at:

- http://sce.uhcl.edu/garrison/survey6/results.asp

The last General Physics Needs Assessment Survey is located at:

- http://www.surveymonkey.com/s/XH58M76

The Joint Physics PhD Needs Assessment Survey is located at:

- http://www.surveymonkey.com/s/P9BBJQG

FACULTY ANNUAL REPORT

David Garrison, Associate Professor and Chair of Physics
January 1, 2013 through December 31, 2013

Please note that in Spring and Fall 2013 I was eligible to go on Family Leave because of the birth of my son and the fact that my wife is still stationed at Lackland Airforce Base in San Antonio. I did not go on leave either semester because there was nobody available to take over my teaching or service obligations.

TEACHING AND EDUCATIONAL ACTIVITIES

Virtually all the students who filled out teaching evaluations enjoyed my courses and felt that they have learned a lot from me. My colleagues tend to agree. I also maintain a roughly 50% pass rate on Ph.D. candidacy exams which is about as good as any faculty in a typical Physics Ph.D. program.

Classroom Instruction:

Spring 2013:

- PHYS 5311 Recitation for Electrodynamics I – 7 graduate students. This is the recitation for Physics 5331. Each week I would work out example problems with students in order to prepare them for the Ph.D. Candidacy Exam.
- PHYS 5331 Electrodynamics I – 6 graduate students. This is the standard PhD level Electrodynamics course taught using the textbook by J. D. Jackson. This course counts towards PhD candidacy through our Collaborative PhD program.
- PHYS 4732 / 6838 Modern Physics Research / Research Project and Seminar – 10 undergraduate student and 3 graduate students. PHYS 4732 is a course developed to expose undergraduates to current topics of interest using our physics guest lecture series. This has since become a capstone course for our undergraduate Physics and Physical Sciences Degrees. PHYS 6838 is the capstone course for students completing the Masters of Physics degree. This course focuses on teaching communication skills as well as research. Students complete research projects and then present research papers both orally and in written form. The seminar portion of this course has become very popular in the local community.

Fall 2013:

- PHYS 5511 Recitation for Mathematical Methods 1 – 3 graduate students. This is the recitation for Physics 5531. Each week I would work out example problems with students in order to prepare them for the Ph.D. Candidacy Exam.
- PHYS 5531 Mathematical Methods in Physics 1 – 3 graduate students. This was a class, which I originally introduced in the spring of 2003. The course covers 10 topics of advanced mathematics which include: Ordinary Differential Equations, Infinite Series, Integration Techniques, Fourier Series and Transforms, Complex Variables, Linear Algebra, Tensors, Partial Differential Equations, Special Functions and Probability & Statistics. Students consider this to be an intense

core physics course and the most essential to further success in physics. Those who survive the course tend to do very well in the other physics classes.

Course evaluations:

PHYS 5311 / 5331:
Pace: 3.6/4.0
Overall Quality: 3.6/3.8
Subject Knowledge: 4.2/4.2
Overall Teaching: 4.2/4.2
Stimulate & Challenge Students: 4.2/4.0
Encourage Class Participation: 4.4/4.4
Helping Students Understand: 4.4/4.6

PHYS 5511 / 5531:
Pace: 3.5/3.5
Overall Quality: 5.0/5.0
Subject Knowledge: 5.0/5.0
Overall Teaching: 5.0/5.0
Stimulate & Challenge Students: 3.5/3.5
Encourage Class Participation: 4.0/4.0
Helping Students Understand: 5.0/5.0

PHYS 4732 / 6838:
Pace: N/A
Overall Quality: N/A
Subject Knowledge: N/A
Overall Teaching: N/A
Stimulate & Challenge Students: N/A
Encourage Class Participation: N/A
Helping Students Understand: N/A

Selected Comments:

"Very prepared and organized. Excellent use of blackboard. Really nice not to be scribbling down notes; provides opportunity to focus on content/understanding. Willingness to accept student questions."

"Sometimes glossing over math details is no good since this is what we struggle with. Rectified by willingness to accept questions in most cases."

"It is so wonderful to have a physics instructor whose intention is to make the material accessible. Keep up the great work, it's much appreciated."

"He will record the class. It was good for me."

"He will record every class, so we can learn something again which I am not really understanding at first."

"Format of course is awesome, w/ Blackboard & recorded lectures!"

Ability to explain things in a simple way, not over our heads. Deliberate w/ terminology & kind w/ assumption of prior knowledge in order to make material accessible. Approachable attitude & willingness to answer questions."

Individual Instruction and Advisement (other than organized classes)

- Advised about 20 undergraduate and graduate physics students both formally and informally.
- Advised 1 PhD student through our Collaborative Physics PhD program.
- Served as Chair of 1 Masters Thesis Committee and as a member of 2 more Masters Thesis Committees.
- Advised 5 independent studies.
- In 2013, we graduated a total of 3 Physics graduate students and 6 Physics undergrad students (one in the Engineering Physics sub-plan). Also in 2013, we had our first Engineering Physics graduate pass the FE Exam for Professional Engineering Certification.

COURSE AND PROGRAM DEVELOPMENT

- Served as the UHCL Physics PSM director to manage, promote, assess and fine-tune the Physics Technical Management Sub-Plan.
- Promoted the Collaborative PhD, Traditional Physics MS, PSM, Engineering Sub-plan and BS Physics programs at the 2013 April APS conference in Denver, CO.
- Continued to promote and implement a new sub-plan in Engineering Physics under our new Physics BS program.
- Maintained a Facebook page to promote the Physics Program.
- Worked with our Advisory Board for the UHCL Physics Program, which met once each long semester.
- Participated in UHCL's downward expansion planning process.
- Helped the UHCL Physics program join the APS Bridge Program.
- Participated in several SCE Strategic Planning meetings.
- Toured Tietronix and worked to develop new collaborations with them and the UHCL Physics program.
- Meet with Career Services to discuss Internship opportunities for Physics Students. This involved giving a presentation on the physics major to the Career Services staff and arranging for a resume workshop for Physics students.
- Worked with Rice University to develop an option for UHCL graduate students to continue onto a PhD at Rice University.
- Sent posters and letters to several other Texas Physics Departments to help recruit more graduate students.
- Recruited physics students at the Spring and Fall 2013 Open Houses.
- Chaired 2 Physics Search committees with over 166 total applicants.

RESEARCH, SCHOLARLY AND ARTISTIC ACTIVITIES

- Organized and hosted a weekly Spring Seminar Series to stimulate interest in Space Science and Physics and to directly involve JSC researchers in activities at

UHCL. I assembled a group of twelve speakers and advertised the talks through the Physics Program website, Facebook and LinkedIn. In addition, I worked with the UHCL communications office to publicize the series through the local newspapers. This seminar was given in conjunction with the Research Project and Seminar class and PHYS 4732. We had an audience of about 30 people per week.

- Continued development of a General Relativistic Magnetohydrodynamics (GRMHD) computer code for cosmological simulations. This is being used for a numerical cosmology research project. Paper submitted for publication in 2013.
- Developed a code to simulate Chern-Simons modified gravity. Paper published in 2013 with a graduate student co-author.
- Advised a PhD student through our Collaborative PhD Program.
- Chaired 1 MS Thesis committee in 2013.
- Resubmitted a pending NSF REU site grant proposal as PI.
- Submitted an unfunded NSF WIDER Grant proposal as PI.
- Participated in a grant with Tietronix.
- Participated in the writing of an APS Bridge Grant pre-proposal.
- Participated in a funded S-STEM grant proposal as Co-I.
- Member of the Space and Complex Systems Research Cluster at UH.

PUBLICATIONS

- Published the book: "What Every Successful Physics Graduate Student Should Know" by David Garrison, Smashwords, 2013
- A Numerical Simulation of Chern-Simons Inflation by David Garrison and Christopher Underwood, Advances in Astronomy, Vol. 2013, 207218.

PAPERS PRESENTATIONS, ABSTRACTS AND POSTER SESSIONS

- Gave a contributed talk at the 2013 April APS in Denver, CO.
- Gave an invited talk at Rice University.
- Gave a talk as part of our Physics and Space Science Seminar Series.
- Gave an invited talk at WALIPP TSU Preparatory Academy as part of Back to School with the History Makers. I got more questions than former NBA player and NCAA champion David Lattin.
- Gave an invited talk at the North Houston Astronomy Club.
- Greeted the graduates on behalf of the faculty at the December 2013 Commencement ceremony.

PROFESSIONAL ACTIVITES AND SERVICE

- Served as Program Chair of Physics – My duties included biennial planning, creating a strategic plan for the physics program, preparing class schedules, service on the school curriculum committee, hiring and supervising roughly four to seven adjunct professors per semester, promoting the physics program and managing the physics program's resources.

- Served as President of the UHCL Faculty Senate. Member of the Faculty Senate Executive Committee, Academic Council, University Council, Texas Council of Faculty Senates and University Faculty Executive Council.
- Served on the SCE Post-Tenure Review Committee.
- Served on the Physical Sciences program review committee.
- Served as the UHCL Goldwater Scholarship Faculty Representative.
- Served on the Space Center Houston's Educational Advisory Board.
- Attended the SCE/Community College breakfast.
- Served on the AUM Clean Energy Group Investment Board.
- Served on the Latin Deaf Services Advisory Board.

WEB LINKS

The Texas Educational Grid Project website is located at:

- http://www.txgrid.org

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The latest results of the second Professional Physics Program Survey are located at:

- http://sce.uhcl.edu/garrison/survey4/results.asp

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The last General Physics Needs Assessment Survey is located at:

- http://www.surveymonkey.com/s/XH58M76

The Joint Physics PhD Needs Assessment Survey is located at:

- http://www.surveymonkey.com/s/P9BBJQG

FACULTY ANNUAL REPORT

David Garrison, Associate Professor, Chair of Physics and Director of Graduate Programs

January 1, 2014 through December 31, 2014

TEACHING AND EDUCATIONAL ACTIVITIES

Virtually all the students who filled out teaching evaluations enjoyed my courses and felt that they have learned a lot from me. My colleagues tend to agree. I also maintain a roughly 50% pass rate on Ph.D. candidacy exams which is about as good as any faculty in a typical Physics Ph.D. program.

Classroom Instruction:

Spring 2014:

- PHYS 4231 Intermediate Mechanics – 10 undergraduate students. This is an undergraduate core course for our BS of Physics degree. This is the first time I taught the course.
- PHYS 4732 / 6838 Modern Physics Research / Research Project and Seminar – 11 undergraduate student and 3 graduate students. PHYS 4732 is a course developed to expose undergraduates to current topics of interest using our physics guest lecture series. This has since become a capstone course for our undergraduate Physics Degree. PHYS 6838 is the capstone course for students completing the Masters of Physics degree. This course focuses on teaching communication skills as well as research. Students complete research projects and then present research papers both orally and in written form. The seminar portion of this course has become very popular in the local community.

Summer 2014:

- PHYS 4333/5931 Special Relativity - 4 undergraduate student and 1 graduate students. This was one of my absolute favorite courses to teach. I originally developed this class in the spring of 2003 and I can honestly say that it is unique among physics curricula anywhere. I created the class as a way of preparing students to take general relativity at the graduate level. Students are taught about special relativity and tensors from a graphical rather than purely mathematical approach. Special relativity is derived from first principles and towards the end of the class Maxwell's equations of electrodynamics are derived.

Fall 2014:

- PHYS 5511 Recitation for Mathematical Methods 1 – 8 graduate students. This is the recitation for Physics 5531. Each week I would work out example problems with students in order to prepare them for the Ph.D. Candidacy Exam.
- PHYS 5531 Mathematical Methods in Physics 1 – 8 graduate students. This was a class, which I originally introduced in the spring of 2003. The course covers 10 topics of advanced mathematics which include: Ordinary Differential Equations, Infinite Series, Integration Techniques, Fourier Series and Transforms, Complex

Variables, Linear Algebra, Tensors, Partial Differential Equations, Special Functions and Probability & Statistics. Students consider this to be an intense core physics course and the most essential to further success in physics. Those who survive the course tend to do very well in the other physics classes.

Course evaluations:

PHYS 4231:
Pace: 3.6
Overall Quality: 4.2
Subject Knowledge: 4.4
Overall Teaching: 4.6
Stimulate & Challenge Students: 4.2
Encourage Class Participation: 4.4
Helping Students Understand: 4.2

PHYS 4333/5931:
Pace: 3.67
Overall Quality: 4.67
Subject Knowledge: 4.67
Overall Teaching: 4.33
Stimulate & Challenge Students: 4.33
Encourage Class Participation: 4.33
Helping Students Understand: 4.67

PHYS 5511/5531:
Pace: N/A
Overall Quality: N/A
Subject Knowledge: N/A
Overall Teaching: N/A
Stimulate & Challenge Students: N/A
Encourage Class Participation: N/A
Helping Students Understand: N/A

PHYS 4732/6838:
Pace: 3.14
Overall Quality: 4.5
Subject Knowledge: 4.63
Overall Teaching: 4.75
Stimulate & Challenge Students: 4.57
Encourage Class Participation: 4.43
Helping Students Understand: 4.29

Selected Comments:

"Really attempts to teach you the material, Supportive"

"Very Knowledgeable"
"Incredibly helpful with any questions over course material"
"Dr. Garrison is a very good instructor show works really hard for physics department"
"He was always prepared with notes and lectures. He utilized technology to allow us access to lectures at home. Extremely knowledgeable of the subject."
"Used the text from the book extremely well. Explained work in the book well. Good speed with the course."

Individual Instruction and Advisement (other than organized classes)

- Advised about 20 undergraduate and graduate physics students both formally and informally.
- Advised 1 PhD student through our Collaborative Physics PhD program.
- Served as Chair of 1 Masters Thesis Committee and as a member of 3 more Masters Thesis Committees.
- Advised 1 independent study.
- In 2014, we graduated a total of 6 Physics graduate students and 8 Physics undergrad students (1 in the Engineering Physics sub-plan).

COURSE AND PROGRAM DEVELOPMENT

- Served as the UHCL Physics PSM director to manage, promote, assess and fine-tune the Physics Technical Management Sub-Plan.
- Continued to promote and implement a sub-plan in Engineering Physics under our new Physics BS program.
- Maintained a Facebook page to promote the Physics Program.
- Worked with our Advisory Board for the UHCL Physics Program, which met once each long semester.
- Participated in UHCL's downward expansion planning process.
- Helped the UHCL Physics program join the APS Bridge Program.
- Participated in several SCE Strategic Planning meetings.
- Recruited physics students at the Spring and Fall 2014 Open Houses.
- Chaired 2 Physics Search committees with over 166 total applicants.

RESEARCH, SCHOLARLY AND ARTISTIC ACTIVITIES

- Organized and hosted a weekly Spring Seminar Series to stimulate interest in Space Science and Physics and to directly involve JSC researchers in activities at UHCL. I assembled a group of twelve speakers and advertised the talks through the Physics Program website, Facebook and LinkedIn. In addition, I worked with the UHCL communications office to publicize the series through the local newspapers. This seminar was given in conjunction with the Research Project and Seminar class and PHYS 4732. We had an audience of about 30 people per week.
- Continued development of a General Relativistic Magnetohydrodynamics (GRMHD) computer code for cosmological simulations. This is being used for a numerical cosmology research project.

- Advised a PhD student through our Collaborative PhD Program.
- Chaired 1 MS Thesis committee to completion in 2014.
- Resubmitted a pending NSF REU site grant proposal as PI.
- Participated in an NSF iTEST grant with Tietronix.
- Participated in an NSF MRI Grant with UH.
- Participated in a funded S-STEM grant proposal as Co-I.
- Member of the Space and Complex Systems Research Cluster at UH.
- Won a FRSF grant in Fall 2014.

PUBLICATIONS

- Gauge Field Turbulence as a Cause of Inflation in Chern-Simons Modified Gravity by David Garrison, to appear in the Proceedings of the 7th Chaotic Modeling and Simulation International Conference.

- Numerical Relativity as a tool for studying the Early Universe by David Garrison, Journal of Gravity, vol. 2014, Article ID 407197, 11 pages, 2014. doi:10.1155/2014/407197, gr-qc/1207.7097

PAPERS PRESENTATIONS, ABSTRACTS AND POSTER SESSIONS

- Gave a contributed talk at the 2014 CHAOS conference in Lisbon, Portugal.
- Gave a contributed talk at the Fall 2014 TSAPS meeting in College Station, TX.
- Gave an invited talk at San Jacinto College.
- Gave an invited talk at WALIPP TSU Preparatory Academy as part of Back to School with the History Makers.
- Gave Television (Fox 26) and Radio (Radio One) interviews.
- Greeted the graduates on behalf of the faculty at the May 2014 Commencement ceremony.
- Gave an invited talk at the UHCL screening of "Gravity".
- Gave an invited talk at the UH Supercomputing Center.
- Gave a talk at the UHCL Student Conference for Research.
- Gave two invited talks at Summer Creek High School's Avid Program.

PROFESSIONAL ACTIVITES AND SERVICE

- Served as Director of Graduate Programs for SCE – some duties include rewriting our assistantship policies and improving our graduate admissions process.
- Served as Program Chair of Physics – some duties included biennial planning, creating a strategic plan for the physics program, preparing class schedules, service on the school curriculum committee, hiring and supervising roughly four to seven adjunct professors per semester, promoting the physics program and managing the physics program's resources.
- Served as President and Past President of the UHCL Faculty Senate. Member of the Faculty Senate Executive Committee, Academic Council, University Council, Texas Council of Faculty Senates and University Faculty Executive Council.
- Served on the SCE Post-Tenure Review Committee.

- Served as the UHCL Goldwater Scholarship Faculty Representative.
- Served on the Space Center Houston's Educational Advisory Board.
- Attended the SCE/Community College breakfast.
- Attended SGA Luncheon.
- Attended Midterm Luncheon.
- Member of the Emergency Planning Committee.
- Served on the Latin Deaf Services Advisory Board.
- Reviewed 2 articles for the Physical Science International Journal.
- Helped plan and implement the Fall 2014 Faculty Retreat and follow-up meetings with the UHCL Administration
- Attended NASA's Orion test launch as a guest of the JSC Center Director.
- Member of the Provost's TLEC taskforce.
- Member of the SCE Programmer Search committee.
- Member of the SCE Advisor Search committee.

WEB LINKS

The Physics Program website is located at:

- http://sce.uhcl.edu/Physics

The latest results of the first Physics Program Survey are located at:

- http://sce.uhcl.edu/garrison/survey/results.asp

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The latest results of the second Professional Physics Program Survey are located at:

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The latest results of the Physics Ph.D. Program Survey are located at:

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The last General Physics Needs Assessment Survey is located at:

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The Joint Physics PhD Needs Assessment Survey is located at:

- http://www.surveymonkey.com/s/P9BBJQG

FACULTY ANNUAL REPORT

David Garrison, Associate Professor of Physics
January 1, 2015 through December 31, 2015

TEACHING AND EDUCATIONAL ACTIVITIES

Virtually all the students who filled out teaching evaluations enjoyed my courses and felt that they have learned a lot from me. My colleagues tend to agree. I also maintain a roughly 50% pass rate on Ph.D. candidacy exams which is about as good as any faculty in a typical Physics Ph.D. program.

Classroom Instruction:

Spring 2015:

- PHYS 4732 Modern Physics Research - 12 undergraduate students. PHYS 4732 is a course developed to expose undergraduates to current topics of interest using our physics guest lecture series. This has since become a capstone course for our undergraduate Physics Degree. The seminar portion of this course has become very popular in the local community.
- PHYS 5311 Recitation for Electrodynamics I – 8 graduate students. This is the recitation for Physics 5331. Each week I would work out example problems with students in order to prepare them for the Ph.D. Candidacy Exam.
- PHYS 5331 Electrodynamics I – 8 graduate students. This is the standard PhD level Electrodynamics course taught using the textbook by J. D. Jackson. This course counts towards PhD candidacy through our Collaborative PhD program.

Fall 2015:

- PHYS 5511 Recitation for Mathematical Methods 1 – 17 graduate students. This is the recitation for Physics 5531. Each week I would work out example problems with students in order to prepare them for the Ph.D. Candidacy Exam.
- PHYS 5531 Mathematical Methods in Physics 1 – 17 graduate students. This was a class, which I originally introduced in the spring of 2003. The course covers 10 topics of advanced mathematics which include: Ordinary Differential Equations, Infinite Series, Integration Techniques, Fourier Series and Transforms, Complex Variables, Linear Algebra, Tensors, Partial Differential Equations, Special Functions and Probability & Statistics. Students consider this to be an intense core physics course and the most essential to further success in physics. Those who survive the course tend to do very well in the other physics classes.

Course evaluations:

PHYS 4732:
- Pace: 3.14
- Overall Quality: 4.86
- Subject Knowledge: 5.0
- Overall Teaching: 5.0

Stimulate & Challenge Students: 5.0
Encourage Class Participation: 5.0
Helping Students Understand: 5.0

PHYS 5311 / 5331:
Pace: 4.14
Overall Quality: 4.33
Subject Knowledge: 4.14
Overall Teaching: 4.17
Stimulate & Challenge Students: 4.43
Encourage Class Participation: 4.86
Helping Students Understand: 4.86

PHYS 5511/5531:
Pace: 4.0
Overall Quality: 4.5
Subject Knowledge: 4.8
Overall Teaching: 4.7
Stimulate & Challenge Students: 4.3
Encourage Class Participation: 4.5
Helping Students Understand: 4.6

Selected Comments:

"Covers a wide breath of subjects, is very fair in grading & assignment of problems"
"… He is the best teacher"
"He works hard to explain the subject well"
"He has high knowledge"
"Very knowledgeable, helpful"
"Dr. Garrison provides intricate details on how to approach applications dealing w/ topic"
"Highly knowledgeable in the course material taught"
"Broad minded, patient, inquisitive, friendly & knowledgeable"
"Very fun, very informative"
"He manages the speakers very well & knows who to bring"
"Knowledgeable of most presented topics"
"Very knowledgeable of the course material. Useful examples."
"Provides notes, records lectures, good w/ office hours and answering questions and providing sample review tests for midterm and finals"
"Dr. Garrison always showed a strong understanding of the material. His ability to properly weigh the difficulty of the subject allowed an objective approach to the material"
"I like how structured the course is. I know exactly what to expect and when assignments are due"

“Very knowledgeable, is able to connect to other fields to give adequate examples”
“Dr. Garrison is expertly knowledgeable in advanced math methods!”

Individual Instruction and Advisement (other than organized classes)

- Advised about 10 undergraduate and graduate physics students both formally and informally.
- Served as a member of 1 Masters Thesis Committees.
- Advised 4 independent studies (2 undergrad, 2 grad).

COURSE AND PROGRAM DEVELOPMENT

- Served as the UHCL Physics PSM director to manage, promote, assess and fine-tune the Physics Technical Management Sub-Plan.
- Continued to promote and implement a sub-plan in Engineering Physics under our new Physics BS program.
- Maintained a Facebook page to promote the Physics Program.
- Worked with our Advisory Board for the UHCL Physics Program, which met once each long semester.
- Participated in UHCL’s downward expansion planning process.
- Helped the UHCL Physics program become an APS Bridge Program Partnership Institution. We are one of only ten APS Bridge Program Partnership Institutions including MIT, Columbia University, Princeton University and University of Chicago.
- Hosted a site visit by the APS Bridge Program.
- Participated in the graduate student recruiting fair at UH Downtown.
- Attended the SpaceCOM expo at George R Brown to learn about potential partnerships and opportunities for our students.

RESEARCH, SCHOLARLY AND ARTISTIC ACTIVITIES

- Organized and hosted a weekly Spring Seminar Series to stimulate interest in Space Science and Physics and to directly involve JSC researchers in activities at UHCL. I assembled a group of twelve speakers and advertised the talks through the Physics Program website, Facebook and LinkedIn. In addition, I worked with the UHCL communications office to publicize the series through the local newspapers. This seminar was given in conjunction with the Research Project and Seminar class and PHYS 4732. We had an audience of about 30 people per week.
- Continued development of a General Relativistic Magnetohydrodynamics (GRMHD) computer code for cosmological simulations. This is being used for a numerical cosmology research project.
- Resubmitted a pending NSF REU site grant proposal as PI.
- Submitted a pending NSF RUI grant proposal as PI.
- Participated in an NSF iTEST grant with Tietronix.
- Participated in a successful NSF MRI Grant with UH.
- Participated in a funded S-STEM grant proposal as Co-I.

- Member of the Space and Complex Systems Research Cluster at UH.

PUBLICATIONS

- Invariants in Relativistic MHD Turbulence by David Garrison and Phu Nguyen, 2015. arXiv:1501.06068, accepted for publication in the Journal of Modern Physics
- Primordial Gravitational Wave Calculations: Nonlinear vs Linear Codes by David Garrison, 2015. arXiv:1503.04764

PAPERS PRESENTATIONS, ABSTRACTS AND POSTER SESSIONS

- Gave an Invited talk at Texas A&M University at Commerce
- Gave an Invited talk at Trinity University in San Antonio Texas
- Gave a Contributed talk at the 2015 NSBP meeting in Baltimore, MD
- Gave a Contributed talk at the Spring 2015 Meeting of the Texas Section of the American Physical Society at Lee College
- Gave an invited talk at MC Williams Middle School as part of Back to School with the History Makers.
- Gave Radio (Radio One) interview.
- Greeted the graduates on behalf of the faculty at the Fall 2015 Commencement ceremony.

PROFESSIONAL ACTIVITES AND SERVICE

- Served as Director of Graduate Programs for SCE – some duties include rewriting our assistantship policies, improving our graduate admissions process, organizing 2 Advising and Registration Events and looking into ways to improve our Domestic Graduate Student Enrollment.
- Served as Program Chair of Physics – some duties included biennial planning, creating a strategic plan for the physics program, preparing class schedules, service on the school curriculum committee, hiring and supervising roughly four to seven adjunct professors per semester, promoting the physics program and managing the physics program's resources.
- Served as Past President and President (elected twice) of the UHCL Faculty Senate. Member of the Faculty Senate Executive Committee, Academic Council, University Council, Texas Council of Faculty Senates and University Faculty Executive Council.
- Served on the SCE Post-Tenure Review Committee.
- Served as the UHCL Goldwater Scholarship Faculty Representative.
- Served on the Space Center Houston's Educational Advisory Board.
- Attended the SCE/Community College breakfast.
- Member of the Emergency Planning Committee.
- Served on the Latin Deaf Services Advisory Board.
- Member of the Provost's TLEC taskforce – I visited University of Colorado Denver and Texas A&M University Commerce as part of the research needed for this project.

- Member of the SCE Programmer Search committee.
- Member of the SCE Advisor Search committee.
- Member of the Foundations of Excellence Steering committee – also attended the launch meeting in Ashville, NC.
- Member of Houston GPS Structured Schedules committee at the UHCL and system level.

FACULTY ANNUAL REPORT

David Garrison, Associate Professor of Physics
January 1, 2016 through December 31, 2016

TEACHING AND EDUCATIONAL ACTIVITIES

Virtually all the students who filled out teaching evaluations enjoyed my courses and felt that they have learned a lot from me. My colleagues tend to agree. I also maintain a roughly 50% pass rate on Ph.D. candidacy exams which is about as good as any faculty in a typical Physics Ph.D. program.

Classroom Instruction:

Spring 2016:

- PHYS 4372 Modern Physics Research / PHYS 6838 Research Project and Seminar - 5 undergraduate students and 3 graduate students. PHYS 4372 is a course developed to expose undergraduates to current topics of interest using our physics guest lecture series. This has since become a capstone course for our undergraduate Physics Degree. PHYS 6838 is the capstone course for students completing the Masters of Physics degree. This course focuses on teaching communication skills as well as research. Students complete research projects and then present research papers both orally and in written form. The seminar portion of this course has become very popular in the local community.
- PHYS 5911 Computational Physics with Cactus – 10 graduate students. I developed this as a special topics course to introduce our graduate students to computational physics. Since our core courses are now 4 hours each, this course allows full-time physics graduate students to sign up for exactly 9 hours. This course also served to introduce our students into my research area.

Fall 2016:

- PHYS 2125 Laboratory for University Physics 1 – 19 undergraduate students. This is a lab course for our introductory calculus based physics class. This was the first time I have taught the course since coming to UHCL 14 years ago.
- PHYS 5511 Recitation for Mathematical Methods 1 – 14 graduate students. This is the recitation for Physics 5531. Each week I would work out example problems with students and answer their questions from the problem sets in order to prepare them for the Ph.D. Candidacy Exam.
- PHYS 5531 Mathematical Methods in Physics 1 – 14 graduate students. This was a class, which I originally introduced in the spring of 2003. The course covers 11 topics of advanced mathematics which include: Ordinary Differential Equations, Infinite Series, Integration Techniques, Fourier Series and Transforms, Complex Variables, Linear Algebra, Tensors, Eigenvalue Problems, Partial Differential Equations, Special Functions and Probability & Statistics. Students consider this to be an intense core physics course and the most essential to further success in physics. Those who survive the course tend to do very well in the other physics classes. In Fall 2016, I taught this as a flipped class using my recorded lectures

from previous semesters. As far as I know, nobody has ever taught an advanced graduate level core physics course in this way.

Course evaluations:

PHYS 2125: 3/19 students completing evaluations
- Pace: 3.0
- Overall Quality: 3.67
- Subject Knowledge: 3.67
- Overall Teaching: 3.67
- Stimulate & Challenge Students: 4.0
- Encourage Class Participation: 4.67
- Helping Students Understand: 3.0

PHYS 4372: 5/5 students completing evaluations
- Pace: 3.4
- Overall Quality: 5.0
- Subject Knowledge: 5.0
- Overall Teaching: 5.0
- Stimulate & Challenge Students: 5.0
- Encourage Class Participation: 5.0
- Helping Students Understand: 5.0

PHYS 5511/5531: 3/14 students completing evaluations
- Pace: 4.0
- Overall Quality: 4.0
- Subject Knowledge: 4.0
- Overall Teaching: 4.0
- Stimulate & Challenge Students: 5.0
- Encourage Class Participation: 4.67
- Helping Students Understand: 4.0

PHYS 5911: 7/10 students completing evaluations
- Pace: 3.33
- Overall Quality: 3.67
- Subject Knowledge: 4.67
- Overall Teaching: 4.17
- Stimulate & Challenge Students: 4.33
- Encourage Class Participation: 4.60
- Helping Students Understand: 4.67

PHYS 6838: 3/3 students completing evaluations
- Pace: 4.33
- Overall Quality: 4.67
- Subject Knowledge: 5.0
- Overall Teaching: 5.0

Stimulate & Challenge Students: 5.0
Encourage Class Participation: 5.0
Helping Students Understand: 5.0

Selected Comments:

"Passionate about the subject (public speaking)"
"very knowledgable"
"clear on his expectations and grading schedule"
"He is excellent with teaching onethodology"
"He is a good instructor"
"very good lecturer"
"The reverse class setting was advantageous for a graduate level course. It aligned the students to spend most of the time in class clarifying things they didn't understand."
"Strong visualization skills. Provided many real world examples to keep us engaged."
"Thank you for a good year. I know I wasn't the best student, but you were a great teacher!"

Individual Instruction and Advisement (other than organized classes)

- Advised about 10 undergraduate and graduate physics students both formally and informally.
- Served as chair of 1 Masters Thesis Committee.
- Taught 4 independent studies (2 undergrad, 2 grad).

COURSE AND PROGRAM DEVELOPMENT

- Served as the UHCL Physics PSM director to manage, promote, assess and fine-tune the Physics Technical Management Sub-Plan.
- Served as Interim Chair of Physics during Dr. Masood's development leave.
- Served on the Physics Program Review committee.
- Maintained a Facebook page to promote the Physics Program.
- Worked with our Advisory Board for the UHCL Physics Program, which met once each long semester.
- Participated in physics planning for the STEM Building.
- Participated in a student recruiting fair at the Energy Institute High School.
- Attended the 2016 APS National Mentoring Community Conference in Houston, TX.
- Developed a new computational physics course using the Cactus framework.
- Developed a plan for a new undergraduate concentration in Computational Physics.

RESEARCH, SCHOLARLY AND ARTISTIC ACTIVITIES

- Organized and hosted a weekly Spring Seminar Series to stimulate interest in Space Science and Physics and to directly involve JSC researchers in activities at UHCL. I assembled a group of twelve speakers and advertised the talks through the Physics Program website, Facebook and LinkedIn. In addition, I worked with the UHCL communications office to publicize the series through the local newspapers. This seminar was given in conjunction with the Research Project and Seminar class and PHYS 4732. We had an audience of about 20-30 people per week. Two major talks were included in the series with attendances of about 100 people: one talk on the direct observation of Gravitational Waves and another talk on the Jazz of Physics.
- Continued development of a General Relativistic Magnetohydrodynamics (GRMHD) computer code for cosmological simulations. This is being used for a numerical cosmology research project.
- Resubmitted a pending NSF RUI grant proposal as PI. NSF (Research at Undergraduate Institutions) RUI Grant - $259,919 pending. This is based on my research in Numerical Cosmology. The purpose of the grant is to study relativistic plasma dynamics in the early universe. A component of the grant is also to develop a cosmology course (with Walter Thompson) for undergraduate students. I am the PI on the grant and there are is no Co-I.
- Participated in a successful NSF MRI Grant with UH. NSF MRI - $1,000,000 funded. We used the grant to build a GPU based cluster at UH. This machine was funded in 2015 and began running in 2016 at the UH Center for Academic Computing and Data Center. I am a senior personal on this project, the only one from UHCL. I gave input into writing the grant and designing the cluster to support my research. My student and I helped to test the cluster when it went online. Here is it's website: https://uhpc-mri.uh.edu
- Participated in a funded S-STEM grant proposal as Co-I. NSF STEM - $592,468 funded. This was a grant to establish the Natural Science Scholars program here at UHCL. Rick Puzdrowski was the PI and I, along with several other Natural Science program chairs, served as Co-I. I represent Physics among the members of the Natural Science Scholars faculty advisory board. This was a 4 year grant from 2013-2017.

PUBLICATIONS

- Invariants in Relativistic MHD Turbulence by David Garrison and Phu Nguyen, *Journal of Modern Physics*, **7**, 281-289. doi: 10.4236/jmp.2016.73028, arXiv:1501.06068
- Using Gravitational Waves to put limits on Primordial Magnetic Fields by David Garrison, *Submitted to International Journal of Modern Physics D*, arXiv: 1608.01005
- Extracting Gravitational Waves Induced by Plasma Turbulence in the Early Universe through an Averaging Process by David Garrison and Christopher Ramirez, *in final preparation for submission*, arXiv: 1503.04764

PAPERS PRESENTATIONS, ABSTRACTS AND POSTER SESSIONS

- Presented a poster at the 2016 GR21 International Conference in New York, NY
- Gave an invited talk at The Lawson Academy as part of Back to School with the History Makers.
- Presented a poster at the Sustainable Research Pathways Meeting at LBNL in Berkley, CA.
- Greeted the graduates on behalf of the faculty at the Spring 2016 Commencement ceremony.

PROFESSIONAL ACTIVITES AND SERVICE

- Served as Director of Graduate Programs for SCE – some duties include rewriting our assistantship policies, improving our graduate admissions process, organizing 2 Advising and Registration Events, looking into ways to improve our Domestic Graduate Student Enrollment, developing a targeting marketing project and college marketing plan.
- Served as Interim Program Chair of Physics during Dr. Masood's development leave in Spring 2016.
- Served as President (elected twice) of the UHCL Faculty Senate. Member of the Faculty Senate Executive Committee, Academic Council, University Council, Texas Council of Faculty Senates and University Faculty Executive Council.
- Served as Chair of the SCE Policy Committee, which rewrote the college bylaws in Fall 2016.
- Served on the UHCL Presidential Search Committee to find a replacement for President Bill Staples.
- Served as the UHCL Goldwater Scholarship Faculty Representative.
- Served on the Space Center Houston's Educational Advisory Board.
- Member of the Emergency Planning Committee.
- Served on the Latin Deaf Services Advisory Board.
- Member of the Provost's TLEC taskforce and on the search committee for the Director of the new Center for Faculty Development.
- Member of the Foundations of Excellence Steering committee – also attended the meetings in Ashville, NC.
- Member of Houston GPS Structured Schedules committee at the UHCL and system level.
- Honored as a Houston History Maker at the Night with Mayor Sylvester Turner event.

5 CORRESPONDENCE: 3RD YEAR REVIEW

David Garrison Notice of 3rd Year Review 20040408

To: David Garrison, Assistant Professor of Physics

XC: Robert N. Ferebee, Associate Dean, School of Science and Computer Engineering
Dennis M. Casserly, Division Chair of Natural Sciences

From: Charles W. McKay, Dean, School of Science and Computer Engineering

On: April 8, 2004

Subject: Third Year Review of Assistant Professors

Dear Dr. Garrison:

According to university records, you are scheduled to participate in a Third Year Review of Assistant Professors in the fall semester of 2004.

You are a valued faculty member and I would like for you to use this opportunity to help strengthen your documented case for your promotion and tenure review in the fall of 2007. The relevant policy and procedures for a third year review can be accessed through the following on-line navigational path:

http://www.cl.uh.edu/
- About UHCL
  - Policies
    - Faculty Handbook
      - 5.3 UH-Clear Lake Promotion and Tenure

As stated in the Faculty Handbook, the purpose of the third year review is "to provide guidance to non-tenured faculty with regard to their candidacy and progress toward promotion and tenure." I will work with your division chair to form your peer review committee by May 1, 2004. You should submit your vita and documentation to me no later than September 26, 2004*. The expectations for the content of your vita and documentation are described in the Faculty Handbook. You may confer with me, your division chair, program chair and tenured faculty members in your program for suggestions on format. The recommendation of your peer review committee will be due to your division chair by November 19, 2004*. The recommendation of your division chair will be due to me by December 10, 2004*. I will then complete my review and schedule a debriefing with you, your division chair and me in January 2005.

Thank you for your contributions to your program, school and university. Don't hesitate to contact me should you have any questions about this letter and the related policy and procedures.

Best regards,

Charles W. McKay, Dean

* Dates for fall 2004 are an estimate pending approval of the university calendar.

INTEROFFICE MEMORANDUM

TO: DR. DENNIS CASSERLY-DIVISION CHAIR, NATURAL SCIENCES, SCHOOL OF SCIENCES AND COMPUTER ENGINEERING

FROM: DR. RAMIRO SANCHEZ ON BEHALF OF DRS. MILLS, HOWARD, SAGE, AND HARMAN

SUBJECT: REVIEW OF DR. DAVID GARRISON'S DOCUMENTATION IN SUPPORT OF HIS INTERIM REVIEW

DATE: 12/06/04

CC: DEAN CHARLES MCKAY, DRS. MILLS, HOWARD, HARMAN AND SAGE

The committee has reviewed the documentation put forward by Dr. David Garrison for assessment of his progress toward P&T. In performing this review, the committee assumed that its main function in this process was to study the documentation submitted and, based on said information, attempt to assess progress toward promotion and tenure. The committee sincerely hopes that all involved in this process receive the committee's input in the vein that it was intended. Further, the committee hopes that Dr. Garrison realizes that, even though his formal P&T committee may have a different composition, the suggestions and assessments by this interim review committee may also be of relevance to a future formal P&T committee. Thus, it is probably in Dr. Garrison's best interests to address all areas identified by this committee as areas that may be deemed even remotely problematic at this time, and to continue to pursue the endeavors assessed as positive by the committee with the same fervor and excitement that he has done to date. While it is true that a future formal P&T committee is not bound by anything that this interim committee has concluded, the combined experiences of the members of this committee lead it to conclude that addressing any identified areas of potential concern will not be work done in vain. It should be noted that all observations, comments and conclusions put forward by this committee are based upon the documentation that Dr. Garrison submitted to the committee in the format in which it was submitted.

General Feedback Regarding Dr. Garrison's Documentation of Narrative: Dr. Garrison needs to understand that all conclusions that he puts forward in his future formal P&T file must be supported by detailed documentation. Some of the committee members felt that the documentation that Dr. Garrison put forward for interim assessment of his progress toward a positive recommendation with respect to P&T were not as detailed as they could have been. In an attempt to prevent any problems that may arise in a future P&T committee, this committee ***strongly*** recommends that Dr. Garrison avail himself of the P&T documentation recently put forward by at least two members of the Division who have submitted actual P&T files for consideration during 2004 (and have gotten positive recommendations from their peer review committees) to see how he can make his future documentation more favorable with respect to his committee's assessment of his potential when he does put in his formal P&T file. From discussions that arose during this interim assessment it can be concluded by Dr. Garrison that the committee may not have gotten all of the impact that Dr. Garrison was attempting to have on it regarding his performance to date. This, the committee concluded, may have been a result of a lack of detailed documentation via the format he submitted for the interim review. Dr. Garrison might be well served by following the old but true axiom with respect to P&T documentation by candidates: "It is sometimes better to give "too much" detail about one's endeavors and accomplishments, than to attempt to be succinct and miss the mark."

Teaching and Educational Activities (classroom and one-on-one teaching): Dr. Garrison's documentation indicates that he has taught a total of 12 courses during the two-year period of fall 2002 to summer 2004. He also indicates that he not only uses traditional lecture methods for his classroom courses but also has begun (as of fall 2003) an effort at doing "web enhancement" of his course offerings. Dr. Garrison also states that he is responsible for the addition of a total of 19 courses to the ASTR and PHYS curriculum. Dr. Garrison additionally indicates that his teaching evaluations for most of his classes are rated between 3.5-4.5 and that in some of his courses he improved greatly after teaching the same course a second time. Dr. Garrison includes various examples of student comments that indicate that he has very good command of the subjects' content for the courses that he teaches and that he is indicating to the students that he is enthusiastic and willing to help them in any way that he can.

Other Educational Activities: a) *Independent studies and related research advising activities*. Dr. Garrison indicates that he is the graduate advisor for all graduate students majoring in physics. This includes the selection of courses by the students as well as preparation of their CPS's. Dr. Garrison also indicates that he has advised a total of 14 students in capstone, independent studies and has advised one student during the preparation of a thesis research proposal. Dr. Garrison further indicates that he has mentored two high school students during his appointment at UHCL. b) *New Program Development.* Dr. Garrison states that he feels that to date his greatest contribution to UHCL has been in the area of New Program Development. He has overseen the development of a new degree (MS in Physics) from the preparation of the proposal to the approval of the new degree by the THECB. Dr. Garrison also solicited and was awarded a planning grant from the Council of Graduate Schools and the Sloan Foundation to assess the implementation of a new professional degree in Physics. He has been collecting data with respect to this latter undertaking via the development and implementation of online surveys, and focus groups to assess the local industry needs for such a professional degree and the potential student population that would pursue such a degree if offered. C) Dr. Garrison indicates that he also is the program chair in the programs that he is a member of and does all of the day to day work necessary to keep the programs going and moving forward. This includes, program marketing via various routes including the preparation of student brochures, doing face-to-face presentations at various external meetings and functions, as well as attending the formal recruiting undertakings sponsored by the university every fall and spring term. The committee concurs with Dr. Garrison's comments that his major contribution to date has been the work that he has done with respect to program development. The committee realizes that this type of undertaking *de facto* impacts other areas of professional responsibilities (mainly the establishment of one's own research program and service to the profession, the division, the school, the university and the community). It would be remiss not to state formally that Dr. Garrison has in fact done a tremendous job with respect to revitalizing the physical sciences program and by being able to work tirelessly on all aspects of approval of a new degree by the THECB. His teaching evaluations do in fact also indicate that he is getting "better" as time goes on with respect to the perception of the students that he teaches in the classroom. The involvement of students in research projects and independent studies at this early point in his career is also a very positive sign and the committee encourages Dr. Garrison to continue to involve students in this type of one-on-one teaching/learning activity.

Research: Dr. Garrison indicates that during his first year at UHCL he spent much of his research time finishing projects from his doctoral work at Penn State and presenting the results of those endeavors (one peer-reviewed publication as well as two peer-reviewed proceedings articles and two invited talks). He also states he gave four contributed talks at international and national meetings and has one internal NASA/JSC report. Dr. Garrison goes on to state that he is beginning to pursue research in a new area (not affiliated with Penn State work done previously) as well as collaborating with the Advanced Space Propulsion Lab at NASA/JSC. He also states that the latter resulted in a summer research fellowship at NASA/JSC (summer 2004) and the award of funding for an ISSO Post-doc to continue to pursue these research undertakings. The committee sees that Dr. Garrison is in fact now in the process of setting up his own research program at UHCL and also understands that his extreme commitment to program development may have slowed down some of his own research program development at UHCL. It is admirable that he has been able to get a highly competitive NASA/JSC research fellowship and an ISSO Post Doc grant. The committee recommends that Dr. Garrison focus as intensely in this area of professional responsibility (the establishment of his own documentable research program via commonly used parameters, e.g. peer-reviewed publications and solicitations for and attainment of external funding for his research program) as he has been doing on program development and Dr. Garrison should expect that a future P&T committee will expect to see tangible proof of this when he submits his formal P&T file. It is very important for Dr. Garrison to become a bit more selfish with his professional time and dedicate a larger amount of it toward attainment of this goal, as say for example keeping up the pace he has set in program development activities.

Service: Dr. Garrison holds membership in the American Physical Society, American Association of Physics Teachers and the National Society of Black Physicists. Other than mention of membership, Dr. Garrison does not expand further on his service to these organizations. He also states that he is program chair of Physics and physics club advisor. Furthermore, he is a member of the curriculum committee at the school level. With respect to service to the community, Dr. Garrison indicates that he: 1) participated in the Bay Area Houston Science Teacher Institute Partnership Proposal Team; 2) is a Center counselor at the ethnic college counseling center; 3) was a judge at the 2003 science engineering fair of Houston; 4) was a Celebrating Our elders Essay scholarship competition judge; 5) was a 2004 Black History Month faculty panelist; 6) was a 2004 Science Olympiad judge; 7) was a helper in shipping surplus library books to Nigeria; and 8) was a Stepping Up-Speaker. Dr. Garrison seems to belong to many very important community and professional organizations but his documentation does not seem to indicate what he is specifically doing for them as service. For example, does he review proposals and manuscripts for physics journals? Also he needs to start getting a little more involved in school and university committees. The latter is probably more important at this time, to start seeing how these benefit not only his own professional growth but the profession and the university.

Respectfully,

Dr. Ramiro Sanchez – Professor of Organic Chemistry and Chair of the Interim Review Committee

University
of Houston
Clear Lake

To: Dr. Charles W. McKay, Dean

From: Dr. Dennis Casserly, Chair of Natural Sciences

Date: December 21, 2004

Subject: Interim Performance Review for Dr. David Garrison
Assistant Professor of Physics

I have reviewed the materials submitted by Dr. Garrison regarding his academic performance. The materials provide convincing evidence that he is making progress toward promotion and tenure. I agree with the committee that his P&T file could be improved by documenting and explaining the significance of his scholarly activities and by removal of extraneous correspondences that do not serve to document or explain them.

Teaching:
Dr. Garrison has taught the following graduate courses (some had undergraduate crosslistings): Classical Mechanics, Principles of Electromagnetism, Electrodynamics, Special Relativity, Mathematical Methods in Physics I, Mathematical Methods in Physics II, Spacetime Physics, Using Mathematica to Solve Physics Problems, Research Project and Seminar and Research Methods in Space Science. Dr. Garrison uses a traditional chalk/blackboard lecture format with web enhancement as a recent addition to his teaching resources. His teaching has steadily improved since arriving at UHCL and he currently receives high student evaluations. He oversaw the approval of the BS in Physical Science Program with 8-12 Teacher Certification, developed and oversaw the approval of a new Graduate Physics Program, developed a proposal for a Professional Science Master's Degree Program with the Council of Graduate Schools and the Sloan Foundation and worked with the Bay Area Houston Science Teacher Institute Partnership on an NSF proposal to enhance K-12 science education. Dr. Garrison is the advisor for all students majoring in physics and physical sciences. This includes the selection of courses by the students as well as preparation of their CPS's. Dr. Garrison has advised a total of 14 students in capstone, independent studies and has advised one student during the preparation of a thesis research proposal. Also, he has mentored two high school students.

2700 Bay Area Boulevard Houston, Texas 77058-1098

Research:
Dr. Garrison has an active research program focused on numerical relativity. His publications and presentations include: "Black Hole Spectroscopy: testing general relativity through gravitational-wave observations" in *Classical and Quantum Gravity* 21 (2004) 787-803; "Introduction to Gravitational Wave Physics" presented at the 2003 NSBP meeting in Atlanta; and "Testing Binary Black Hole Codes using Cosmological Spacetimes" and "Gravity Gradients in LIGO: A Proposal for Data Analysis", both presented at the Tenth Marcel Grossman Meeting on Gravitational Physics (MGX) in Rio de Janeiro. He has recently expanded his research to include the development of Doubly Special Relativity and he has collaborations with the Advanced Space Propulsion Laboratory's VASMIR project for the development of a plasma rocket engine. His efforts were awarded with a summer research fellowship at NASA/JSC and the funding for an ISSO Post-doc to continue to pursue these research undertakings. He has continued to conduct a weekly Astrophysics Seminar series between NASA-JSC and UHCL, and he attends a weekly teleconference on numerical relativity hosted by Penn State's Center for Gravitational Physics and Geometry.

Service:
Dr. Garrison has dependably and productively served as Chair of Physics and Physical Science. Those duties include revising courses and curricula, building schedules, advising students, developing mentoring programs for prospective students, securing adjuncts and ordering texts, laboratory and instructional materials. He also served on the SCE curriculum committee, Convocation Committee, Faculty Senate Research Task Force, Student Affairs Committee, served as advisor to the Physics Club, served as Total Success Mentor, served as Science and Engineering Fair of Houston judge, Science Olympiad judge, served on the Office of University Advancement's Inclusion Committee, served as a judge for the Celebrating our Elder's Scholarship Competition, worked on developing a Memorandum of Understanding between the Physics Program and NASA-JSC and was featured on NASA's African-Americans in Space Science Poster. Dr. Garrison holds membership in the American Physical Society, American Association of Physics Teachers and the National Society of Black Physicists. Dr. Garrison's involvement in some of these service activities was not explained so their significance could not be assessed.

Recommendation:
I agree with the interim review committee that Dr. Garrison should:

- Focus intensely on his research.
- Submit grant proposals to both UHCL sources and external granting agencies and win funding for these proposals.
- Publish work from UHCL in peer-reviewed journals.
- Present results from work at UHCL at national and international conferences.

- Take on service activities at the university, in the profession and in the community.

Dr. Garrison is a productive and valued member of the Physics and Physical Science Programs and he has made significant progress toward promotion and tenure.

Respectively Submitted,

Dennis Casserly

Dr. Dennis Casserly,
Chair of Natural Sciences

XC: Dr. Sanchez
Dr. Garrison

Interim Review Summary for David Garrison 20050205

To:	David Garrison, Assistant Professor of Physics and Physical Sciences
XC:	Dennis M. Casserly, Division Chair of Natural Sciences Ramiro Sanchez, Chair of the Interim Performance Review Committee
From:	Charles W. McKay, Dean
On:	February 7, 2005
Subject:	Interim Performance Review

Dear Dr. Garrison:

I have reviewed the documentation submitted by you for your interim performance review, the interim performance review submitted by the Division Chair and the interim performance review submitted by the Interim Performance Review Committee. I think I speak for all of us in saying that we want you to gain tenure in your fall 2007 review. I will divide my remarks into four categories:

1. documentation and next steps toward promotion and tenure
2. teaching and educational activities
3. research and scholarly activities
4. service.

I will not attempt to replicate all of the observations of your division chair and review committee (I urge you to study these reviews carefully!), but I will add my own and highlight some of the most salient points and recommendations for further progress as I perceive them in my role as dean. The relevant policy and procedures related to my recommendations can be accessed through the following on-line navigational path:

http://www.cl.uh.edu/

- About UHCL
    - Policies
        - Faculty Handbook
            - 5.3 UH-Clear Lake Promotion and Tenure

Documentation and Next Steps Toward Promotion and Tenure

To continue your momentum and progress toward the sixth year review for promotion and tenure. I believe it is important that you understand three major factors that differ between an interim review and a final review:

1. the number and scope of reviewers
2. the sequence of the review cycle
3. the charge of the reviewers.

The Number and Scope of Reviewers

The purpose of an interim review is for members of our "school" to help a future candidate for promotion and tenure prepare a strong and documented case based upon an honest and frank assessment of the strengths and weaknesses of the documentation for the interim review and to offer suggestions for strengthening the documented case for P&T in the sixth year review. Thus these three reviews are internal to our school. By contrast, the final review begins with your documentation and at least three reviews from peers external to our university.

The Sequence of the Review Cycle

The sixth year review begins with:

- your request for the review and your completion of your documentation
- the formation of your peer review committee
- your identification of at least three peer reviewers external to the university and the concurrence of your peer review committee that these external reviewers are acceptable to your peer review committee
- the request from our school's associate dean to the external reviewers agreed to above. Those who have the time and agree to serve are then sent a subset of your documentation in each of the areas of teaching, research and service and a deadline for their findings and recommendations. At least three such external reviews are required.
- The review of your documentation plus that of the three external reviewers is considered "in parallel" and "independently" by your division chair and your peer review committee and both sets of results are sent to your dean.
- The dean considers all these inputs and forwards his findings and recommendations to the provost.
- In turn, the provost considers these collective inputs and presents his findings and recommendations to the president.
- Then the president considers these collective inputs and presents his findings and recommendations to the chancellor.

The Charge of the Reviewers

All reviews must comply with the university policy and procedures for sixth year reviews. Specifically, this requirement means that judgments rendered must be substantiated by your documentation. Personal knowledge of the candidate's performance in each of the three areas of assessment cannot be used in lieu of adequate documentation of evidence. It also means that in each of the three areas, all reviewers are asked to respond to the question: “What level does the documented evidence substantiate was achieved by this candidate during the period covered by this sixth year evaluation?”

Teaching and Educational Activities

I concur with your division chair and review committee that your teaching and educational activities including, in particular, your program development activities at UHCL have been commendable. You have successfully proposed, gained approval and implemented a new MS in Physics degree program. You have also revamped the undergraduate degree leading to a BS in Physical Sciences with certification support for teachers in grades 8-12. You have developed a proposal for a Professional Science Program in Physics that is likely to be successful. You have taught at least eight different organized graduate courses in addition to numerous sections of research methods and projects. You have supervised at least 14 capstone students and one thesis advisee and have mentored a couple of high school students on their science and engineering fair projects. You serve as the faculty advisor for all students majoring in the graduate physics program or the undergraduate program in physical science. Your student evaluations of your teaching have improved during the time you have been at UHCL. In particular, I note that the web assisted course materials you have developed in the past year have been particularly well received by your students and I join your division chair and review committee in encouraging you to continue such development of improved course materials. However, I also join your reviewers in encouraging you to begin to shift some of your emphasis on the development of the instructional component of your program to devote more time to the complementary component of your own research agenda.

For the sixth year tenure review, I recommend you improve the documentation of how your teaching, research and professional service are synergistically interrelated and advancing toward an appropriate plan and agenda for advancing your own development, your program and your school. Specifically, your current set of documentation identifies a number of potentially important activities in each of the areas of teaching, research and professional service. But the significance and interrelationships of each and their relevance to a particular agenda and plan for your own development and that of your program and school are often left unspecified.

Research and Scholarly Activities

Since joining UHCL, you have had one peer-reviewed journal publication, two papers published in peer-reviewed conference proceedings and two invited presentations at national and international forums. All of these are related to work done on your dissertation prior to joining UHCL and all of these are commendable. However, I join with your division chair and review committee in emphasizing the importance of the research agenda and the actual research you have been doing since joining UHCL. In particular, we are all pleased that you have adapted your original research direction to focus upon a new area more in attune with the needs of our university and the constituencies of your program. Your successful proposals for the summer research fellowship at NASA/JSC and the grant to obtain funding for an ISSO Post-Doctoral colleague should be very helpful in building your research record in this new and important area. I encourage you to focus more time and effort in the next few years on achieving peer reviewed publications and externally funded research grants for you, your students and your peer collaborators in areas that are consistent and synergistic with your program's instructional, research and professional service needs. As a part of my recommendation to help achieve this, please see my final recommendation in the "Service" section of this memo.

Service

I join your division chair and your review committee in applauding your service to your program since joining UHCL. I also recommend balancing this commitment with increased service to your university, community and profession and, in particular, with improved documentation of the nature and importance of this service. For example, your service as faculty advisor to the Physics Club and as a judge for the regional Science and Engineering Fairs are entirely commendable and are self-evident as you have documented them. However, merely stating your membership in important professional societies without explaining the level of your participation and the significance of this participation to your own development and that of your program, school and profession is not very helpful toward documenting progress toward promotion and tenure. Of perhaps even more importance for improving your progress toward P&T, seek opportunities to review papers for professional journals and conferences that are relevant to your research and scholarly activities as well as your teaching interests.

In Conclusion

I agree with your division chair and review committee that you are making good progress toward promotion and tenure. I commend and encourage you. Ms. McFadden will arrange a meeting this month with you, Dr. Casserly and me to discuss these reviews.

Respectfully,

Charles W. McKay, Dean
School of Science and Computer Engineering.

6 CORRESPONDENCE: TENURE REVIEW

To: David Garrison, Assistant Professor of Physics

XC: Robert Ferebee; Dennis Casserly; Debbie McFadden; Sadegh Davari

From: Sadegh Davari, Interim Dean, School of Science and Computer Engineering

On: April 18, 2007

Subject: Promotion and Tenure Review of Assistant Professors

Attached: Promotion-Tenure Schedule 07-08

Dear Dr. Garrison:

According to university records, you are scheduled to participate in a Promotion and Tenure Review of Assistant Professors in the fall semester of 2007. (Please see the attached schedule)

The relevant policy and procedures for a promotion and tenure review can be accessed through the following on-line navigational path:

http://prtl.uhcl.edu/portal/page?_pageid=284,168415&_dad=portal&_schema=PORTALP

Or

http://www.uhcl.edu/

- About UHCL
  - Policies & Handbook
    - Faculty Handbook
      - 5.3 UHCL Promotion and Tenure

Your list of at least three recommended individuals who are qualified and likely to be willing to serve as external peer reviewers of the major aspects of your work will be due to me by April 27, 2007, which will be forwarded to your peer review committee. By May 11, 2007, the committee will elect a chair and notify you with copies to the individuals cited in the above copy list whether they approve your recommendations for external peer reviewers. Your external evaluation files should be provided to the associate dean by no later than June 1, 2007. You should submit your vita and documentation to me no later than September 12, 2007. The expectations for the content of your vita and documentation are described in the Faculty Handbook. The recommendations of your peer review committee and your division chair will be due to me with copies to you by October 31, 2007. I will then complete my review and provide my recommendation to the provost with a copy to you by November 17, 2007. The provost's recommendation will be due to the president with a copy to you by December 15, 2007. Should you wish to appeal the result, you will have until January 8, 2008 to do so. The president's recommendation will be due to the chancellor by March 31, 2008.

Thank you for your contributions to your program, school and university. Don't hesitate to contact me should you have any questions about this letter and the related policy and procedures.

Best regards.

University
of Houston
Clear Lake

MEMORANDUM

To: Dr. Sadegh Davari, Interim Dean

Subject: Peer Review Committee Recommendation on the Request by Dr. David Garrison for Promotion to Associate Professor with Tenure

Date: October 31, 2007

The peer review committee has met and carefully examined the documentation accompanying Dr. David Garrison's request for promotion to Associate Professor with tenure. We have also reviewed the recommendations by the three external evaluators, each of whom recommended Dr. Garrison's promotion. Based on the submitted materials and positive recommendations of the external reviewers, the peer review committee believes he has met the standards listed in the UH-Clear Lake Faculty Handbook in the areas of teaching, research and service unanimously supports Dr. Garrison's promotion to Associate Professor with tenure.

TEACHING

The committee rates Dr. Garrison's overall performance in teaching as "very good with the promise of becoming excellent". This belief is based in part on the following:

1) Dr. Garrison is an effective teacher in the classroom. His area of specialization is physics. Dr. Garrison has regularly received good ratings on the student evaluations. For example, over numerous courses for the last 4 years his average student rating was 4.0 out of 5.0 for "Overall quality of the course" and 4.0 out of 5.0 for "Overall teaching capability." One student wrote about his teaching. "Great class."

2) Dr. Garrison has developed and taught a wide range of courses to meet student needs. He has taught 13 different courses at UHCL, most at the graduate level. Some examples are the following: Classical Mechanics, Mathematical Methods in Physics I & II, General Relativity, Special Relativity, Spacetime Physics, Electrodynamics, Fundamentals of Spacetime, Numerical Methods in Physics, Research Methods and several others. In addition, he introduced or upgraded the curriculum on a total of 26 courses in the ASTR and PHYS rubrics. Because he has developed such an array of graduate courses it is not surprising that

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one of his students wrote on an evaluation form, "This was a good course to start my graduate program with—it was truly enjoyable and beneficial."

3) Dr. Garrison also has been active in individualized student instruction and advising. Since coming to UHCL he has supervised 23 independent study students. In addition, he has been the sole advisor for physics graduate students; currently there are 29 students accepted in the physics program and 10-20 others taking course in physics who are not seeking degrees.

4) Dr. Garrison also has truly excelled in program development. Between 2002 and 2004 he oversaw development and approval of a revised B.S. program in physical science and a new M.S. program in physics. In 2006 he led further modification of the physical science curriculum into two sub-plans, one in support of teacher certification and the other in preparation for graduate study in physics. In addition, he received a Sloan Foundation Grant to work with local government agencies and industry to develop a professional physics M.S. degree with the aim of filling the needs of the local community for technically skilled managers. One of his external reviewers, Professor S. James Gates of the University of Maryland, noted about Dr. Garrison, "The progress he has made in moving forward your physics program is simply breath-taking." Finally, Dr. Garrison worked with faculty and administrators at UHCL and UH-Central Campus to establish a joint Ph.D. degree in physics. Thus, for the first time at UHCL, natural science faculty members will be able to direct research of doctoral students on campus. Professor Lawrence Pensky, Chair of Physics at UH and another outside reviewer, wrote, "...he has single-handedly advocated and organized the initiation of a joint Ph.D. program which will soon be put in place between our two institutions. Everything about this program owes a debt to David's competence and perseverance."

The committee believes that Dr. Garrison clearly deserves a rating of "very good with the promise of becoming excellent in teaching." UHCL is lucky to have a faculty member of his knowledge and dedication, as well as his willingness to do whatever it takes to support the students and move the physics program forward.

RESEARCH AND SCHOLARLY ACTIVITY

The committee rates Dr. Garrison's overall performance in Research and Scholarly Activity as "satisfactory with the promise of becoming very good"; this belief is based in part on the following:

1) Dr. Garrison had several important publications and presentations in the period 2000-2003 (two in refereed journals including the important Physical Review, two in peer-reviewed conference proceedings and he gave three invited presentations. Since fall of 2002 when he came to UHCL, his publication record has been good. He has a new paper just accepted in Classic and Quantum Gravity, 2 papers from the Marcel Grossmann Meeting on General Relativity in Brazil and he has given several seminars at national and international conferences as well as invited lectures at the University of Oregon and Grinnell College.

2) Dr. Garrison has been quite prolific in pursuing external funding. For example he has submitted proposals to external funding agencies requesting over $1.5 million. He has been successful in gaining an ISSO Postdoctoral grant, an ASEE-NASA summer faculty fellowship and a CGS/Sloan Professional Science Master's Degree Implementation Grant, plus many other smaller grants to support his research with total funding exceeding $125,000. He also has worked with other faculty in SCE to obtain the donation of computers from ConocoPhillips to set up a Beowulf high-performance parallel computing cluster at UHCL.

In summary, the committee believes that Dr. Garrison's performance in Research and Scholarly Activities is "satisfactory with the promise of becoming very good."

SERVICE

The committee rates Dr. Garrison's overall performance in service as "excellent." While at UHCL, he has been exceptionally active and effective in service to the profession, and particularly the university and local community. This view is based in part on the following:

1) Dr. Garrison has been unusually dedicated to service at the university, particularly for someone as an assistant professor. At the university level, he has served on the Faculty Senate, Faculty Senate Research Task Force, Convocation Committee, Black History Month Panel, Student Orientation Board and several others. He was the primary host for a public lecture at UHCL by the renowned physicist S. James Gates. At the school level, he has acted on the Curriculum Committee (chair 2006-present), the Student Affairs Committee and the Library Committee. At the division level he has served as Chair of Physics from 2002-2007 and Chair of Physical Science (2002-2005). It is very unusual for an assistant professor to take on the role of program chair. Nonetheless, Dr. Garrison did so with enthusiasm and has done an exceptional job in this role, even when compared to far more experienced faculty. In addition, he served on the Aerospace Engineering Task Force, developed an IPA with NASA to bring a visiting professor in physics at no cost to UHCL, helped organize the UH/UHCL Physics Journal club and participate in many other activities. He has also been quite supportive of student organizations. He encouraged students to form the Physics Club and acted as its advisor (though the club is now in an inactive phase). He also acted as advisor to the Black Student Association and served as a Total Success mentor. Finally, he participated in a wide range of other service actives in the local community.

2) Dr. Garrison has been active in service to the profession and community. He served on the Local Organizing Committee for the American Association for the Advancement of Science Southwestern and Rocky Mountain Division (AAAS-SWARM) regional meeting that was held at UHCL in spring of 2007. In addition, he is a member of the American Physical Society, American Association of Physics Teachers and the National Society of Black Physicists.

In summary, Dr. Garrison's performance in service has been outstanding, particularly for an assistant professor. We believe that he has clearly earned a rating of "excellent in service."

SUMMARY

The committee members believe that Dr. Garrison has earned a rating of "very good with the promise of becoming excellent" in teaching, "satisfactory with the promise of becoming very good" in research and "excellent" in service. He has met and exceeded the standards listed in the UHCL Faculty Handbook; thus, we unanimously support his promotion to Associate Professor with tenure.

W. Ronald Mills, Committee Chair

Carl Zhang, Committee Member

George E. Blanford, Committee Member

Robert C. Hopkins

Robert C. Hopkins, Committee Member

Jack Y. Lu, Committee Member

Xc: Dr. David Garrison
Dr. Dennis Casserly,
Chair of Natural Sciences

University
of Houston
Clear Lake

MEMORANDUM

TO: Dr. Sadegh Davari, Interim Dean, School of Science and Computer Engineering

FROM: Dr. Dennis Casserly, Chair of Natural Sciences

SUBJECT: Recommendation of Promotion to Associate Professor with Tenure for Dr. David Garrison

DATE: October 31, 2007

I have reviewed the narrative and documentation, including letters of recommendation by external evaluators, supporting Dr. Garrison's request for promotion and tenure. He has clearly exceeded the criteria for tenure at UHCL and we are fortunate to have dedicated and productive faculty such as Dr. Garrison. I am honored and pleased to have him as a colleague and I highly recommend him for promotion to Associate Professor of Physics with Tenure.

Dr. Garrison was hired in 2002 as a Visiting Assistant Professor of Physics and was essentially charged to revise and revitalize the Physical Science program. This he achieved nearly single-handedly with few resources, while initiating and maintaining a very active research agenda and still finding the time and energy for professional service. The specific findings in the three areas of professorial responsibility follow:

Teaching and Educational Activities: Very Good with promise of being Excellent

Dr. Garrison has developed and taught a variety of Physics courses (some had undergraduate crosslistings) to meet student and curricular needs: Classical Mechanics, Principles of Electromagnetism, Electrodynamics I & II, General Relativity, Mathematical Methods in Physics I & II, Spacetime Physics, Using Mathematica to Solve Physics Problems, Modern Physics Research, and Research Methods in Space Science. Modern Physics Research was developed to expose non-physics majors to current topics of interest using the Physics Guest Lecture Series that he instituted. Dr. Garrison uses a traditional chalk/blackboard lecture format with web enhancement as a recent addition to his teaching resources. His teaching has steadily improved since arriving at UHCL and he receives high student evaluations.

Dr. Garrison is the advisor for all students majoring in Physics and Physical Sciences. This includes the selection of courses by the students as well as preparation of their CPS's. Dr. Garrison has advised 22 students in capstone, independent studies and has advised one thesis research proposal. Capstone topics include: "Space Radiation Research", "Field Relationships", "Plasma Physics", "Magnetohydrodynamics", "Theory of Pair Production", "Data Visualization", "Early Universe Gravitational Wave Production", "Cosmology", "Computational Physics", "Initial Conditions for GRMHD", "Optimization of GRMHD Code", "Data Analysis for GRMHD Code" and "Visualization of GRMHD Data".

He oversaw the approval of the BS in Physical Science Program with 8-12 Teacher Certification and worked with the Bay Area Houston Science Teacher Institute Partnership on an NSF proposal to enhance K-12 science education.

He developed and implemented a new Graduate Physics Program, managed grant funding for a Professional Science Master's Degree Program with the Council of Graduate Schools and the Sloan Foundation, developed a Physics track under the Physical Science program, developed and implemented an agreement for a joint Ph.D. program in Physics with UH, and implemented it this fall semester, and he oversaw the development of a new University Physics Lab, a Computational Physics Lab and a Plasma Physics lab. He also developed an IPA agreement with NASA JSC for a Visiting Professor of Physics (Dr. John Shebalin).

Research and Scholarly Activities: Very Good

Dr. Garrison has an active research program focused on numerical relativity and cosmology. To support his research and students, he has submitted 29 proposals, requesting $2.3M and receiving $129K from Sloan Foundation, American Physics Society, NASA-ISSO, FDF & FRSF. His publications include: "Black Hole Spectroscopy: testing general relativity through gravitational-wave observations" in *Classical and Quantum Gravity* 21 (2004) 787-803 which has been frequently cited; "Serving Non-traditional Graduate Students' in *Physics Today* (2007); "Development of a Comprehensive Physics Program at a non-traditional upper-level undergraduate and graduate small university", *APS Forum On Education Spring 2006 Newsletter;* and "Gravity Gradients in LIGO: a proposal for Data Analysis by David Garrison and Gabriela Gonzalez", *Proceedings of the Tenth Marcel Grossman Meeting on General Relativity, 2006.* He has also given 3 invited lectures and 6 contributed presentations at national and international conferences as well as numerous local presentations. He has recently expanded his research to include the development of Doubly Special Relativity and he has collaborations with the Advanced Space Propulsion

Laboratory's VASMIR project for the development of a plasma rocket engine. His efforts were awarded with a summer research fellowship at NASA/JSC and the funding for an ISSO Post-doc to continue to pursue these research undertakings. He has continued to conduct a weekly Astrophysics Seminar series between NASA-JSC and UHCL, and he attends a weekly teleconference on numerical relativity hosted by Penn State's Center for Gravitational Physics and Geometry. To foster research and to promote Physics and Space Science at UHCL, he developed and implemented the Astrophysics Colloquium Series, the Fall and Spring Physics and Space Science Seminar Series, the MOU with JSC's ARES, the Joint UH/UHCL Physics Journal Club and the special guest lecture by Professor James Gates, Jr.

Service: Excellent

Dr. Garrison has dependably and productively served as Chair of Physics and Physical Science. Those duties include revising courses and curricula, building schedules, recruiting, advising students, developing mentoring programs for prospective students, securing and managing 10 adjunct faculty and ordering texts, laboratory and instructional materials. He also led or participated in a number of important service activities, examples include: Chair of the SCE Curriculum Committee, Chair of the physics visiting assistant professor search committees, member of the search committee for an environmental geologist, hosted a public lecture by Professor James Gates, member of the SCE Aerospace Engineering Task Force, member of the Student Affairs Committee, member of SCE Library, Research and Computing Committee, advisor to the Physics Club, co-advisor for the Black Student Association, judge for the Science Olympiad, judge for the Science and Engineering Fair of Houston, judge for Celebrating Our Elder's Scholarship Competition, member of the 2005 and 2006 UHCL Convocation Committee, honored guest at the National Society of Black Engineer's Annual Martin Luther King Luncheon, counselor for the Ethnic College Counseling Center, and he was a regular attendee at commencement. He also attended and spoke at a number of academic training fairs to promote the Physics program and he peer-reviewed other Physics Departments for *US News and World Report*,

Respectively submitted,

Dennis Casserly

Dr. Dennis Casserly
Chair of Natural Sciences

XC: Dr. David Garrison
Dr. W. Ronald Mills, Chair of Peer Review Committee

University
of Houston
Clear Lake

To: Carl Stockton, Senior Vice President for Academic Affairs and Provost

XC: David Garrison, Assistant Professor of Physics
Robert Ferebee, Associate Dean
Dennis Casserly, Chair of Natural Sciences Division

From: Sadegh Davari, Interim Dean S. Davari
School of Science and Computer Engineering

Date: November 19, 2007

Subject: Tenure and Promotion Review for Dr. David Garrison

Attached: Candidate's Folder
Recommendation of Candidate's Evaluation Committee
Recommendation of Candidate's Division Chair
Recommendation of Candidate's External Reviewers

Executive Summery

Dr. Garrison joined UHCL as a Visiting Assistant Professor of Physics in fall 2002. His position was converted to a tenure-track position in fall 2003. I believe Dr. Garrison has established an "excellent" record in Teaching and Educational Activities, a "very good with the potential of becoming excellent" record in Research and Scholarly Activities, and an "excellent" record in service. I join his peer evaluation committee and his division chair in commending him on these achievements and in recommending him for tenure with promotion to the rank of Associate Professor of Physics.

Important Back Ground Information

Dr. Garrison received his B.S. degree in Physics from Massachusetts Institute of Technology in 1997 and his Ph.D. degree in Physics from Pennsylvania State University in 2002. He joined UHCL as a Visiting Assistant Professor of Physics in fall 2002. His position was converted to a tenure-track position in fall 2003 when the tenure-track position became available. When we hired Dr. Garrison we did not have any program called Physics. We had an undergraduate and a graduate program in Physical Sciences.

Along with his tenure-track appointment, Dr. Garrison was also appointed to be the Chair of the undergraduate and graduate programs in Physical Sciences. He subsequently created a Physics track in the undergraduate Physical Sciences program and he transformed the graduate Physical Sciences program into a graduate program in Physics. To make these transitions possible, he created and taught several new courses in Physics. He held the chair position for both programs until 2005. During this time, he oversaw the approval of the BS in Physical Sciences program with 8-12 Teacher Certification. In 2005 Dr. Mills became the Chair of the undergraduate program in Physical Sciences and Dr. Garrison remained as the Chair of graduate Physics program. David is a very energetic person. He continued his program development path. First, starting with a planning grant from the Council of Graduate Schools and the Slone Foundation, he created the graduate Professional Physics program for the professionals in the community. Then, after conducting a needs assessment survey, he teamed up with his colleagues from the Physics Department at UH and championed the creation of a joint Doctoral program in Physics with UH. He was the main driving force from the start to the end in this process. With the help of Dr. Pinsky, the Chair of Physics Department at UH, he came up with the first draft of the joint Doctoral program agreement. He then tried to get approvals from the administrative ladders at both institutions. The original draft went through a series of revisions in this process and in each step of the way David was the sole driving force behind the processing of the agreement document. With his persistence in every step of the way, the signing of the final version of the agreement was completed towards the end of Spring 07 semester. We started offering the joint Doctoral program in fall 2007. I was a participant in this process and closely witnessed David's efforts in each step of the way. I am so glad and so proud to have David as a colleague in our school. He has done so much to the Physics program at UHCL during the last 5 years. We are lucky to have him here.

Dr. Garrison's peer review committee and his division chair have rated his teaching as "very good with the promise of becoming excellent" and his service as "excellent". His peer review committee has rated his research as "satisfactory with the promise of becoming very good" and his division chair has rated his research as "very good". All three of his external reviewers have provided very positive recommendations. My own evaluation of Dr. Garrison in the three areas of teaching, research, and service follows. These evaluations are based on a careful examination of the supporting documentation provided by Dr. Garrison, and also based on my own observation of Dr. Garrison during the time that I have know him as a colleague.

Teaching and Educational Activities

Dr. Garrison's evaluation committee and his division chair have done a good job of documenting his achievements in teaching. Without replicating all of their observations, I will add my own observations and some highlights that support my conclusion.

Along with his excellent program development efforts, Dr. Garrison has made very significant contributions to the Physics programs at UHCL through his teaching and his efforts in new course development. He has successfully taught a total of 13 different courses at UHCL. Most of these courses are at the graduate level. In support of the new curriculums he introduced or was responsible for upgrading a total of 26 Physics and Astronomy courses. He has supervised a total of 23 students on independent study projects. He has been the faculty advisor of all graduate students in Physics. As their faculty advisor, he has helped them with their Candidate Plan of Study, with their course selections, and with their career planning and research projects. He has started utilizing web technologies in his courses. The student evaluations of Dr. Garrison's courses have consistently been positive. Students often comment very positively on his knowledge of the subjects, his enthusiasm in teaching, and his ability to teach complex topics. He takes his teaching responsibilities very seriously and he has continuously been improving his delivery methods.

Dr. Garrison is a dedicated and an enthusiastic teacher. His contributions to the physics education at UHCL have been superb and out of ordinary. I rate his contributions in Teaching and Educational Activities at UHCL as **excellent.**

Research, Scholarly or Artistic Activities

Dr. Garrison's evaluation committee and his division chair have done a good job of documenting his achievements in research and scholarly activities. Without replicating all of their observations, I will add my own observations and some highlights that support my conclusion.

Dr. Garrison became interested in research during his undergraduate education at MIT, where he was fortunate to receive mentorship and advice from a number of prominent individuals, including three Nobel Prize winners. He participated in several research projects in physics at MIT. After MIT, he started his research activities under the supervision and mentorship of several other prominent individuals at the Center for Gravitational Physics and Geometry in Pennsylvania State University. After participating on several projects at Penn State, he chose numerical relativity as his area of research. Numerical relativity is a field that combines computational physics with the Einstein's general theory of relativity to simulate astrophysical events. He developed a new technique to test the stability of numerical relativity codes using cosmological space-times. He presented different aspects of this work at several conferences. He then started working on another project that focused on Black Hole Spectroscopy using gravitational wave detectors. The result of this work was published as a refereed paper in 2004 in the *Classical and Quantum Gravity*, a prestigious journal. He has also published a paper in another important refereed journal called *Physical Review*.

While at UHCL, he started collaborating with colleagues at the Advanced Space Propulsion Lab at NASA/JSC in the area of Plasma Physics. This collaboration resulted in a summer faculty fellowship at JSC and a post doctoral grant from the Institute of Space Systems Operation (ISSO). His collaboration with his colleagues at NASA/JSC has continued. He continues to conduct a weekly Astrophysics Seminar series between

NASA/JSC and UHCL. In his evaluation of Dr. Garrison's research, Dr. Casserly, his division chair, wrote:

> "To foster research and to promote Physics and Space Science at UHCL, he developed and implemented the Astrophysics Colloquium Series, the Fall and Spring Physics and Space Science Seminar Series, the MOU with JSC's ARES, the Joint UH/UHCL Physics Journal Club and the special guest lecture by Professor James Gates, Jr."

Dr. Garrison's current focus in research is *Numerical Cosmology*. He has started developing codes to test his new hypothesis which claims that gravitational waves in the early universe excited turbulent modes in the primordial plasmas, which contributed to the formation of cosmic structure. To support his research in this area he started acquiring powerful computers mainly through donations. Working with his colleagues in SCE and using the computers donated by ConocoPhillips, he was able to set up a Beowulf high-performance parallel computing cluster at UHCL.

His major publications and presentations include:

- Two publications in peer-reviewed journals
- Two peer reviewed proceeding articles
- One internal NASA/JSC report
- One article in industry news letter
- Three invited talks
- Six contributed talks in national and international conferences
- Several local talks on his research interests and the history of physics

He has submitted a total of 14 internal and 15 external grant proposals. He has received funding for 12 of his internal proposals for a total amount of $23,722. He has received funding for 8 of his external proposals for a total amount of $107, 743. His external grants include three ISSO grants with a total amount of $63,743, a $12,000 fellowship grant from NASA, and two grants from the Council of Graduate Schools and the Slone Foundation for a total amount of $31,000. His internal grants include 5 FRSF grants for a total amount of $14,916, and 7 FDF grants for a total amount of $8,706.

Dr. Garrison has had these accomplishments while devoting a large portion of his time to program development and service. With his talent and his enthusiasm, with curriculums already in place, with the new joint Doctoral program in place, and with access to Doctoral students, I think Dr. Garrison's research productivity will flourish to a much higher level in near future.

I rate the overall research and scholarly accomplishments and activities of Dr. Garrison as **very good with a potential of becoming excellent.**

3. Service

Dr. Garrison has been an active member of several university level, school level and program level committees. At the university level, he has served on Faculty Senate Research committee, on two Convocation committees, on two Black History Month Faculty Panels, and on a Faculty Panel during New Students Orientation. He hosted a visit and public lecture by Professor James Gates, Jr. At school level, he has served on SCE Curriculum committee (first as a member and then as the chair), on SCE Students Affairs Committee, and on Aerospace Engineering Taskforce. Along with his JSC colleagues, he has been trying to establish a Memorandum of Understanding with JSC in order to increase UHCL faculty access to JSC research facilities. At the division and program level, he first served as the Chair of Physical Sciences program, and then as the Chair of Physics program. His accomplishments as program chairs have been enormous. He has been the driving force behind several major initiatives, including: the development of a MS program in Physics, the development of a MS program in Professional Physics, the development of a BS track in Physical Sciences program, the development of a 8-12 Certification program in Physics, the development of a joint Ph.D. program in Physics with UH, and the development of many new Physics courses. As program chair, he was also responsible for class scheduling and recruiting adjunct faculty to classes. He has served on several faculty Search Committees, both as a member and as a chair. He has served as advisor to Physics club, as judge on several community events including multiple times on Science Engineering Fair of Houston and Science Olympiad. He has given talks on numerous community events.

Dr. Garrison is a member of the following professional organizations: American Physical Society, American Association of Physics Teachers, National Society of Black Physicists, and Council of Graduate Schools.

I rate Dr. Garrison's service as **excellent**.

In summery, I have rated Dr. Garrison as **very good with a potential of becoming excellent** in Research and Scholarly Activities, as **excellent** in Teaching and Educational Activities, and as **excellent** in service. I believe Dr. Garrison's academic accomplishments meet or exceed the criteria set for promotion and tenure at the University of Houston-Clear Lake. Therefore, I enthusiastically recommend that Dr. Garrison be awarded tenure and promoted to the rank of Associate Professor.

University
of Houston
Clear Lake

December 19, 2007

Dr. William A. Staples
President
University of Houston-Clear Lake

Dear President Staples:

Executive Summary

Upon review of the materials submitted by Dr. David Garrison, I recommend that he be granted tenure and promoted to the rank of Associate Professor. I concur with the positive recommendations by the Peer Review Committee, the Division Chair and the Interim Dean of the School of Science and Computer Engineering.

Teaching:

Since 2002, Dr. Garrison has been the person responsible for building the physics curriculum at UHCL. Based on much hard work, Dr. Garrison was responsible for enhancing the UHCL graduate professional physics program. His efforts also led to the development of a collaborative Doctoral program with the University of Houston. His teaching evaluations have averaged 4.0 over the last four years. This is especially significant as Dr. Garrison has taught many demanding physics courses at the graduate level. Dr. Garrison has been responsible for developing or enhancing 26 physics and astronomy courses during his time at UHCL. Therefore, I rate Dr. Garrison as **very good** in the category of teaching and educational activities with the promise of becoming excellent.

Research and Scholarly Activity:

Dr. Garrison has a bright future in research and scholarly activities. His research interest is in the area of Black Hole Spectroscopy using gravitational wave detectors. The result of this work was published in Classical and Quantum Gravity, which is a very prestigious journal. Dr. Garrison has also published a paper in another important refereed journal called Physics Review. Dr. Garrison has several other publications in peer reviewed manuscripts. Dr. Garrison has been active over the last 5 years in submission of grants. He has submitted 29 proposals with 20 of them being funded. Many of Dr. Garrison's funding has come from sources such as NASA, the Slone Foundation and ISSO, just to name a few. In just a short timeframe, Dr. Garrison has demonstrated the potential to significantly enhance

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research and scholarship at UHCL. Therefore, I evaluate Dr. Garrison as **good** in this category with the promise of becoming very good to excellent. I encourage Dr. Garrison to continue to enhance original research.

Service:

In reviewing Dr. Garrison's service to the university, I concur with the dean, the division chair and the peer review committee in rating him as **excellent** in this category. Dr. Garrison has been very active in several university, school and program level committees. He has also served on many external committees and has been active in working with Johnson Space Center to begin the process of establishing a Memorandum of Understanding for UHCL. Dr. Garrison has been active in his professional organizations including the American Physical Society, the American Association of Physics Teachers, and the Council of Graduate School. I commend Dr. Garrison for his hard work.

Summary

Based on the evidence provided to me, I concur with the recommendations from the Dean, the Division Chair and the Peer Review Committee and support the granting of tenure and promotion to Associate Professor for Dr. David Garrison.

Sincerely,

Dr. Carl A. Stockton
Senior Vice President for Academic Affairs and Provost

Copies: Dr. David Garrison, Assistant Professor
Dr. Robert Ferebee, Associate Dean
Dr. Dennis Casserly, Division Chair
Dr. Ron Mills, Chair, Peer Review Committee
Dr. Sadegh Davari, Interim Dean

University
of Houston
Clear Lake

March 26, 2008

Dr. David Garrison
Assistant Professor
School of Science and Computer Engineering
University of Houston-Clear Lake
Houston, Texas 77058

Dear David:

This is to notify you that I have received from Senior Vice President for Academic Affairs and Provost Carl A. Stockton the recommendation that you be promoted to the rank of Associate Professor, with tenure. It is a pleasure to inform you that I have approved this recommendation and am forwarding it to the University of Houston System Chancellor and the University of Houston System (UHS) Board of Regents.

Faculty promotions are expected to be acted on by the UHS Board of Regents on May 15, 2008, and you may expect to receive formal notification after that date.

Sincerely,

William A. Staples

William A. Staples
President

xc: Carl A. Stockton, Senior Vice President for Academic Affairs and Provost
Sadegh Davari, Interim Dean, School of Science and Computer Engineering

Office of the President
2700 Bay Area Boulevard Houston, Texas 77058-1098 (281) 283-2004 FAX (281) 283-2010 www.uhcl.edu

University
of Houston
Clear Lake

May 16, 2008

Dr. David Garrison
Assistant Professor
School of Science and Computer Engineering
UHCL Box 39

Dear David:

Although you will receive official notification from University of Houston System Chancellor Renu Khator, it is my pleasure to formally congratulate you on the UH System Board of Regents' approval on May 15 of your promotion to the rank of Associate Professor, with tenure, effective September 1, 2008.

This marks a significant academic and professional accomplishment, of which you can be justly proud. Early in the fall semester Provost Stockton and I will host a luncheon honoring you and your faculty colleagues whose promotions were approved this spring, and my office will be in contact with you to schedule.

Again, please accept my sincere congratulations!

Sincerely,

William A. Staples

William A. Staples
President

xc: Carl A. Stockton, Senior Vice President for Academic Affairs and Provost
Sadegh Davari, Interim Dean, School of Science and Computer Engineering

UNIVERSITY OF HOUSTON SYSTEM
UNIVERSITY OF HOUSTON

RENU KHATOR
Chancellor, UH System
President, University of Houston

May 20, 2008

David Garrison
Assistant Professor
School of Science and Computer Engineering
University of Houston-Clear Lake
2700 Bay Area Boulevard
Houston, Texas 77058

Dear Professor Garrison:

I am very pleased to inform you that on May 15, 2008, the University of Houston System Board of Regents approved my recommendation that you be promoted to the rank of associate professor at the University of Houston-Clear Lake, effective September 1, 2008.

Additionally, I am pleased to approve the recommendation that you be granted tenure as a member of the faculty of the University of Houston-Clear Lake, also effective September 1, 2008.

I take this opportunity to offer my personal congratulations on your outstanding achievements. There are really only two major promotions in a faculty member's career, and promotion to the rank of associate professor is truly a significant milestone. What is more, the University awards tenure only to those who have demonstrated exceptional merit and who have been recommended for this status through a rigorous process of peer review.

On behalf of the entire University of Houston System family, I wish you continued success in your professional endeavors.

Sincerely,

Renu Khator

Renu Khator

cc: William A. Staples, President

212 E Cullen Building • Houston, TX 77204-2018 • (713) 743-8820 Fax: (713) 743-8837 • e-mail: rkhator@uh.edu

7 CORRESPONDENCE: PROMOTION TO FULL PROFESSOR

University of Houston Clear Lake

To: David Garrison, Associate Professor of Physics

XC: Ju Kim, Associate Dean
Magdy Akladios, Division Chair of Natural Sciences

From: Zbigniew Czajkiewicz, Dean, School of Science and Computer Engineering

On: April 28 2017

Subject: Promotion to Professor

Attached: 2017-2018 Academic Affairs Administration Calendar

Dear Dr. Garrison:

You have applied for Promotion to Professor in the fall semester of 2017.

The relevant policy and procedures for a promotion and tenure review can be found in Faculty Handbook on-line.

Your list of at least three recommended individuals who are qualified and likely to be willing to serve as external peer reviewers of the major aspects of your work will be due to me by May 16, 2017, which will be forwarded to your peer review committee. By May 26, 2017, the committee will elect a chair and notify you with a copy to Dr. Kim and Dr. Akladios whether they approve your recommendations for external peer reviewers. Your external evaluation files should be provided to the associate dean by no later than June 3, 2017. You should submit your vita and documentation to me no later than September 1, 2017. The expectations for the content of your vita and documentation are described in the Faculty Handbook. The recommendations of your peer review committee and your division chair will be due to me with copies to you by October 31, 2017. I will then complete my review and provide my recommendation to the provost with a copy to you by November 14, 2017. The provost's recommendation will be due to the president with a copy to you by January 5, 2018. Should you wish to appeal the result, you will have until January 26, 2018 to do so. The president's recommendation will be due to the chancellor by March 30, 2018.

Thank you for your contributions to your program, college and university. Don't hesitate to contact me should you have any questions about this letter and the related policy and procedures.

Best regards.

8 PUBLICATIONS

INSTITUTE OF PHYSICS PUBLISHING CLASSICAL AND QUANTUM GRAVITY

Class. Quantum Grav. **21** (2004) 787–803 PII: S0264-9381(04)68357-2

Black-hole spectroscopy: testing general relativity through gravitational-wave observations

Olaf Dreyer[1], **Bernard Kelly**[2], **Badri Krishnan**[3], **Lee Samuel Finn**[4], **David Garrison**[5] **and Ramon Lopez-Aleman**[6]

[1] Perimeter Institute of Theoretical Physics, 35 King Street North, Waterloo, Ontario, N2J 2G9, Canada
[2] Center for Gravitational Wave Physics, Center for Gravitational Physics and Geometry and Department of Physics, 104 Davey Laboratory, University Park, PA 16802, USA
[3] Max Planck Institut für Gravitationsphysik, Am Mühlenberg 1, D-14476 Golm, Germany
[4] Center for Gravitational Wave Physics, Center for Gravitational Physics and Geometry, Department of Physics and Department of Astronomy and Astrophysics, 104 Davey Laboratory, University Park, PA 16802, USA
[5] University of Houston, Clear Lake, 2700 Bay Area Bvd, Room 3531-2, Houston, TX 77058, USA
[6] Physical Sciences Department, University of Puerto Rico, Rio Piedras Campus, Rio Piedras, Puerto Rico 00931, USA

E-mail: odreyer@perimeterinstitute.ca, kelly@gravity.psu.edu, badkri@aei.mpg.de, lsfinn@psu.edu, garrison@cl.uh.edu and rlopez@uprrp.edu

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Abstract

Assuming that general relativity is the correct theory of gravity in the strong-field limit, can gravitational-wave observations distinguish between black holes and other compact object sources? Alternatively, can gravitational-wave observations provide a test of one of the fundamental predictions of general relativity: the no-hair theorem? Here we describe a definitive test of the hypothesis that observations of damped, sinusoidal gravitational waves originate from a black hole or, alternatively, that nature respects the general relativistic no-hair theorem. For astrophysical black holes, which have a negligible charge-to-mass ratio, the black-hole quasi-normal mode spectrum is characterized entirely by the black-hole mass and angular momentum and is unique to black holes. In a different theory of gravity, or if the observed radiation arises from a different source (e.g., a neutron star, strange matter or boson star), the spectrum will be inconsistent with that predicted for general relativistic black holes. We give a statistical characterization of the consistency between the noisy observation and the theoretical predictions of general relativity and a demonstration, through simulation, of the effectiveness of the test for strong sources.

PACS number: 04.80.Cc

1. Introduction

The formation of a black hole (BH) is the ultimate expression of strong-field gravity. Although we lack detailed information about the gravitational radiation produced through most of the formation process, our knowledge of the near-end point affords us important insight into the nature of general relativity.

During the late stages in the aspherical formation of an astrophysical black hole the gravitational waves emitted are dominated by a set of quasi-normal modes (QNMs) [1–3]: waves with exponentially damped sinusoidal time dependence, whose frequency and damping times are characteristic of the mass and angular momentum of the black hole[7]. If we observe a QNM from a black hole and also know which particular normal mode we are observing, we can determine, from the mode's frequency and damping time, the black-hole mass and angular momentum [4, 5].

If, on the other hand, we simultaneously observe two or more QNMs from the same source and find that they are inconsistent with the spectrum predicted by general relativity in the sense that they *cannot* be explained by a single value of the mass and angular momentum, we may infer that we are not observing a black hole.

A different perspective is offered by future observations by the Laser Interferometer Space Antenna (LISA) [6]. LISA is expected to observe mergers of compact objects with masses in the range 10^6–$10^8 M_\odot$ [7]. In our present understanding, these compact objects can *only* be black holes. Thus, observations by LISA of QNMs inconsistent with black holes would also conflict with the general relativistic no-hair theorem since an inconsistency in this mass range with black-hole sources would indicate that physical scales other than mass and angular momentum were involved in the generation of the radiation.

Here we develop this observation into an experimental test of the existence of black holes or, alternatively, a test of general relativity itself. In either sense the test described here is of general relativity based on gravitational-wave observations.

Damped sinusoidal motion is ubiquitous for systems approaching equilibrium and one expects that collapse or coalescence will lead, in any theory of gravity, to some form of QNM ringing. If we observe a QNM spectrum that is inconsistent with an isolated black hole, then there are two possibilities. On the one hand, general relativity may not be the correct theory of gravity in the strong-field limit. On the other hand, general relativity may yet be correct, but we are not observing an isolated black hole approaching equilibrium[8]. Alternatively, we may be observing the radiation arising from a compact body that is not a black hole, for example, a neutron star [8], a boson star [9] or strange matter star [10], whose QNM spectrum will be determined by the properties and configuration of the appropriate matter fields, or a black hole carrying a previously unknown macroscopic charge (e.g., a dilaton field [11]). Thus, while no single observation may rule out general relativity, a set of observations, each of a different source, *none* of which is consistent with an isolated black hole, could suggest the need to consider alternative theories of gravity in the strong-field limit.

Gravitational waves have been suggested before as probes of general relativity. Eardley *et al* [12] proposed the first test of general relativity using gravitational-wave observations. They investigated the polarization modes of gravitational waves in various metric theories of gravity and described how to identify the polarization modes experimentally and use these

[7] And electric charge, as well; however, astrophysical black holes, which are our interest here, have negligible charge-to-mass ratio.
[8] In fact, the uniqueness theorems have only been proved for vacuum spacetimes and they are not true in the presence of arbitrary matter fields or radiation. Nevertheless, it would be a great surprise if the spacetime in the vicinity of a black hole is not close to Kerr in some approximate sense.

observations to identify the spin content of dynamical gravity. The first actual test of general relativity relying on its prediction of the existence of gravitational waves was made by Taylor and Weisberg [13], who showed that the observed orbit and orbit decay of the Hulse–Taylor binary pulsar PSR B1913+16 led to a strong consistency check on the predictions of general relativity. Finn [14] proposed a different test of the spin content of dynamical gravity, based on the possibility of a space-based detector in circumsolar orbit observing the induction-zone field associated with solar oscillations. Ryan [15] has outlined how observations of the gravitational radiation from capture orbits of solar mass compact bodies about a supermassive black hole may allow the determination of certain multipole moments of the central hole, thereby testing the prediction of general relativity. More recently, Will [16] and Finn and Sutton [17, 18] have described tests of general relativity that bound the mass of the graviton, and Scharre and Will [19] and Fairhurst *et al* [20] have shown how gravitational-wave observations of pulsars may be used to bound the value of the Brans–Dicke coupling constant.

The preceding tests can be grouped into three different classes. One set of tests, including [13, 15, 17, 19], is based on energy conservation arguments: the observed evolution of a system or of the radiation from a system is related to the energy loss expected owing to the radiation. A second class of tests [12, 14, 20] focuses on the observed polarization modes of the field. The third class [16] involves the frequency-dependent dispersion relationship associated with a massive graviton. The test described in this paper is of a new class, based on the unique character of the radiation spectrum associated with a disturbed black hole.

This paper is organized as follows. In section 2 we briefly describe the QNMs of a Kerr black hole and explain how the idealized observation of two or more modes in the absence of noise enables us to extract the mass and angular momentum of the black hole. Real boats, of course, rock, and section 3 generalizes the discussion to include experimental errors and describes how one can use noisy gravitational-wave observations of QNMs to test general relativity. In section 4 we provide a proof-of-principle demonstration, via numerical simulation, of the use of this method as applied to LISA observations. Section 5 investigates the observable range (and associated event rate) within which we can expect LISA to observe sources strong enough for this test to be applied. We conclude in section 6 with a summary of our main results.

2. Ideal observations

2.1. Quasi-normal modes of Kerr black holes

Following aspherical collapse to a black hole, one expects that the final spacetime can be described as the perturbation of a stationary Kerr hole. The dominant part of the gravitational waves emitted as the black hole settles down can be described as a sum over a countably infinite set of damped sinusoids, each characterized by an amplitude, phase, frequency and damping time. (At still later times, the radiation will be dominated by power-law tails arising from the backscatter of radiation off the spacetime curvature in the neighbourhood of the black hole [1–3]; however, here we are interested in the earlier, and higher amplitude, QNM ringing.) In this sub-section we review those properties of the black-hole QNM spectrum that are important for our investigation; more detailed examinations of the spectrum itself can be found in [21–26].

QNMs appear as solutions to the equations describing perturbations of a stationary black-hole spacetime, subject to the boundary conditions of no in-going radiation from infinity and no up-coming radiation from the horizon. The perturbation equations describing Schwarzschild black holes were first described by Regge and Wheeler [27] and Zerilli [28, 29]. The first

QNM solutions to these equations were found by Vishveshwara [30]. Teukolsky found the corresponding perturbation equations for Kerr black holes [31, 32], and, with Press, first investigated their QNM solutions [33].

Gravitational-wave detectors respond to a linear combination of the radiation in the two polarization modes of the incident gravitational waves. The observable strain $h(t)$ in, for example, the arms of an interferometric detector may be written, for QNMs, in the form

$$h(t) \simeq \mathrm{Re}\left[\sum_{\ell,m,n} A_{\ell mn}\,\mathrm{e}^{-\mathrm{i}(\omega_{n\ell m}t+\phi_{n\ell m})}\right] \tag{1}$$

where the summation indices characterize the particular mode, which is related to the angular dependence of the mode amplitude and phase on a sphere of constant (Boyer–Lindquist) radius about the black hole through ℓ and m, and the 'harmonic' through the index n: $\ell = 2, 3, \ldots, |m| \leqslant \ell$ and $n = 1, 2 \ldots$. For the Schwarzschild geometry the symmetry is spherical, the appropriate decomposition of the metric perturbation is given by the usual spherical harmonics and modes differing only in m are degenerate. For Kerr the symmetry is axisymmetric and the orthonormal decomposition of the perturbation is by spheroidal harmonics [32]. The amplitudes $A_{n\ell m}$ and phases $\phi_{n\ell m}$ depend on the initial conditions and the relative orientation of the detector and the source; however, the complex frequency $\omega_{n\ell m}$ depends only on the intrinsic parameters of the underlying black hole, i.e., its mass M and angular momentum aM^2. (We assume that the black hole carries no significant electric charge.)

For fixed a the complex frequency $\omega_{n\ell m}$ scales as M^{-1}; thus, we define the dimensionless frequency $\Omega_{n\ell m}$,

$$\Omega_{n\ell m} := M\omega_{n\ell m} := \left(2\pi F_{n\ell m} + \frac{\mathrm{i}}{T_{n\ell m}}\right) \tag{2}$$

where $F_{n\ell m}$ and $T_{n\ell m}$ are the real dimensionless frequency and damping time of the modes, respectively. The corresponding physical frequency $f_{n\ell m}$ and damping time $\tau_{n\ell m}$ are given by

$$\omega_{n\ell m} = 2\pi f_{n\ell m} + \mathrm{i}/\tau_{n\ell m} = 2\pi F_{n\ell m}/M + \mathrm{i}/(MT_{n\ell m}). \tag{3}$$

(We use geometrical units with $G = 1$ and $c = 1$.) The dimensionless $\Omega_{n\ell m}$ (or $F_{n\ell m}$ and $T_{n\ell m}$) depend (for astrophysically relevant black holes) *only* on the also dimensionless black-hole angular momentum parameter a. Figure 1 shows $\Omega_{n\ell m}$ as a function of a for $n = 1, 2$ and $\ell = 2, 3$, and $|m| \leqslant \ell$.

2.2. From quasi-normal modes to testing relativity

If we observe only one mode, characterized by its complex frequency ω (cf equation (3)), what can we say about the underlying black hole?

Corresponding to the observed ω is the line $\Omega = M\omega$, $M \in \mathbb{R}_{\geqslant 0}$, in the dimensionless Ω plane (cf equation (2)). Such a line is shown in figure 1. This line will intersect some subset of the family of $\Omega_{n\ell m}$ curves, characteristic of black-hole normal modes. Each intersection corresponds to a black-hole mass M, angular momentum parameter a and mode $n\ell m$ consistent with the observed ω. Knowing only f and τ, then, we cannot uniquely identify the black-hole mass and angular momentum, but we can reduce the possibilities to a (possibly countably infinite) set of (a, M) pairs. If we knew $n\ell m$ as well, we would know a and M exactly.

Now suppose that we observe two modes from the same black hole, each characterized by its own frequency and damping time. Figure 2(*a*) shows, in schematic form, the line $M\omega$ for each of the two modes (denoted by + and ×) and their intersection with several different $\Omega_{n\ell m}$

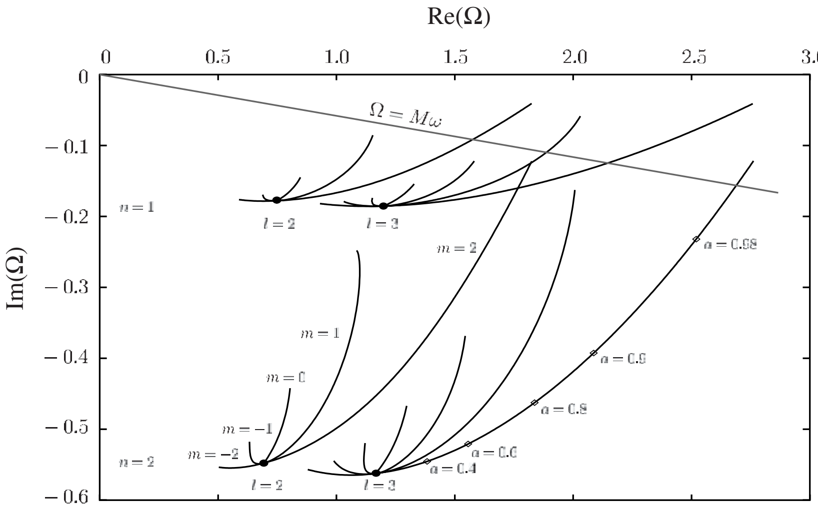

Figure 1. The dimensionless, complex QNM frequencies $\Omega_{n\ell m}$ for rotating, uncharged black holes. Each family of curves corresponds to one $n\ell$ pair, and each branch to a possible value of m. The large black dot at the base of each family is the Schwarzschild ($a = 0$) limit, where the frequencies are degenerate in m. This degeneracy is broken for $a \neq 0$, and the curves emanating from the dots give the QNM frequencies for Kerr black holes as a function of positive a for different m. In this figure a ranges from 0 to 0.9958, with the small diamonds on the $\ell = 3, m = 3, n = 2$ branch marking the QNM frequencies for $a = 0.4, 0.6, 0.8, 0.9$ and 0.98. In this figure an observation, corresponding to a (complex) frequency ω, is represented by the line $\Omega = M\omega$, parametrized by the (unknown) black-hole mass M. Each intersection of this line with a QNM curve in dimensionless Ω represents a candidate $n\ell m$, M and a for the mode.

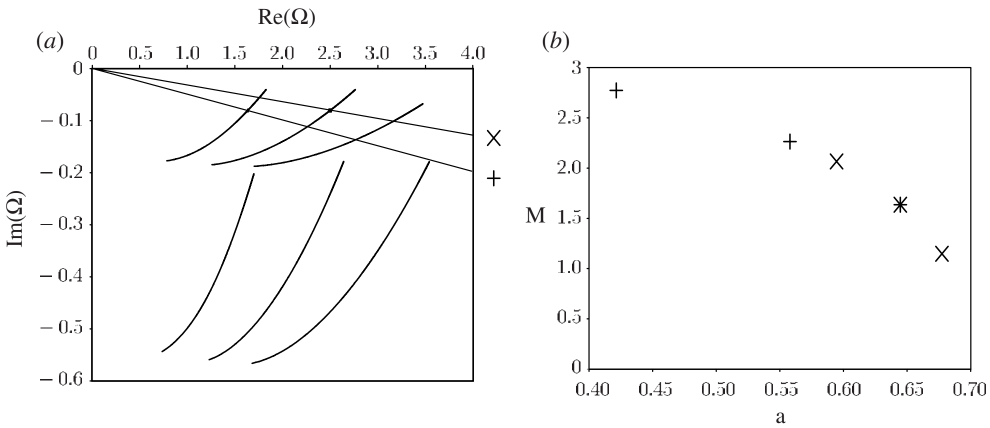

Figure 2. (a) Here we show, in schematic form, several $\Omega_{n\ell m}(a)$ curves and their intersection with the lines $M\omega_i$, $M > 0$, $i = 1, 2$, corresponding to two observed modes. We denote these two lines by + and $\times$, respectively. (b) The candidate (a, M) pairs determined in (a) are plotted here in the (a, M)-plane. The pairs belonging to ω_1 are denoted by +, those belonging to ω_2 by $\times$. There is only one candidate (a, M) consistent with both observations, indicated by the overlapping + and $\times$, and this is the actual mass and angular momentum of the underlying black hole.

curves in the complex Ω plane. Corresponding to each mode is a set of candidate (a, M) pairs that may describe the underlying black hole. Each candidate mass and angular momentum parameter is a point in the (a, M)-plane, as shown in figure 2(*b*). With two or more modes, there must be at least one common candidate mass and angular momentum, indicated by the intersection of a + and a $\times$.

This is, in essence, our proposed test: interpreting the observation of several normal modes ω_k, $k \geqslant 2$, as arriving from a single, general relativistic black hole, and assuming that the no-hair theorem is true, then the observed ω_k will be consistent with at least one black hole (a, M). If no such (a, M) exists for the observed ω_k either we have observed something other than an isolated black hole or we have a contradiction with the predictions of the theory.

(As an aside, it is possible (though unlikely) that we get more than one value of (a, M) consistent with the observed frequencies. This can happen if we have two mode pairs $(n_1\ell_1m_1; n_2\ell_2m_2)$ and $(\tilde{n}_1\tilde{\ell}_1\tilde{m}_1; \tilde{n}_2\tilde{\ell}_2\tilde{m}_2)$, which give rise to the same frequency ω. In this case the observations would still be consistent with general relativity though we could not use that observation to measure M and a. The important point of our test is the existence of *at least one* (a, M) pair consistent with the observations.)

Noise and other experimental realities ensure that there will be no *exact* agreement between the observed ω_k and a general relativistic black hole even if general relativity is correct. The challenge, then, in developing a practical test is to determine when the differences between the candidate (a, M) pairs associated with the different observed modes are so great as to be statistically inconsistent with general relativity. In the following section we face this challenge.

3. A test of relativity

3.1. A reformulation of the test

Before we discuss the role that noise plays in our analysis it is helpful to reformulate the test described in section 2.2 and figure 2. Consider an ordered N-tuple of QNMs,

$$\mathcal{Q} := \{(n_k\ell_km_k) : k = 1, \ldots, N\}. \tag{4}$$

This may be regarded as a function that maps a source (a, M) to a set of observable frequencies

$$\mathcal{Q}(a, M) := \left\{M^{-1}\Omega_{n_k\ell_km_k}(a) : k = 1, \ldots, N\right\}. \tag{5}$$

Each N-tuple $\mathcal{Q}$ thus describes a two-dimensional surface in the $(2N + 2)$-dimensional space $\mathcal{S}$,

$$\mathcal{S} := (a, M, \omega_1, \ldots, \omega_N), \tag{6}$$

with different N-tuples corresponding to different sets of N modes. (In section 3.3 we will understand the ω_k to represent observed QNM frequencies and damping times.)

An observation $\boldsymbol{\omega}$ consists of an N-tuple

$$\boldsymbol{\omega} := (\omega_1, \ldots, \omega_N)\,. \tag{7}$$

The observation $\boldsymbol{\omega}$ also corresponds to a surface in $\mathcal{S}$. The observation is consistent with a black hole if the surface of constant $\boldsymbol{\omega}$ intersects one of the surfaces $\mathcal{Q}$. Figure 3 shows a low-dimensional projection of such an observation $\boldsymbol{\omega}$ together with several surfaces (which appear as curves) for different N-tuples $\mathcal{Q}$. A moment's consideration should convince one that this new criterion is equivalent to the test as described in section 2.2.

In practice the situation is less than ideal: noise distorts our observation, so that—even if we are observing black-hole QNMs—the measured ω will not intersect a surface $\mathcal{Q}$. In the remainder of this section we describe how this test is made practical and meaningful for real observations.

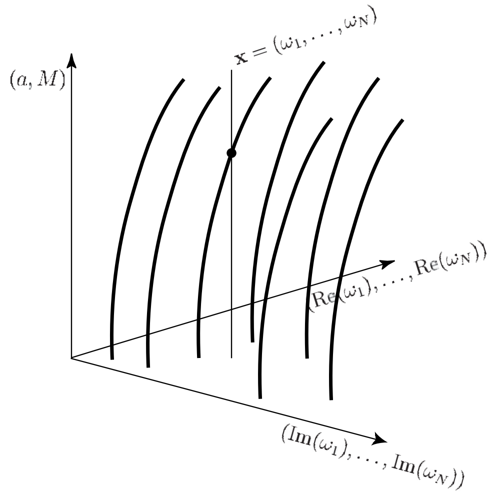

Figure 3. A reformulation of the consistency criterion. A set of quasi-normal modes $\mathcal{Q} = \{(n_k \ell_k m_k) : k = 1, \ldots, N\}$ corresponds to a surface in the $(2N + 2)$-dimensional space depicted in this figure. A measurement $\boldsymbol{\omega} = (\omega_1, \ldots, \omega_N)$ is consistent with general relativity if the constant surface that is obtained by ranging over all (a, M) while keeping the frequencies $\boldsymbol{\omega}$ fixed intersects at least one of the surfaces corresponding to one of the sets $\mathcal{Q}$. This intersection is indicated in this figure by a dot.

3.2. Confidence intervals and testing general relativity

In a frequentist analysis, the observation, the sampling distribution, an ordering principle and a probability combine to determine a confidence interval. In this section we use this construction to form a confidence region in the (a, M)-plane, given a noisy observation $\boldsymbol{\omega}$.

We begin by reviewing the construction of a classical confidence interval for the one-dimensional case following [34] (alternatively, see, e.g., [35]). We suppose that we make measurements of a random variable x from which a quantity μ is determined. The sampling distribution $P(x|\mu)$ is the probability of making the observation x given a particular μ. Formally, an *ordering principle* is a function $R(x|\mu)$, which we use to identify a sub-interval J of x according to

$$J(\mu|r) := \{x : R(x|\mu) > r)\}. \tag{8}$$

The parameter r is chosen such that the region $J(\mu|r)$ encloses a fixed probability p:

$$\int_{J(\mu|r)} P(x|\mu)\,\mathrm{d}x = p. \tag{9}$$

Given an observation x_0, the probability-p *confidence interval* $\mathcal{R}$ is the range of μ for which $J(\mu|r(p))$ includes x_0 as shown in figure 4. In an actual experiment, the choice of the value of the parameter p is made by the experimentalist. Typical choices are 90%, 95% and 99%.

The choice of the ordering principle $R(x|\mu)$ is a key ingredient in the construction of confidence intervals. Different choices will lead to different confidence intervals for the same observation: for example, one choice of ordering principle will always determine intervals of the form $(-\infty, x)$, while another choice will always determine intervals of the form (x, ∞). Neither choice is *a priori* right or wrong. Here we will choose $R(x|\mu) = P(x|\mu)$ so that the intervals are given by level surfaces of the distribution $P(x|\mu)$. The main advantage of this ordering principle is that it is simple and it works in any dimension. Consider, for example,

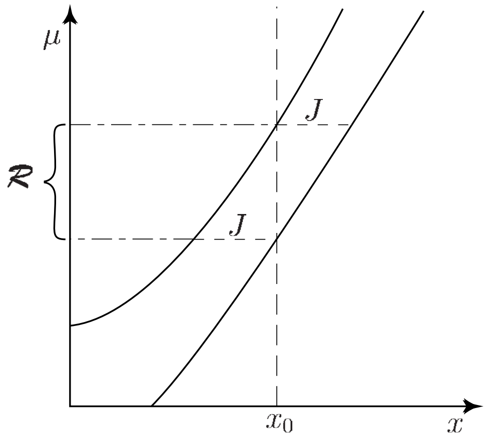

Figure 4. The construction of classical confidence intervals. A sampling distribution $P(x|\mu)$, an ordering principle R and a probability p are needed to construct a confidence interval. The ordering principle is used to find the intervals $J(\mu)$ such that $\int_{J(\mu)} \mathrm{d}x\, P(x|\mu) = p$. The classical confidence interval $\mathcal{R}$ is then given by the set of μ for which $J(\mu)$ contains the measured value x_0.

a two-component observation depending on one parameter a. There is, as before, a sampling distribution $P(x, y|a)$ and an ordering principle $R(x, y|a) = P(x, y|a)$. Confidence intervals can be defined in the same way as in the case of a one-dimensional observation; the interval J is now a two-dimensional region. Since this system is over-determined—we are now trying to determine *one* parameter a by measuring *two* quantities x and y—the measured x and y will have to satisfy additional constraints in order to give a non-vanishing confidence region. This is in fact precisely what happens in the black-hole quasi-normal mode problem: any single measurement of ω can be explained by *some* (a, M), but a measurement of two or more ω can be simultaneously consistent with at least one (a, M) pair only if the no-hair theorem is true and the modes arise from a single black hole.

We can now describe our test of relativity: note that some observations $\boldsymbol{\omega}$ will lead to an empty confidence interval; i.e., for some $\boldsymbol{\omega}$ there will be no (a, M) consistent with the observation. If we make an observation $\boldsymbol{\omega}$ for which the probability-p confidence interval is empty, then we say that the observed normal modes are inconsistent with an isolated black hole with confidence p. Conversely, if there does exist a non-empty probability-p confidence interval, then we have verified that general relativity is self-consistent at this confidence level.

Finally, we should point out an aesthetic flaw of our choice of ordering principle. The function $P(x|\mu)$ is a density and, therefore, not invariant under a reparametrization of x. If we were to use a new parameter $x' = f(x)$ for some smooth monotonic function f, the confidence region obtained for μ using a measurement of x may not coincide with the region obtained using a measurement of x'. In the one-dimensional case, there exists another ordering principle based on the likelihood ratio [36] which is reparametrization invariant; however, we have not been able to generalize this to higher dimensions. While aesthetically displeasing, there is nothing wrong with the choice we have made, which is natural given the physical association of the parameters M and a with the black-hole mass and angular momentum.

3.3. Generalization to quasi-normal modes

The generalization to QNM observations is straightforward. Each observation consists of N complex QNM frequencies ω_k and associated amplitude signal-to-noise ratios ρ_k, which

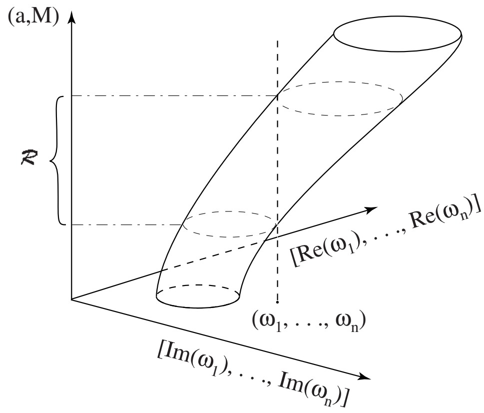

Figure 5. The construction of classical confidence intervals generalized to higher dimensions. Given a sampling distribution P, an ordering principle R and a probability p one can construct classical confidence regions $\mathcal{R}$ just as in the one-dimensional case. The difference here is that we are now trying to determine a small number of parameters (a, M) from a larger number of observations $\boldsymbol{\omega} = (\omega_1, \ldots, \omega_N)$. There are thus additional consistency conditions that need to be satisfied to obtain a non-empty confidence region $\mathcal{R}$.

characterize both the amplitude of the signal at that frequency and the uncertainty in the determination of ω_k (cf [5]):

$$\boldsymbol{\omega} := (\omega_1, \ldots, \omega_N) \tag{10}$$

$$\boldsymbol{\rho} := (\rho_1, \ldots, \rho_N). \tag{11}$$

For definiteness suppose that ω_k and ρ_k are identified via maximum likelihood techniques [5]. There is a minimum signal-to-noise associated with each mode, which is set by the requirement that the observation must identify N modes.

Observations $\boldsymbol{\omega}$ corresponding to a black hole characterized by (a, M) and signals-to-noise $\boldsymbol{\rho}$ are distributed according to the sampling distribution

$$P(\boldsymbol{\omega}|a, M, \mathcal{Q}, \boldsymbol{\rho}) := \begin{pmatrix} \text{Probability of making observation} \\ \boldsymbol{\omega} \text{ given the actual } N\text{-tuple } \mathcal{Q} \\ \text{and signals-to-noise } \boldsymbol{\rho}. \end{pmatrix}. \tag{12}$$

In general, the sampling distribution depends upon the nature of the detector noise and the analysis procedure that identifies the modes ω_k. For large signal-to-noise ratios it will generally reduce to a multivariate Gaussian in $\mathrm{Re}(\omega_k)$ and $\mathrm{Im}(\omega_k)$ and for smaller signal-to-noise ratios it can be determined via simulation.

Now consider the region of the space $\mathcal{S}$ (cf section 3.1) defined by

$$P(\boldsymbol{\omega}|a, M, \mathcal{Q}, \boldsymbol{\rho}) > p_0 \tag{13}$$

with p_0 such that

$$\int_{P(\boldsymbol{\omega}|a,M,\mathcal{Q},\boldsymbol{\rho})>p_0} P(\boldsymbol{\omega}|a, M, \mathcal{Q}, \boldsymbol{\rho}) \, \mathrm{d}^{2N}\omega = p \tag{14}$$

for a fixed p. We say that the observation $\boldsymbol{\omega}$ is consistent with a black hole if the actual observation $\boldsymbol{\omega}$ is included in this region for some (a, M). Figure 5 illustrates the comparison of an observation with the region defined by equations (13), (14).

To help in specifying p it is useful to examine its meaning more closely. Suppose we have chosen a value of p. That value determines a confidence region. Now consider an ensemble of identical detectors, each observing simultaneously the same black-hole event and its corresponding QNMs. The fraction of these observations that does not intersect the confidence region is the *false alarm probability* $\alpha(p)$, so-called because it is the probability that an observation will be falsely deemed to be inconsistent with a black hole. The probability α is a monotonic function of p; therefore, we can specify α in lieu of p. For observations that we are confident originate with black holes (because their characteristic frequency corresponds to masses greater than neutron star masses), we propose setting p so that $\alpha(p)$—the probability of falsely rejecting the hypothesis that we have in fact observed a black hole—is small (e.g., less than 1%). In other words, the standard of evidence for declaring that we have discovered 'new physics' should be high.

The false alarm probability function $\alpha(p)$ will depend on the signal strength, as characterized by the signal-to-noise ratios; consequently, it will need to be determined on an observation-by-observation basis. Thus the calculation of $\alpha(p)$ by a Monte Carlo simulation is the final ingredient we need. In the following section we demonstrate the test through a numerical example where we calculate $\alpha(p)$.

4. A numerical example

In the previous section we described a general procedure for testing general relativity by observing QNMs. In this section we explore its effectiveness numerically through a set of simulated observations drawn from a hypothetical black-hole population inspired by potential LISA observations, and a hypothetical population of non-black-hole compact object sources, or NBHs. (We say 'inspired' because, in fact, for the purpose of this analysis the observations are characterized entirely by the dimensionless signal-to-noise ratio and mode quality factor, with the dimensioned mode frequency simply setting a scale. Thus, the conclusions we reach are as valid for LISA observations as they are for observations at the same signal-to-noise with ground-based detectors.)

For the black-hole (BH) observations we find the relationship between the false alarm probability α and the probability p that appears in equation (14). For the NBH observations there are no 'false alarms': every observation is of something not a black hole. Instead, there are *false dismissals*: observations that we mistakenly classify as consistent with a black hole. The probability of a false dismissal, denoted by β, depends on the choice of p or, alternatively, the choice of false alarm probability $\alpha(p)$ that we make for the purpose of defining the test. (The false dismissal probability depends also on how the spectra of BHs and NBHs differ.) The smaller the false dismissal probability the more sensitive the test is to discovering 'new physics' or identifying non-black-hole sources. For the NBH observations we evaluate the false dismissal probability as a function of the false alarm probability.

4.1. Mode detection

Our concern here is with the question of statistical inference from QNM observations, characterized by their signal-to-noise, frequency and damping time. We do not venture to explore how, from a signal-processing standpoint, these events are identified and so characterized and none of the qualitative conclusions drawn in this section depend on the method of event identification and characterization. Nevertheless, it is worthwhile to comment briefly on the challenges associated with detecting and characterizing damped sinusoidal signals.

Matched filtering is often invoked as the preferred method for detecting signals in noise when the signal is known exactly, up to a few parameters. This does not mean, however, that matched filtering is the most computationally efficient means of detection. Similarly, while matched filtering may be optimal for these problems, it does not mean that there is necessarily a large difference in efficiency between matched filtering and other less optimal methods of event identification. Matched filtering stands-out only when the signal being sought has significant defining features that allow it to be discriminated from noise events. This is not the case for damped sinusoids with low quality factor Q.

In fact, matched filtering is known to be a very poor way to search for damped sinusoids. A matched filter search for a damped sinusoid of unknown frequency and damping time in a time-series $h(t)$ is equivalent to taking the Laplace transform of $h(t)$, which is computationally difficult to do accurately. (A set of 'matched filter templates', consisting of damped sinusoids, applied to a time-series $h(t)$ corresponds to a sample of the Laplace transform of h.) Fortunately, the problem of analysing noisy data for damped sinusoidal signals is not unique to gravitational-wave physics and other methods, beyond matched filtering, exist (cf, e.g., [37, 38]).

While none of the results below depend on the method of detection, we chose, where choices need to be made, to use theoretical results from matched filtering studies to describe the uncertainties associated with frequency and damping time determination. Such choices do not affect our qualitative conclusions and, in any event, relevant quantitative conclusions could not be drawn without both LISA data and the choice of a specific analysis method.

4.2. Simulating black-hole QNM observations

For definiteness we focus on observations of two QNMs (this corresponds to $N = 2$ in section 3). For the purpose of illustration we consider black-hole masses and angular momenta consistent with potential observations by the LISA detector [7]. We first draw an (a, M) pair from the distribution

$$P(a, M) = P(a)P(M) \tag{15}$$

$$P(a) \propto \begin{cases} 1 & \text{for } a \in [0, 0.986) \\ 0 & \text{otherwise} \end{cases} \tag{16}$$

$$P(M) \propto \begin{cases} M^{-1} & \text{for } M \in (2.5 \times 10^5 M_\odot, 4.5 \times 10^8 M_\odot) \\ 0 & \text{otherwise.} \end{cases} \tag{17}$$

The range of M is determined by the frequency band where LISA is expected to be most sensitive; the range of a is determined by the maximum angular momentum expected of a black-hole spun-up by thin-disc accretion [39].

Corresponding to each (a, M) pair we choose the QNMs corresponding to $(n = 1, \ell = 2, m = 2)$ and $(n = 1, \ell = 4, m = 4)$. We assign each mode the same signal-to-noise ratio, which we treat here as sufficiently large that the errors associated with the measurements are normally distributed with covariance matrix C_{ij} equal to the inverse of the *Fisher information matrix* I_{ij} (see, e.g., [35]) as given in [5, equation (4.14)]. This is in fact a mathematical lower bound—the *Cramer–Rao bound*—on the covariance matrix. We draw from this error distribution errors in the frequencies and damping times that we add to the 'real' frequencies and damping times to determine the simulated observations: noisy QNM frequencies and damping times.

Given this pair of QNM frequencies and damping times with errors we ask whether the two modes are in fact observationally distinguishable: if the frequencies and damping times are not sufficiently different, then no real observation would ever result in the given pair. For instance, the five ($n = 1, l = 2$) modes are degenerate at $a = 0$; consequently, no matter how large the signal-to-noise ratio, if a is sufficiently small it is impossible to resolve these five modes observationally.

To decide whether the two modes we investigate are observationally distinguishable we invoke a 'resolvability criterion': denoting the frequencies (damping times) of the two modes as f_1, f_2 (τ_1, τ_2) we say that the two modes are distinguishable if

$$|f_1 - f_2| > \frac{1}{\min(\tau_1, \tau_2)}. \tag{18}$$

We discard any mode pair that does not satisfy this criterion.

The result of this procedure is an *observation,* which consists of a pair of signal-to-noise ratios and associated distinguishable frequencies and damping times. (The observation does *not* include knowledge of the black-hole mass or angular momentum, or the $n\ell m$ associated with the frequencies or damping times.)

4.3. False alarm probability α

For each simulated observation $\boldsymbol{\omega}$, constructed as described in section 4.2, we evaluate the smallest probability $p = p_{\min}$ such that equations (13) and (14) describe a region $\mathcal{S}$ that covers $\boldsymbol{\omega}$ for some (a, M). The false dismissal fraction $\alpha(p)$ is the fraction of $p_{\min}$ determinations that are greater than p, i.e., the fraction of BH observations that we would reject as originating from a black hole for threshold p.

Ideally, in evaluating p we would consider every possible $n\ell m$ for each ω_k. In practice, we consider only a finite subset of low-order (in both n and ℓ) modes, corresponding to our expectation that these are the modes most likely to be excited to large amplitude. In our simulations we considered only modes corresponding to ($n = 1, \ell = 2, m = 0$), ($n = 1, \ell = 2, m = 2$), ($n = 1, \ell = 3, m = 3$) and ($n = 1, \ell = 4, m = 4$). Since for these simulations we observed two distinguishable QNMs there were 12 possible ordered pairs of modes. Figure 6 shows α as a function of p for four different signal-to-noise ratios. Each $\alpha(p)$ curve is constructed from 10^4 simulated observations with that amplitude-squared signal-to-noise in each mode.

4.4. False dismissal probability calculation

Complementary to α, the probability that we incorrectly decide we have observed QNMs from something other than a black hole, is the probability that we falsely conclude we have observed QNMs from a black hole. This probability is referred to as the false dismissal probability and commonly denoted as β.

The false dismissal probability depends on the detailed character of the source, which is not a black hole. Strong gravitational-wave sources are compact, with radius R not much greater than their mass GM/c^2 and oscillation periods of order GM/c^3. At the frequencies where LISA will have its greatest sensitivity, 10^{-2}–10^{-4} Hz, corresponding to masses of order 10^6–$10^8 M_\odot$—we know of no compact sources that are not black holes. For the purpose of illustration and to give a sense of the ability of the test described here to 'discover' new physics, we suppose a population of sources whose frequencies and damping times share the same relationship as certain neutron star w-modes calculated in [8]. Referring to [8, table 1, column 1, lines 3, 5] we consider observations consisting of two modes

$$M\omega_1 = 0.471 + 0.056\mathrm{i}, \qquad M\omega_2 = 0.654 + 0.164\mathrm{i}, \tag{19}$$

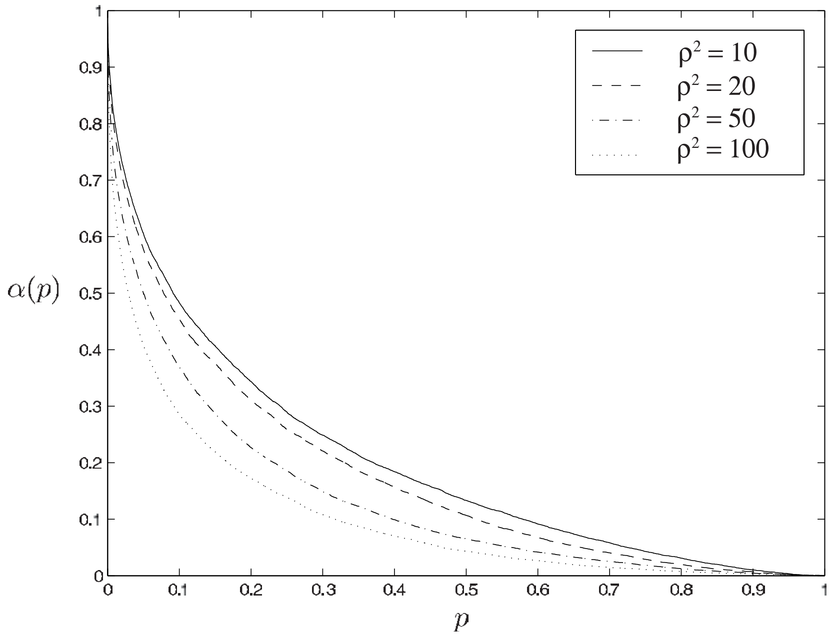

Figure 6. False alarm probability α as a function of the probability p appearing in equation (14). A false alarm is a misidentification of a QNM pair as arising from something other than a general relativistic black hole.

where M is drawn from the distribution given in equation (17). In exactly the same way that we used simulations in section 4.3 to determine α as a function of p we calculate from these simulations β as a function of p. Together $\alpha(p)$ and $\beta(p)$ determine $\beta(\alpha)$, which we show in figure 7. A measure of the effectiveness of the test is the degree to which the curves for different signal-to-noise fall below the $\beta = 1 - \alpha$ diagonal. (A 'test' that randomly picked a fraction α of observations as not black holes would have $\beta = 1 - \alpha$. Any 'test' that can do better than randomly choosing in this way will have a $\beta(\alpha)$ curve that falls below this diagonal.) As expected the test also does better with stronger signals. Consider a false alarm threshold of 1%. Then for observations with $\rho^2 = 10$ we have a better-than-40% chance of distinguishing NBH sources from BH sources. This climbs to better-than-90% chance for observations with $\rho^2 = 100$.

5. Potential for application

We have shown that, given at least two QNM signals from the same source and with sufficiently large signal-to-noise we can clearly distinguish black holes from other astrophysical sources. We have also demonstrated how this can be used as a test of general relativity. In this section, we investigate the potential for application of this test in future LISA observations by asking, first,

- How distant can LISA-scale black-hole sources be and still have multiple QNMs detected at sufficiently high signal-to-noise?

and, secondly,

- What is the rate of sources that we may expect within this distance?

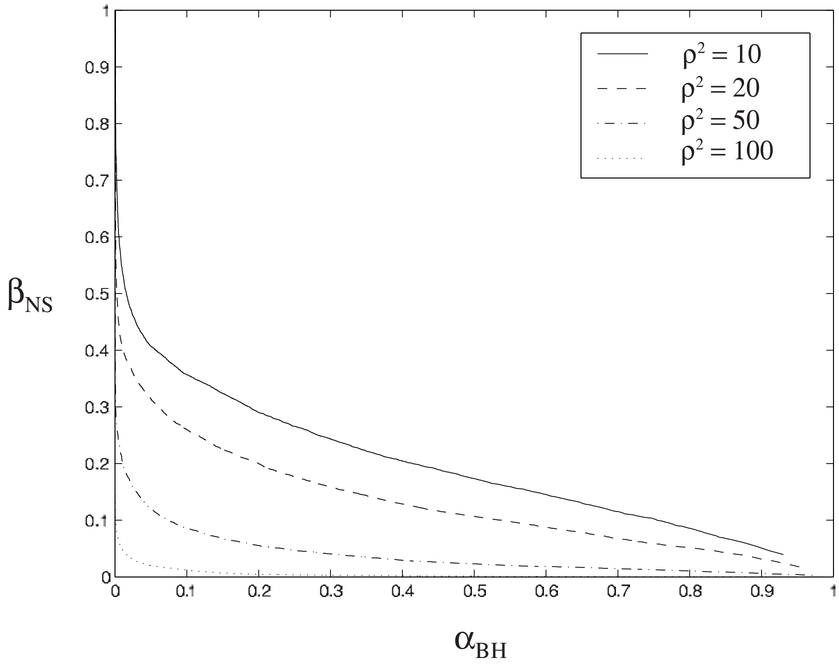

Figure 7. False dismissal probability as a function of false alarm probability $\beta(\alpha)$. The false dismissal probability depends on the non-black-hole QNM spectrum, which we have taken to have the same ratio of frequencies and relationship between frequencies and damping times as neutron star w-modes.

To begin we evaluate, as a function of distance and energy radiated in a QNM, the signal-to-noise in the LISA detector. We focus attention on an individual QNM. The signal strength, characterized by the signal-to-noise ratio at the detector, depends on the energy radiated in the mode the radiation pattern associated with the mode and the relative orientation of the detector and the source. Following [40, equation (2.30)] we can average over these latter angles to obtain the mean-square signal-to-noise associated with the $n\ell m$ mode as a function of the mode energy

$$\langle\rho^2\rangle = \frac{2(1+z)^2}{5\pi^2 D(z)^2}\int_0^\infty \mathrm{d}f\,\frac{1}{f^2 S_n(f)}\,\frac{\mathrm{d}E_e}{\mathrm{d}f_e}[(1+z)f] \tag{20}$$

where z and $D(z)$ are, respectively, the redshift and the luminosity distance to the source.

For the mode, we assume the form

$$h_{n\ell m}(t) = A_{n\ell m}\exp\left(-\frac{\pi f_{n\ell m} t}{Q_{n\ell m}}\right)\sin\left(2\pi f_{n\ell m} t\right) \tag{21}$$

where $Q_{n\ell m} \equiv \pi f_{n\ell m}\tau_{n\ell m}$. Note that $Q_{n\ell m}$, which is an observable property of a QNM, is independent of source redshift, while the observed $f_{n\ell m}$ and $\tau_{n\ell m}$ depend on redshift.

The ringdown energy spectrum of the $n\ell m$ mode is taken from equation (3.18) of [40]

$$\frac{\mathrm{d}E_e}{\mathrm{d}f_e} = \frac{\epsilon_{n\ell m}}{F_{n\ell m}}\frac{Q_{n\ell m}}{\left(4Q_{n\ell m}^2+1\right)}\frac{M^2 f^2}{\pi^3\tau^2}\left[\frac{1}{[(f-f_{n\ell m})^2+(2\pi\tau)^{-2}]^2}+\frac{1}{[(f+f_{n\ell m})^2+(2\pi\tau)^{-2}]^2}\right], \tag{22}$$

where the mode amplitude $A_{n\ell m}$ has been replaced with the fraction $\epsilon_{n\ell m}$ of the mass radiated in that mode, defined by

$$\epsilon_{n\ell m} := \frac{1}{M}\int_0^\infty \frac{\mathrm{d}E}{\mathrm{d}f}\,\mathrm{d}f. \tag{23}$$

Using this spectrum in the formula above, and approximating the LISA noise power spectral density $S_n(f)$ as constant over the signal band, we integrate over frequencies and invert the result to obtain an approximate distance to which we can observe a mode $n\ell m$ with signal-to-noise greater than $\rho^2_{n\ell m}$:

$$D(z)^2 < \frac{8}{5\pi^2}\frac{Q^2_{n\ell m}}{4Q^2_{n\ell m}+1}\frac{(1+z)^3M^3}{F^2_{n\ell m}}\frac{\epsilon_{n\ell m}}{S_n\rho^2_{n\ell m}}\frac{G^3}{c^7}. \tag{24}$$

The relationship between luminosity distance and redshift we take to be given by equations (23), (25) of [44]. This relationship depends on cosmological parameters that characterize the universe and its expansion and for these we use the values determined by the first season's WMAP observations [45]. Thus, given a threshold $\rho^2_{n\ell m}$, black holes radiating a fraction $\epsilon_{n\ell m}$ of their rest energy in mode $n\ell m$ are observable within a redshift z satisfying equation (24).

Numerical simulations suggest that the energy emitted in QNMs during ringdown may be of order 1% of the rest-mass energy of the hole [41, 42]. For equal-mass black-hole mergers, the simulations suggest that the $\ell = 2$ modes will be by far the strongest with total emitted energies greater than the $\ell = 4$ modes by as much as three orders of magnitude (see [43]). Thus we may assume that the weaker mode of a QNM pair produced immediately following an equal mass black-hole merger carries away a fraction 10^{-5} of the final black-hole mass. To be more conservative, we consider instead a considerably smaller emitted mass fraction $\epsilon_{n\ell m} = 10^{-7}$.

LISA will be most sensitive in the frequency band $10^{-3} \leqslant f \leqslant 10^{-2}$ Hz where the noise power spectral density is expected to be 5×10^{-45} Hz^{-1}. Black holes at redshift z whose (low-order) QNM frequencies peak in this band have a mass of order $\mathcal{M}/(1+z)$, where $\mathcal{M}$ ranges from 10^6 to $10^7 M_\odot$. Focusing just on these black holes we find, from equation (24), that LISA can expect to see pairs of QNMs associated with black-hole mergers, with the weaker mode having a signal-to-noise $\rho > 10$, within a redshift of ∼52 (for extremal-spin Kerr) or ∼36 (for Schwarzschild); that is, LISA will be able to observe mergers associated with the assembly of essentially all galaxies throughout the universe. Considering a broader frequency band of 10^{-1}–10^{-4} Hz will increase the mass range (and thus rate of observed mergers) further with the addition of more and less massive (redshifted) black-hole mergers, though to a somewhat smaller redshift.

To summarize, we expect that pairs of QNMs associated with the mergers of supermassive black holes in the redshifted mass range of 10^6–$10^7 M_\odot$ will be observable by LISA with significant signal-to-noise throughout the observable universe as long as the weaker mode carries away at least a fraction 10^{-7} of the final black-hole mass. The rate of such black-hole mergers depends on redshift owing to evolution and the scaling of the intrinsic black-hole mass corresponding to observed QNM frequency with redshift. There is considerable uncertainty at present about the event rate for such observations; however, estimates out to $z = 20$ —far smaller than the range within which LISA is sensitive—range from 0.3 to 100 per year [46–48]. Correspondingly, we expect that this test will find application in forthcoming LISA observations.

6. Conclusion

We have described a qualitatively new test for the existence of general relativistic black holes, based on the gravitational radiation they emit when they are formed or when they are impulsively excited, for example, through a merger event. Radiation from an impulsively excited black hole, such as might arise in the course of a non-spherical black-hole formation event or the coalescence of a black hole with another black hole or compact object, has a component that consists of a sum of damped sinusoids. This signature is characteristic of the radiation from any impulsively excited, damped source. For any given mode, the scale of the frequency and damping time measures the black-hole mass and angular momentum. Similarly, the relationship of the different modes to each other—i.e., the spectrum—is unique to black holes. We have described here how this relationship can be used to test the proposition that observed gravitational waves, characteristic of an impulsively excited, damped source, in fact originate from a general relativistic black hole. Such a test can be characterized in at least two different ways: as a definitive ‘proof’ that a black hole has been observed or as a test of the so-called ‘no-hair’ theorem of general relativity.

To demonstrate the effectiveness of this test we have evaluated numerically the probability that the test will mistakenly fail to identify an actual black hole. By introducing a hypothetical gravitational-wave source whose characteristic frequencies and damping times are similar to those of neutron star w-modes [8], we have also evaluated numerically the probability that the test will incorrectly identify w-mode oscillations of a neutron star, or any object whose spectrum is similar to that of a black hole. Together these results demonstrate that for sources with the signal-to-noise expected of, for example, massive black-hole coalescences detected by LISA, the test proposed here can clearly discriminate black-hole sources. Finally, we have shown that LISA can be expected to observe black-hole ringdown signals of this kind and strength almost throughout the observable universe. However, the event rates for such detections are rather uncertain and further work is needed to ascertain whether this test will be applicable in practice.

This method can also be used to measure mass and angular momentum of a black hole. Using gravitational waves to measure mass and angular momentum is an idea that has been around for some time [4, 5]. In these previous works it was assumed that the mode observed was of a known order (e.g., the mode with the longest damping time or the lowest order, etc.). With the observation of two or more modes the requirement that a single mass and angular momentum explain the complete set likely permits the mass and angular momentum to be determined uniquely.

The field of gravitational-wave detection is new. The current generation of ground- and space-based gravitational-wave detectors is opening a new frontier of physics: *gravitational-wave phenomenology,* or the use of gravitational-wave observations to learn about the physics of gravitational-wave sources and gravity itself. We are only just beginning to learn how to exploit the opportunities it is creating for us. As gravitational-wave observations mature, we can expect more and greater recognition of their utility as probes of the character of relativistic gravity. The opening of this new frontier promises to be an exciting and revealing one for the physics of gravity.

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We are grateful to Soumya Mohanty and Curt Cutler for helpful discussions. We acknowledge support through the Center for Gravitational Wave Physics, which is funded by the NSF under cooperative agreement PHY 01-14375, NSF awards PHY 00-90091 and PHY 00-99559, the Eberly research funds of Penn State and the Albert-Einstein Institut.

References

[1] Cunningham C T *et al* 1978 *Astrophys. J.* **224** 643–67
[2] Cunningham C T *et al* 1979 *Astrophys. J.* **230** 870–92
[3] Cunningham C T *et al* 1980 *Astrophys. J.* **236** 674–92
[4] Echeverria E 1989 *Phys. Rev.* D **40** 3194–203
[5] Finn L S 1992 *Phys. Rev.* D **46** 5236–49
[6] Danzmann K *et al* 1998 LISA—laser interferometer space antenna, Pre-Phase A Report Max Planck Institut für Quantum-Optiks, Report MPQ 233
[7] Finn L S and Thorne K S 2000 *Phys. Rev.* D **62** 124021
[8] Andersson N *et al* 1995 *Mon. Not. R. Astron. Soc.* **274** 1039–48
[9] Seidel E and Suen W 1990 *Phys. Rev.* D **42** 384–403
[10] Alcock C *et al* 1986 *Astrophys. J.* **310** 261–72
[11] Gibbons G W and Maeda K 1988 *Nucl. Phys.* B **298** 741–75
[12] Eardley D M *et al* 1973 *Phys. Rev.* D **8** 3308–21
[13] Taylor J H and Weisberg J M 1982 *Astrophys. J.* **253** 908–20
[14] Finn L S 1985 *Class. Quantum Grav.* **2** 381–402
[15] Ryan F D 1997 *Phys. Rev.* D **56** 1845–55
[16] Will C M 1998 *Phys. Rev.* D **57** 2061–8
[17] Finn L S and Sutton P J 2002 *Phys. Rev.* D **65** 044022
[18] Sutton P J and Finn L S 2002 *Class. Quantum Grav.* **19** 1355–60
[19] Scharre P D and Will C M 2002 *Phys. Rev.* D **65** 042002
[20] Fairhurst S *et al* in preparation
[21] Leaver E W 1985 *Proc. R. Soc. Lond.* A **402** 285–98
[22] Onozowa H 1997 *Phys. Rev.* D **55** 3593–602
[23] Nollert H P 1999 *Class. Quantum Grav.* **16** R159–216
[24] Kokkotas K D and Schmidt B G 1999 *Liv. Rev. Rel.* **2** http://www.livingreviews.org/lrr-1999-2
[25] Berti E and Kokkotas K D 2003 *Phys. Rev.* D **68** 044027
[26] Berti E *et al* 2003 *Preprint* hep-th/0307013
[27] Regge T and Wheeler J A 1957 *Phys. Rev.* **108** 1063–9
[28] Zerilli F 1970 *Phys. Rev. Lett.* **24** 737–8
[29] Zerilli F J 1971 *Phys. Rev.* D **2** 2141–60
[30] Vishveshwara C V 1970 *Nature* **227** 936–38
[31] Teukolsky S A 1972 *Phys. Rev. Lett.* **29** 1114–8
[32] Teukolsky S A 1973 *Astrophys. J.* **185** 635–47
[33] Press W H and Teukolsky S A 1973 *Astrophys. J.* **185** 649–73
[34] Neyman J 1937 *Phil. Trans. R. Soc. Lond.* A **236** 333–80
[35] Stuart A and Ord J K 1994 *Kendall's Advanced Theory of Statistics* vol 1 (London: Edward Arnold)
[36] Feldman G J and Cousins R D 1998 *Phys. Rev.* D **57** 3873–89
[37] Hamming Richard 1987 *Numerial Methods for Scientists and Engineers* (New York: Dover)
[38] Shahram M and Milanfar P 2003 On the resolvability of multiple sinusoids with nearby frequencies in the presence of noise *Preprint* (IEEE Trans. Signal Process. at press)
[39] Thorne K S 1974 *Astrophys. J.* **191** 507–19
[40] Flanagan É É and Hughes S A 1998 *Phys. Rev.* D **57** 4535–65
[41] Brandt S and Seidel E 1995 *Phys. Rev.* D **52** 870–86
[42] Khanna G *et al* 1999 *Phys. Rev. Lett.* **83** 3581–4
[43] Anninos P *et al* 1995 *Phys. Rev.* D **52** 4462–80
[44] Carroll S M and Press W H 1992 *Annu. Rev. Astron. Astrophys.* **30** 499–542
[45] Spergel D N *et al* 2003 *Astrophys. J. Suppl.* **148** 175–94
[46] Haehnelt M G 2003 *Class. Quantum Grav.* **20** S31–6
[47] Haehnelt M G 2003 Joint formation of supermassive black holes and galaxies *Carnegie Observatories Astrophysics Series Vol 1: Co-evolution of Black Holes and Galaxies* ed L C Ho (Cambridge: Cambridge University Press)
[48] Cutler C and Thorne K S 2002 *Preprint* gr-qc/0204090

Computer Simulation of the VASIMR Engine

Final Report

NASA Faculty Fellowship Program – 2004

Johnson Space Center

Prepared by:	David Garrison
Academic Rank:	Assistant Professor
University & Department	University of Houston-Clear Lake
	Physics Department
	Houston, TX 77058
NASA/JSC	
Directorate:	Space and Life Sciences
Division:	Advanced Space Propulsion Laboratory
Branch:	N/A
JSC Colleague:	John Shebalin
Date Submitted:	August 13, 2004
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David Garrison, Ph.D. John Shebalin, Ph.D.

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University & Department	University of Houston-Clear Lake
	Physics Department
	Houston, TX 77058
NASA/JSC	
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Branch:	N/A
JSC Colleague:	John Shebalin

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ABSTRACT

The goal of this project is to develop a magneto-hydrodynamic (MHD) computer code for simulation of the VASIMR engine. This code is designed be easy to modify and use. We achieve this using the Cactus framework, a system originally developed for research in numerical relativity. Since its release, Cactus has become an extremely powerful and flexible open source framework. The development of the code will be done in stages, starting with a basic fluid dynamic simulation and working towards a more complex MHD code. Once developed, this code can be used by students and researchers in order to further test and improve the VASIMR engine.

INTRODUCTION

Variable Specific Impulse Magneto-plasma Rocket

The Variable Specific Impulse Magneto-plasma Rocket (VASIMR) is a project at the Advanced Space Propulsion Laboratory (ASPL) at JSC [2]. The project is led from NASA JSC, and has contracts with several government research centers, industrial companies and universities. In addition, researchers from universities and institutes all around the world collaborate with ASPL.

The Magneto-plasma rocket engine provides propulsion by ionizing and heating neutral gases to high temperatures and then guiding them out of a magnetic nozzle in order to produce thrust, much like a chemical rocket engine. However, the essential difference between VASIMR and a chemical rocket engine is that VASIMR will produce very high specific impulse at relatively low thrust (*i.e.*, a low density, high velocity exhaust), while a chemical rocket engine produces high thrust at relatively low specific impulse (*i.e.*, a high density, low velocity exhaust).

The particular niche filled by VASIMR in the electric propulsion community is that of a relatively high-power plasma propulsion system that is focused on human space flight, rather than on less massive unmanned, robotic space flight missions. The efficiency of the engine permits a favorable ratio of payload mass to spacecraft mass, one that allows long-duration space exploration missions to be realistically contemplated.

In its research configuration, VASIMR utilizes four co-axial magnetic coils and two co-axial antennas to achieve its purpose. The first antenna is a so-called helicon antenna, which serves as a plasma generator in that it ionizes an injected neutral gas (typically hydrogen, deuterium or helium). The second antenna is known as the ion cyclotron resonance heating (ICRH) antenna and it boosts the energy of the plasma by feeding electromagnetic energy preferentially into the ions.

While the helicon antenna is primarily responsible for creating the plasma, the second antenna is used to increase the ion energy and exhaust velocity, and thus the specific impulse of the rocket engine. The magnetic coils work in concert to shape the strong axial magnetic field that guides the strongly magnetized plasma (*i.e.*, magneto-plasma). The final magnetic coil (or a smaller auxiliary coil) serves as a magnetic nozzle, by which the specific impulse and thrust of the plasma exhaust may be varied. When the components are operating together, the result is the Variable Specific Impulse Magneto-plasma Rocket, or VASIMR.

The magnetic nozzle gives VASIMR the unique ability to modulate the plasma exhaust so as to maintain maximum power and efficiency. This technique is termed "Constant Power Throttling" and is similar to adjusting the transmission on an automobile. The VASIMR engine (specific impulse, $I_{sp} \sim 15{,}000$ sec), is designed to run continuously, so that, although it has low thrust, any interplanetary transit time is considerably reduced. In contrast, a chemical rocket, such as the space shuttle main engine ($I_{sp} \sim 450$ sec), is designed to provide very high thrust, but only for about eight minutes. A traditional chemical rocket lifts a space ship off of a planet and gives it an initial velocity, after which it is in free flight towards its objective.

The role of VASIMR is to provide thrust during what would have been unpowered free flight, thereby shortening travel time. For example, using only a chemical rocket would give a transit time of about 300 days to reach Mars. Adding VASIMR for the interplanetary section of the journey (equipped with a nuclear power generation system) would reduce the trip to as little as 39 days carrying 20 tons of cargo, or 115 days for a larger 61-ton cargo load. Also, by minimizing transit time, physical stress and risk to the crew is also minimized.

Our goal in this project is to create a computerized model of the VASIMR system in order to understand the fluid dynamics and thermodynamics of plasma flow in the engine and in its exhaust [4,5]. This model will incorporate variations of such system parameters as magnetic coil current values and magnetic field structure. We found Cactus to be the best framework for developing these models.

Cactus

Cactus [1] is an open source problem-solving environment designed for scientists and engineers. The Cactus framework, which was originally developed for numerical relativity research, has become an extremely powerful and flexible tool. Cactus originated in the academic research community, where it was developed and used over many years by a large international collaboration of physicists and computational scientists. Its modular structure easily enables parallel computation across different architectures and collaborative code development between different groups.

The name Cactus comes from the design of a central core (or "flesh") that connects to application modules (or "thorns") through an extensible interface[1]. Thorns can implement custom developed scientific or engineering applications, such as computational fluid dynamics. Other thorns from a standard computational toolkit provide a range of computational capabilities, such as parallel I/O, data distribution, or checkpointing.

Cactus runs on many architectures. Virtually all Unix based systems as well as Windows NT are supported. Applications, developed on standard workstations or laptops, can be seamlessly run on clusters or supercomputers. Cactus provides easy access to many cutting edge software technologies being developed in the academic research community, including the Globus Metacomputing Toolkit, HDF5 parallel file I/O, the PETSc scientific library, adaptive mesh refinement, web interfaces, and advanced visualization tools.

[1] See Appendix A

We chose to use Cactus because it is flexible, modular and well documented. The Cactus development groups are quick to respond to questions and communication within the development community is freely available. Also, efforts by the Cactus organization as well as third party developers ensure that new features and bug fixes are constantly being developed [3].

GOALS

The goal of this Faculty Fellowship Program (FFP) project was to test the feasibility of using the Cactus framework to develop a magneto-hydrodynamic (MHD) code for use with the VASIMR project. There are many differences between the existing Cactus codes used in numerical relativity and the MHD codes used within the VASIMR project. These differences had to be addressed in order to develop VASIMR simulations within the Cactus framework.

An alternative to using Cactus would be to either develop a new MHD code from scratch or to modify existing codes. However, the main motivation for switching to the Cactus framework is to gain the support of existing documentation and a large development community. Unlike existing software, a program developed with Cactus will be relatively easy for short-term workers (such as students) to modify and use because of the well-designed structure of Cactus and its extensive support network and documentation.

The Physics Program at the University of Houston – Clear Lake (UHCL) focuses on a Masters degree in Physics. Our graduate students are required to complete a research project or thesis but typically only have about a year to work on such a project. Existing codes usually require several years to learn enough about the software to modify and use on original research projects and are therefore not useful for short-term student projects. This research program will provide a suitable vehicle for student theses because original work can be completed in just a few months. This will also provide a framework for the controlled evolution of software suitable for ASPL.

Development will be done in stages, starting with a basic fluid dynamic simulation and working towards a more complex MHD code. The fluid code is designed primarily to test the feasibility of installing and running Cactus on ASPL and UHCL machines. The fluid code will eventually evolve into a full MHD code but before that can happen several technological steps must be taken. These steps are outlined in the section titled “Development Thorn”. Eventually, this code will then be used by students and researchers to further design and improve the VASIMR engine.

INSTALLATION

The first step of this project involved installing Cactus on each of the development machines and testing them using several existing sample thorns. The three development machines were a dual processor Macintosh G4 machine at UHCL, a Linux

Beowulf cluster at ASPL and my personal Macintosh Powerbook G4. Each computer was already equipped with both Fortran and C compilers but I also added additional visualization tools (xgraph, ygraph and gnuplot) to the Macintosh machines.

The biggest challenge during the installation process was finding the correct configuration for Cactus for each different hardware/software setup. The only way to find the correct configuration for each operating system, compiler and software package was to review the documentation and search through the computer's directory structure for the right parameters. This involved some trial and error and in a few cases, we had to correct a few Unix login files. After a couple weeks of searching for the right configurations, all three machines were compiling and running the example codes well.

The test examples ranged for a simple "Hello World" screen printout to a scalar wave simulation that used Cactus' ability to steer computer simulations through a web browser. These tests proved that all the compilers and tools were working correctly so we could move on to the next step, developing an original thorn.

THE COMFLUID THORN

Instead of jumping right into the development of a full MHD thorn, we thought it would be a good idea to first develop a compressible fluid simulation code which has a similar geometry to the VASIMR engine. This involves using a cylindrical coordinate grid and a set of coupled differential equations representing the number density and velocity of particles in the fluid. This is effectively the same problem as in MHD except that the fluid is not charged and there are no magnetic fields. The comfluid thorn was then developed to further test to concept of using Cactus for fluid simulations. The equations, which it evolved, are given below:

$$\frac{\partial n}{\partial t} + \nabla \cdot \left(n\vec{V} \right)$$

$$\frac{\partial \vec{V}}{\partial t} + \vec{V} \cdot \nabla \vec{V} = -\frac{k_B T}{m} \frac{\nabla n}{n}$$

where all units are MKS, $\vec{V}$ is the particle flow velocity, n is the number density (particle/m^3), m is the atomic mass for the fluid under consideration, mass density $\rho = mn$, T is the fluid temperature (assumed to be constant here) and k_B is the Boltzman constant. In addition the energy and momentum is calculated at each grid point for use in our analysis of the code's performance. It should be noted that the above equations are relatively simple, but are suitable to start with.

The equations were evolved in two dimensions in cylindrical coordinates ignoring the angular direction. Because Cactus is based on a Cartesian grid, we had to write subroutines to calculate gradients and divergences in cylindrical coordinates. We also used periodic boundary conditions to "roll" the Cartesian grid into a cylindrical one. As soon as a cylindrical grid thorn becomes available for Cactus, we plan to implement it into our program.

The code compiled and ran on all three development machines without any platform specific modifications. Slices taken in the radial and axial coordinates where then used for data analysis[2]. The initial data for the system modeled a Gaussian distribution of particles with velocities pointing out towards the radial and axial directions. As time evolved the particle distribution dispersed and the particles disappeared out the edges of the simulation domain. Towards the end of the simulation, boundary value errors begin to appear.

This test revealed two problems with the way the simulation was designed. 1) Further work is needed to increase the stability of the code so that it can run longer before significant errors occur. 2) Customized boundary conditions need to be implemented so that we can make some boundaries reflective (example when the radial direction rho = 0) while others are absorbing. Also, the stability of a finite differenced numerical code such as this depends on several factors such as boundary conditions, grid spacing, time step size and other parameters choices. Future work will involve increasing the stability of the code as well as adding new features to make the simulation more realistic.

In order to coordinate the development of improvements to the code while not destroying the progress that we have already made, we split the code and began work on an advanced "development" version. The "stable" version was saved for later study while the development version is continuously changed to improve stability and experiment with new features.

DEVELOPMENT THORN

Time Integration

The first technique adopted in the development code is the Iterated Crank-Nicholson time integrator. By using a second or higher order time integration technique such as Iterated Crank-Nicholson or Runge-Kutta, we can further increase the stability of the code. These techniques work well in numerical relativity and should work well for our program. These systems work by correcting for small errors, which occur as we evolve the equations from the solution at one time to the next. Instead of the growth in errors depending directly on the time step, they depend on the time step squared. This can decrease error growth by several orders of magnitude without a significant decrease in computational speed.

Boundary Conditions

The stable version of our code currently depends on Cactus' built in boundary conditions. By developing our own boundary condition subroutines, we can reduce errors at the boundary by "tuning" the boundaries to our system. Eventually we can introduce absorbing boundary conditions, which eliminate computational artifacts such as unwanted reflections and further reduce boundary errors. Most importantly, we can choose where to apply reflective and absorbing boundary conditions in order to make our

[2] See Appendix B

simulation more realistic. If we are working in cylindrical coordinates, no information should leave the grid when it passes through rho equals zero.

Spectral methods

Cactus is currently designed to use finite differencing as a method of numerically calculating the derivatives of functions. Spectral methods have been shown to be much more accurate and stable than finite difference methods but more difficult to implement. There is currently an effort to develop a general spectral methods thorn for Cactus. Once it has been released, we can begin testing it and eventually add it to our code.

Adaptive mesh refinement

Adaptive mesh refinement (AMR) is a technique where the grid spacing can change depending on the dynamics of the code. This leads to greater accuracy in parts of the grid where it is needed and less accuracy where it is not. This increases both accuracy and computational efficiency. There is currently a third party Cactus Thorn that adds AMR to Cactus.

Other improvements

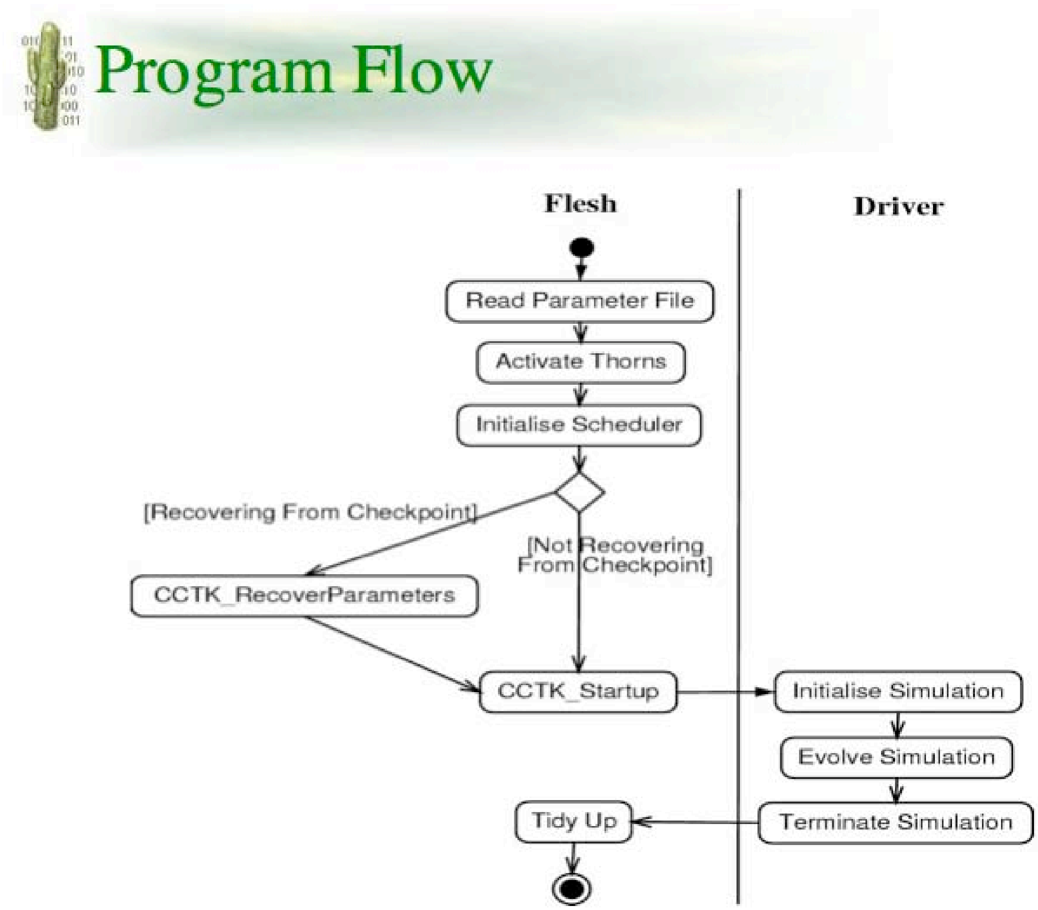
There are several other improvements that can be made to the code including improved initial conditions, the addition of dissipative terms, viscosity, temperature variations in the fluid and much more. These improvements can be added as needed, however, the focus of the code will be to test the concept of using Cactus for VASIMR research and then to develop a MHD code.

Add MHD equations

The long-term goal of this project is to add the MHD equations and turn this fluid dynamic code into a full MHD code [4,5]. This will involve adding a several more evolution equations to the list of coupled differential equations. These include equations for charge density, magnetic field, and the energies and momentum carried by both. There is an additional difficulty at this point in understanding the dynamics of how these equations are evolved and making them as stable as possible. Because of this it is to our advantage to develop a modular, well documented and easy to understand code so that future students can add equations with minimal intimidation.

APPENDIX A

Cactus program structure



APPENDIX B

Preliminary Numerical Results

The energy of the compressible fluid flows to the boundary and disappears, boundary errors develop. For both plots: Blue = early times, Red = late times, x = radial, z = axial. Both plot where produced with ygraph.

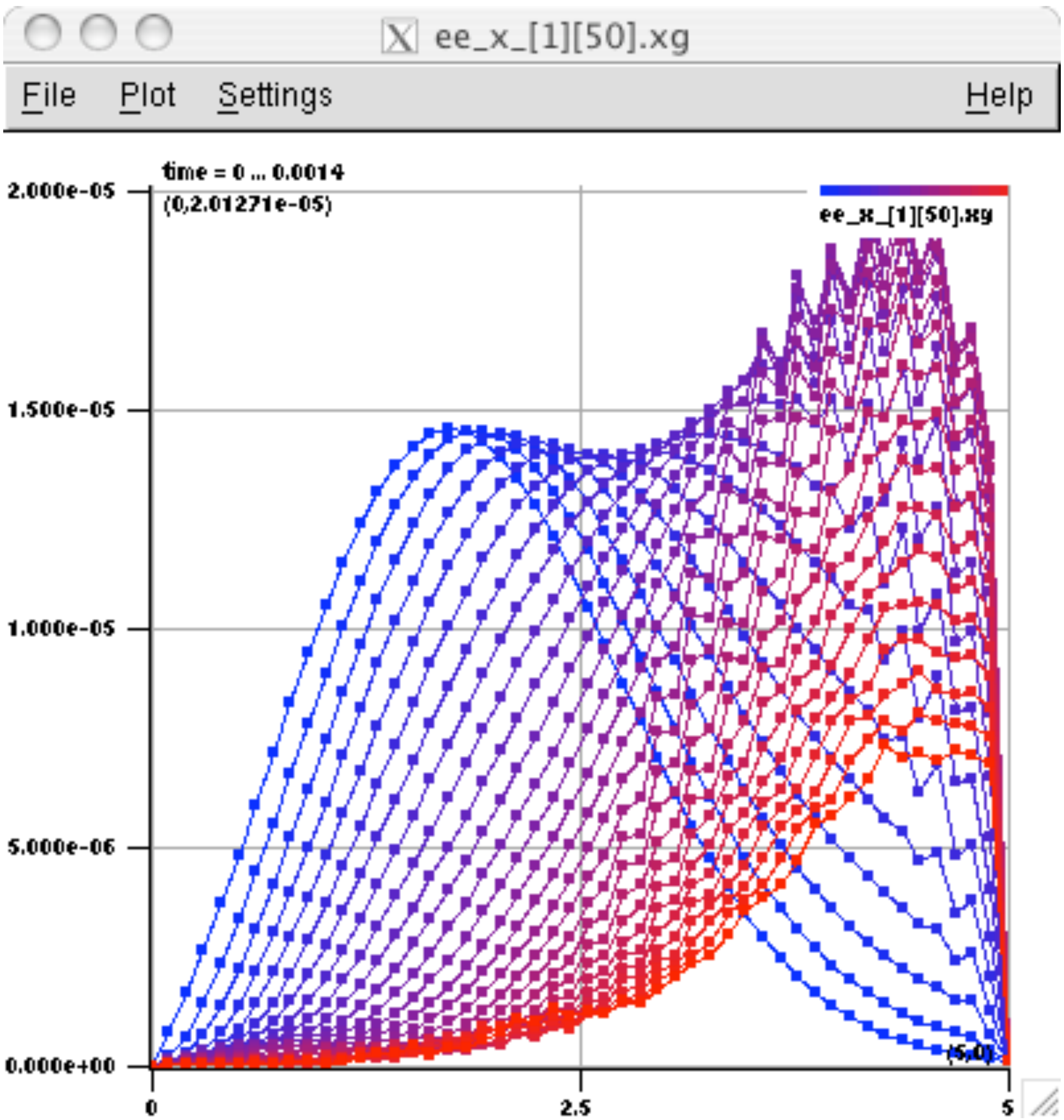


Figure 1 : Above is a plot of energy vs. radial position taken at several times. The y axis is energy amplitude while the x axis shows radial position.

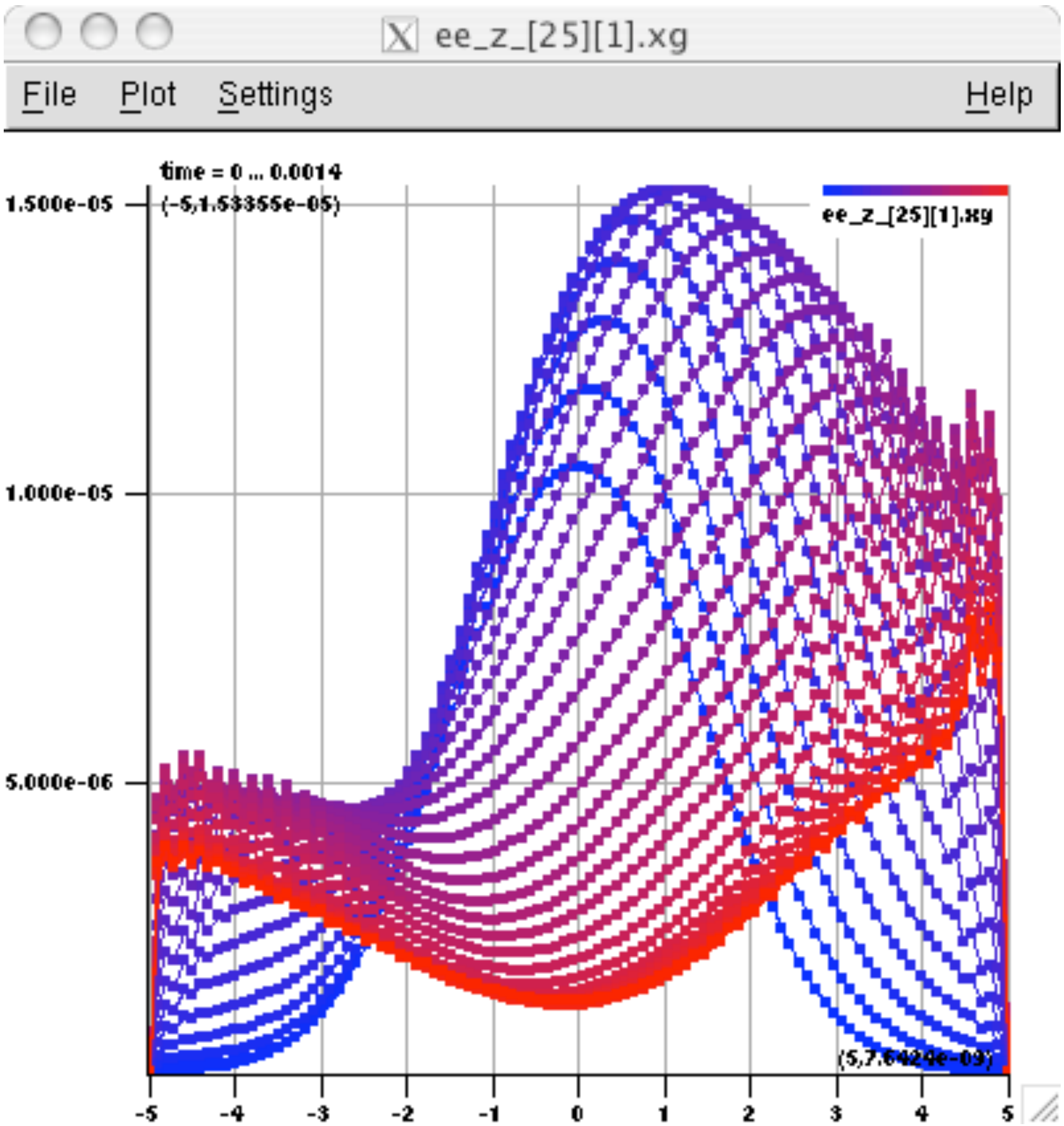


Figure 2 : Above is a plot of energy vs. axial position taken at several times. The y axis is energy amplitude while the x axis shows axial position.

REFERENCES

1. Cactus, **http://www.cactuscode.org**

2. Chang Diaz F. R. (2000) ***The VASIMR Rocket***, Scientific American, 283, (5), 90-97.

3. Goodale, Tom, ***Cactus 4.0: An Introduction and Perspectives On Future Plans***, PowerPoint presentation.

4. Tarditi, A. G. and J. V. Shebalin, ***MHD simulation of flow through the VASIMR magnetic nozzle***, APS Division of Plasma Physics Meeting, Oct. 2003.

5. Tarditi, A. G., J. V. Shebalin, and E. A. Bering, ***MHD simulation of the exhaust plume in the VASIMR advanced propulsion concept***, XXIII General Assembly of the International Union of Geodesy and Geophysics, IUGG2003, Sapporo, Japan, June 2003

GRAVITY GRADIENTS IN LIGO: A PROPOSAL FOR DATA ANALYSIS

DAVID GARRISON

University of Houston - Clear Lake, 2700 Bay Area Blvd., Houston TX 77058, USA
E-mail: garrison@cl.uh.edu

GABRIELA GONZÁLEZ

Department of Physics and Astronomy, Louisiana State University,
202 Nicholson Hall, Baton Rouge LA 70803
E-mail: gonzalez@lsu.edu

We propose a method to analyze seismic noise data to bound the influence of gravitational gradients affecting the sensitivity of gravitational wave detectors. We present results obtained with data taken at the LIGO Hanford Observatory. The data shows that the method is useful, and also suggests local sources of gravitational gradients.

1. Introduction

Seismic activity can generate two types of noise in a gravitational wave interferometer such as LIGO[1], vibrational and gravity gradient noise. Vibrational noise can be filtered out mechanically at frequencies above 3 Hz. Gravity gradient noise is produced by the time-varying newtonian attraction of the earth on the suspended mirrors and is not filtered by seismic isolation[2,3]. The goal of this project is to develop a method of measuring and characterizing gravity gradient and non-gravity gradient noise caused by seismic activity. This information can then be used during the data analysis of gravitational wave signals.

In order to determine whether or not seismic activity in a certain frequency band may be the cause of gravity gradient noise, we use somewhat standard geological techniques[4]. We use two (or more) 3-axis seismometers at varying distances and then analyze the resulting data in order to determine whether or not we have found waves which exhibit the characteristics of density changing Rayleigh waves or Love waves.

2. Method

Using two or more seismometers $i = 1, 2...$, the amplitude of the seismic activity is found as a function of time and position $\vec{u_i}(\vec{x}, t)$ for each of the three directions. The Fourier Transform of the measurements is then calculated for each section of data in order to derive the amplitude as a function of position and frequency for each discrete time section $\vec{u_i}(\vec{x}, f)$.

Given $\vec{u}_i(\vec{x}, f)$, we can calculate the power spectral density $\vec{G}_i(\vec{x}, \omega)$, cross-correlation matrix $S_{ij}(\omega, \vec{x}, \vec{x}')$ and the coherence function $Coh_{ij}(\omega, \vec{x}, \vec{x}')$, where the averages are calculated over finite intervals of time T:

$$\vec{G}_i(\omega, \vec{x}) = \frac{2}{T}\langle|\vec{u}_i(\vec{x}, f)|^2\rangle$$
$$S_{ij}(\omega, \vec{x}, \vec{x}') = \frac{2}{T}\langle|\vec{u}_i^*(\vec{x}, f)\vec{u}_j(\vec{x}', f)|\rangle$$
$$Coh_{ij}(\omega, \vec{x}, \vec{x}') = \frac{|S_{ij}(\omega, \vec{x}, \vec{x}')|^2}{\vec{G}_i(\omega, \vec{x})\vec{G}_j(\omega, \vec{x}')} \tag{1}$$

In addition to the above quantities, we also use the ratio of the spectral densities, the anisotropy ratio $A(\omega)$ of the horizontal to vertical spectral densities and the angular pattern $\rho(\theta, \omega)$ of the seismic wave's distribution.

If the ratio of the spectral densities measured in both seismometers is independent of the distance between them and of their and orientation, the seismic signal is global and isotropic; if not it is caused by a local source. A coherence of greater than 0.5 for all distances implies a common origin of all noise sources. If the coherence is a function of distance, we can calculate a "coherence length" for the source. If the coherence is high for all distances, we can fit $S_{ij}(\omega, \vec{x}, \vec{x}')$ to a Bessel function or to a cosine function, to find the velocity of the seismic wave.

The anisotropy ratio is used to determine wether or not the seismic waves may contain Rayleigh modes. From the horizontal motion measured in the seismometers, an angular pattern for each seismometer can be found, and local sources of noise can be identified.

3. Results

Data was taken at the Hanford Washington LIGO site and later analyzed using the methods described in the previous section. This was done at both the corner and east end stations. The period of each measurement ranged from ten to twenty minutes and the distance between seismometers was between 40 cm and 38 m.

By comparing the power spectra at different times we see that the noise is stationary except for a few brief periods of seismic disturbances caused by external sources. The ratio of power spectra imply that most of the low frequency noise is global while the high frequency noise seems to be caused by local sources. The coherence between data is good at low frequencies and tends to drop off quickly as frequency increases. The correlation function suggests that the wave velocity is on the order of a few hundred meters per second above 2 Hz. This is consistent with what we would expect from Rayleigh waves. The anisotropy ratio results also show evidence of Rayleigh waves above 1 Hz.

The angular pattern calculation tells us that the local waves in the east end station tend to move in the north-south direction while those in the corner station tend to move east-west. This may have something to do with the geometry of the concrete foundation which the building is built on. Finally the correlation between the horizontal and vertical directions seems extremely high, Z/H = 4, for a Rayleigh wave. This suggests that there may be an SV-up wave[5]. A wave which propagates horizontally on a vertical layer medium with a large vertical motion but no subsurface compressions.

Using the technique outlined in this paper and a standing array of seismometers at each of the LIGO sites, it will be possible to coordinate this analysis with the analysis data taken by the interferometers. This would allow us to quantify the limitations to gravitational wave detection presented by gravitational gradients.

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References

1. Abramovici et. al, Science **256**,325 (1992). See also information on http://www.ligo.caltech.edu
2. Peter R. Saulson, *Phys. Rev. D* **30**, 732 (1984)
3. M Beccaria et al, *Class. and Quan. Grav.*, **15**,3339 (1998)
4. Strobach K., *Bull. Seism. Soc. Am.***55**,365 (1965).
5. Scott A. Hughes, Kip S. Thorne, *Phys.Rev. D***58** (1998) 122002

TESTING BINARY BLACK HOLE CODES USING COSMOLOGICAL SPACE-TIMES

DAVID GARRISON

University of Houston - Clear Lake, 2700 Bay Area Blvd., Houston TX 77058, USA
E-mail: garrison@cl.uh.edu

In order to further our understanding of the instabilities which develop in numerical relativity codes, I study vacuum solutions of the cosmological type (T^3 topology). This involves testing the numerical code using the following non-trivial periodic solutions; Kasner, Gowdy, Bondi and non-linear gauge waves. I look for constraint violating and gauge mode instabilities and study numerical convergence. I will discuss techniques developed to investigate the stability properties of the numerical code.

1. Introduction

The goal of this project is to develop a technique of testing the stability of numerical relativity codes which may utilize any system for evolving Einstein's Equations. For the results presented here, I use this technique to test a Cactus Thorn[1,2] based on the standard ADM evolution system using iterated Crank–Nicholson as a time integrator.

An unstable system is classically defined as one where any perturbation of the exact solution diverges as time increases until the numerical solution no longer depends on the initial data. Because an evolution can survive almost infinitely long before this happens, this definition is not always practical. For this reason, I begin by using a more precise definition of a stable or unstable numerical evolution. I refer to an evolution run as type 1 unstable if 1) the solution becomes discontinuous, 2) the space-time becomes unphysical, 3) the L2 norm of the numerical errors grows exponentially or 4) the L2 norm of the constraint errors grow exponentially. A type 1 unstable evolution is therefore one which appears obviously unstable to the casual observer. I refer to a system as type 2 unstable if it is defined as unstable according to the Lax–Richtmyer theorem[3], which means that the numerical errors are not reduced with increasing resolution. If an evolution system can consistently produce both type1 and type 2 unstable modes, we can consider that system to be numerically unstable. Meanwhile a stable evolution is one which can be defined as neither type 1 or type 2 unstable.

2. The Test

In order to develop an effective test for different numerical evolution systems it is important to first eliminate all possible causes of numerical instabilities outside of the evolution system itself. I use cosmological spacetimes in order to avoid black hole type singularities. This eliminates the need for singularity avoiding slicing conditions or special excision techniques. I also use periodic boundary conditions to avoid errors and reflections at the boundaries. Given a space-time with these properties, I try to stimulate gauge and constraint violating type 1 unstable modes and look for type 2 instabilities.

The general form of a diagonal four metric which lacks singularities and is periodic can be written as,

$$ds^2 = -\alpha(x,t)^2 dt^2 + e^{M(x,t)} dx^2 + e^{N(x,t)} dy^2 + e^{P(x,t)} dz^2. \tag{1}$$

With the appropriate choice of $\alpha(x,t)$, this basic metric can be modified to form any periodic diagonal solution to Einstein's equations. In the case where $\alpha = 1$, M = N = P = 0, the result is simply a flat space metric. If M, N and P are constant in x but not in time and $\alpha = 1$, the result is a Kasner spacetime. If α, M, N and P are periodic in x but not in time we get the Gowdy spacetime. If N and P are periodic in x and t but M = 0 and $\alpha = 1$, the result is a plane gravitational wave. This spacetime can only be periodic for the linearized form of Einstein's equations and is then called a Bondi Wave. The last possibility is that flat space is coordinate transformed so N = P = 0 and M and α are both periodic in x and time. The result is what appears to be a longitudinal gravitational wave or "gauge" wave.

3. Results

The linear systems, Kasner and Bondi, became type 1 unstable and produced constraint violating modes when a poor choice of lapse was introduced. The nonlinear systems, Gowdy and "gauge" wave, became type 1 unstable when large amplitude waves were used within the solution. Every run which became type 1 unstable also proved to be type 2 unstable. Only flat space-time evolutions appeared to be unconditionally stable. A Fourier analysis of the unstable runs seems to suggest that the instabilities may be caused by the increasingly large relative amplitudes of high frequency modes as resolution is increased.

4. Conclusion

The ADM evolution system appears to produce constraint violating modes when a poor choice of gauge is made. This system also produces gauge modes when large nonlinearities are introduced. Because of this, the ADM system is unlikely to be suitable for evolving binary black hole systems where different gauge choices and large nonlinearities may become essential. In order to determine which system should be used for binary black hole evolutions, I propose that these tests be used on some of the new hyperbolic numerical evolution systems[4,5,6,7,8].

5. Acknowledgements

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References

1. The Cactus Development Team. *The Cactus Computational Toolkit.* http://www.cactuscode.org.
2. Erik Schnetter. *The Maya Project: General Concepts*, 2000. http://www.eps.org/aps/meet/APR01/baps/abs/S1500041.html.
3. Lloyd N. Trefethen. Finite Difference and Spectral Methods for Ordinary and Partial Differential Equations. http://web.comlab.ox.ac.uk/oucl/work/nick.trefethen/pdetext.html.
4. T. W. Baumgarte and S. L. Shapiro. *Phys.Rev.D59:024007*, 1999.
5. S. Frittelli and O. Reula. *J.Math.Phys.40:5143-5156*, 1999.
6. P. Laguna and D. Shoemaker. gr-qc/0202105.
7. L. E. Kidder, M. A. Scheel, and S. A. Teukolsky. *Phys.Rev.D64:064017*, 2001.
8. M. Shibata and T. Nakamura. *Phys.Rev.D52:5428-5444*, 1995.

Development of a Comprehensive Physics Program at a non-traditional upper-level undergraduate and graduate small university

David Garrison

Abstract.
As more students and universities become involved in life-long learning, it will become more important to develop physics programs which can cater to nontraditional students. We describe the development of a Physics Master's degree program at the University of Houston Clear Lake. This is a non-traditional university which only serves students at the Junior, Senior and Master's degree levels and had not previously developed a physics program throughout its thirty-year history. We show how we were able to establish a graduate physics degree in less than three years using community resources and effective marketing techniques although no significant university funds were committed towards the development of this program.
PACS numbers: 01.40.-d,01.40.Fk,01.40.G

Introduction

The University of Houston Clear Lake (UHCL) is a non-traditional upper-level undergraduate and graduate university. The university was established as a commuter campus for the University of Houston system, southeast of Houston near Clear Lake and the Johnson Space Center (JSC). About half of the university's students take classes part-time. The average age of undergraduates is thirty years old while the average age of graduate students is thirty-two. Beginning in the fall of 2002, we began the development of the university's first physics degree, an M.S. in Physics. The degree officially began operations in fall of 2004. Currently, the program teaches approximately forty to fifty graduate students per semester and graduated seven majors within its first year of its operation. Unlike most physics programs, almost all of our classes are offered in the evenings and a majority of our students work full-time. Many of these students have backgrounds in engineering and some hold advanced degrees. There is not currently an undergraduate Physics degree being offered at UHCL.

History

The University of Houston Clear Lake was founded in 1974 near NASA JSC in Houston Texas. During the planning stages, it was decided that the university would have no freshmen, sophomore or Ph.D. students. Most of the university's undergraduates transfer from local community colleges while many of its master's degree students work full-time in the local aerospace and petroleum industries. As of 2005, the university had yet to employ a provost or president with a background in science or engineering. Also, although the University is located in the heart of Houston's high-tech sector, the School of Science and Computer Engineering is the smallest of the university's four schools.

UHCL was originally structured with interdisciplinary divisions as opposed to large academic departments. The division handles many of the functions traditionally supported at the department level. Within these divisions there are several academic programs.

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One of the original programs within the Natural Science division was the Physical Sciences program, a precursor to our Physics program. A major drawback to interdisciplinary programs, such as Physical Sciences, is that they do not always allow for advanced specialized research in a particular discipline or for the hiring of a critical mass of faculty within a specific discipline. As a result, by 2002, the Physical Sciences program, which originally consisted of faculty with backgrounds in Physics, Astronomy, Environmental Science, Geology and Chemistry, was reduced to a single faculty member whose focus was Planetary Science.

Many problems existed in the Physical Sciences program in 2002. Several students applied for the program but never attended classes. These students were given incentives at their place of employment for being enrolled in a technical master's degree program, but received little or no incentive to graduate. Advanced courses in physics were either not being taught or were only taught at a very low level because there was no requirement for students to take core physics courses. The core courses were not being taught regularly. There was very little on-campus research in Physics or Astronomy. Enrollment was declining and student satisfaction was low. As a result, the program was on the verge of either being closed down or dramatically changed.

Curriculum Development

The first challenge in developing a Physics program was to find a focus. An online survey was developed and distributed to potential students in the Aerospace and Petrochemical industries as well as to students at the local community colleges. Distribution was handled using a combination of electronic newsletters and direct contact with human resources personnel at each institution. The strongest response from industry, both potential students and employers responded. They wanted a program that could prepare students with engineering backgrounds for Ph.D. study in Physics, Astronomy or related areas while at the same time being useful for broadening the technical backgrounds of practicing engineers. Because of this response we decided to forgo development of a Bachelors program and start with a Master of Physics degree. The Physical Sciences M.S. was to be phased out, as all its resources would be transferred to the new M.S. in Physics program. However, the B.S. in Physical Sciences remained and is being retooled to support the M.S. in Physics. We are currently in the process of expanding our undergraduate program to better serve students who are in need of preparation to enter the Physics M.S. program.

The most diifficult part of developing the curriculum for this degree was working within the restrictions of the part-time students. Almost all classes are taught in the evenings and group learning is often used to maximize the effectiveness of the students' time. Using the survey data, we developed a curriculum consisting of five core courses: Mathematical Methods in Physics 1, Classical Mechanics, Quantum Mechanics, Electrodynamics and Statistical Mechanics & Thermodynamics with advanced areas of study in Orbital Mechanics, Astronomy, Plasma Physics and Relativity. The degree consists of thirty-six credit hours providing a balance of core courses, advanced courses and research. Although we included both a thesis and non-thesis option, the majority of our part-time students (who make-up over ninety percent of the program's student body) choose the non-thesis option. The capstone experience for the non-thesis option consists of at least one semester of independent study research and a Research Project and Seminar class where students are taught how to write and publish scientific papers and give oral presentations of their research.

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Because of the immediate popularity of this program among working students, we developed a Professional Physics concentration focusing on the training of project managers. This plan of study uses the physics core to provide students with the broad technical background needed by project managers, while the Systems Engineering and Management programs provide business and organizational training. This concentration was developed thanks to a grant from the Council of Graduate Schools and the Alfred P. Sloan Foundation and follows the Professional Science Master's (PSM) degree standard.

Building Infrastructure

In order to function as a physics program we needed three things; students capable of contributing to research, research facilities and research projects. In 2002, very few resources existed in the Physical Sciences program. As the curriculum for the physics program was being developed and approved, we began training students to participate in research. The money to buy all the necessary research facilities was not available, so we had to build and develop them using freely available resources. External collaborators were not difficult to find due to our close proximity to JSC. However, JSC is primarily an operations center with very little fundamental physics research. We found that the best way to stimulate research collaborations and develop project ideas was by using seminars. This effectively made the UHCL Physics program a focal point for fundamental Physics and Space Science related research in the JSC community. The seminars then lead to research collaborations and became a powerful tool for recruiting students.

Recruiting Students

Recruiting students was done through both traditional and non-traditional means. As part of the needs assessment survey, respondents entered their email addresses to identify them as individual respondents. This became the basis for an electronic distribution list of information on the developing physics program. Whenever the physics faculty gave a seminar or talk, everyone in attendance give their email address for inclusion on the list. Over time the list grew to several hundred people and many of them eventually became students. We also advertised the program at face-to-face events such as open houses and educational fairs. We found that a clear majority of the people who eventually became students had some direct contact with our faculty before joining the program. Eventually, word-of-mouth from graduating or current students, became just as effective for recruiting new students. To a lesser extent we also used websites and print advertisements, such as brochures and posters. These were not nearly as effective as the face-to-face recruiting, because potential students in the program tended to have many questions, which could only be answered by program faculty. As a result of this recruiting effort, graduate enrollment in physics and astronomy grew from around ten to as many as fifty students per long semester.

Initiating Research

In order to initiate a research program, we had to develop our on-campus research facilities. As a Physical Sciences program, we only had one wet laboratory which was being used for planetary science research and a teaching lab which was being shared with the Biological Sciences program. We needed to build a modern research laboratory but lacked the financial resources to do so. In order to do this, we decided to focus all on-campus research in the program on theoretical and computational work. The physics program then partnered with a laboratory at JSC that did experimental plasma physics and we began planning for the development of a remote observatory. This was all done under the assumption that would not receive additional space or funding from the university for laboratory development in the near future.

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We built a computational physics lab, using the space formerly occupied by the planetary science lab. We utilized retired campus computers, now running Linux, as our primary computational architecture. We also acquired two Beowulf clusters, a 12-processor cluster built by a student and a 96-processor system donated by the Texas Educational Grid project.

Our part-time students work well in theoretical and computational research. They appreciate the flexibility that it gives them to work on research within the constraints of their schedules. This model also allows us the opportunity to build a synergistic team of faculty who can share equipment as well as ideas. Under the Physical Science program, students were more likely to do research on their own or with adjunct faculty while under the new Physics program they tend to work more with full-time faculty. This has resulted in a major improvement in the quality of the research being performed. Students are beginning to author or co-author research papers in refereed journals, something that was unheard of under the Physical Sciences program.

Discussion

So far the Physics program has been a major success in terms of enrollment growth, student satisfaction and research productivity. Although there was no significant initial financial commitment from the university to help with the development of the program, there has been an overall improvement in the quality of education. Given that UHCL is a historically non-technical university with limited financial resources does not make all this easy. The biggest problem the program faces is the lack of full-time faculty. Although enrollment has more than doubled and research activity as increased dramatically, we still have only four FTE faculty and rely very heavily on adjuncts to teach at all levels. Because of this, we worked on ways to use adjunct faculty from JSC and elsewhere to make up for our lack of full-time faculty. The result was only partially successful. As a result, we are currently searching for more full-time faculty.

Acknowledgments

We would like to acknowledge the support of the Council of Graduate Schools and Alfred P. Sloan Foundation for their support in developing the Professional Physics concentration. We would also like to acknowledge the support of Conoco Phillips and the Texas Educational Grid Project for the donation of much needed high-performance computing equipment for the program.

References

[1] UHCL Homepage, http://www.uhcl.edu
[2] UHCL Physics, http://sce.uhcl.edu/physics
[3] Professional Science Master's Degree, http://www.sciencemasters.com
[4] Texas Educational Grid Project, http://www.txgrid.org

David Garrison is Faculty Chair and Assistant Professor of Physics and Physical Sciences at the University of Huston , Clear Lakes. He can be reached via e-mail at Garrison@uhcl.edu

David Lynch either has forgotten or never needed to use the pre-computer format for figures submitted to journals: They were either handmade India-ink drawings or glossy photographs of those drawings. Every author had to pay a drawing shop or personally master the art. Computers are easier and cheaper, but enable authors to submit unusable figures. My favorite, from my experience as editor of *Bioelectromagnetics*, is the black-and-white version of a false color map, with both extremes (red and blue) appearing as black and the intermediate yellow showing as white. No editor or publisher can fix that.

Ben Greenebaum
(greeneba@uwp.edu)
University of Wisconsin–Parkside
Kenosha

Lynch replies: I was struck by David Couzens's thoughtful comments on the inherent stumbling blocks of change. When he asks "Does electronic publishing save money?" he goes on to recognize that "Time is money." But whose time and whose money? A scientist can choose to labor over a paper as long as he likes to get it right, using whatever tools he chooses. But then he is slapped in the face and told that his pains are all for naught unless he spends a lot of time—money—conforming to the publisher's scientifically irrelevant submission requirements. "Sorry, your scientific best isn't good enough because your font is wrong."

Has physics unknowingly suffered because the author of a worthy paper didn't have the time or financial resources to meet the publisher's self-enforced, self-serving formatting and submission requirements?

I recently self-published a book. In the past I would have gone to a major scientific publisher. But if I am going to be forced to meet the publisher's onerous formatting and style requirements, I might as well self-publish and do it my way. My hero in this regard is Lawrence N. Mertz (1930–2002), who bypassed the journal requirements by publishing summaries of his scientific work as paid advertisements in the *Journal of the Optical Society of America*.

David K. Lynch
(thule@earthlink.net)
Thule Scientific
Topanga, California

Serving nontraditional graduate students

According to a report from the National Center for Education Statistics,[1] the percentage of undergraduate students who attended college part-time grew from 28% to 39% between 1970 and 1999. This suggests a need for nontraditional graduate study as well. Still, few physics programs actively work with nontraditional graduate students. As more students and universities become involved in lifelong learning, developing physics programs that cater to nontraditional students will become more important. Many master's programs in business administration are already beginning to focus on nontraditional students; it's time for physics programs to do the same.

Instead of following the traditional path in which graduate students are recruited exclusively from undergraduate physics programs and are expected to attend full-time, the University of Houston–Clear Lake (UHCL) developed a program that focuses on part-time, nontraditional students. As a result, we can educate students who would not normally be able to complete a graduate physics degree because of nonacademic obligations.

A nontraditional upper-level undergraduate and graduate university, UHCL was established as a commuter campus for the University of Houston system. About half of its students take classes part-time. The average age of students is 30 years for undergraduates, and 32 for graduate students. In the fall of 2002, we began to develop the university's first physics degree, an MS. The program began operations in fall of 2004 and currently has 40–50 graduate students; seven MS degrees were awarded in 2005. However, unlike most physics programs, almost all of our classes are offered in the evenings, and a majority of our students work full-time.

We developed the physics MS program based on community interest as determined by an online survey of employers and potential students in the local aerospace and petrochemical industries. Overall, the respondents wanted a program that could prepare students with engineering backgrounds for PhD study in physics, astronomy, or related areas while broadening the technical backgrounds of practicing engineers. The most difficult part of developing the curriculum was working within the restrictions of the part-time students. Almost all of our classes are taught in the evenings, and many involve group learning. Although we included both thesis and non-thesis options in the curriculum, the majority of students choose the non-thesis option. The capstone experience for those students consists of at least one semester of independent study research and a class in writing and publishing scientific papers and giving oral presentations. Our part-time students also seem to prefer theoretical and computational work that better allows them to schedule research time. Experimental work is typically done in collaboration with labs at the neighboring Johnson Space Center, where many of our students work full-time.

Because of the immediate popularity of this program among working students, we developed a professional physics sub-plan for the training of technical managers. The plan combines the physics core with business and organizational training from UHCL's systems engineering and management programs.

Overall, the response to the physics MS program has made it clear that a lot of people would love to pursue an advanced degree in physics but can only do so as nontraditional students. In physics we tend to follow an old model that expects students to work continuously from bachelor's degree through graduate school and postdoctoral study. Those who digress from the standard path are accused of leaving physics and are rarely welcomed back. In the wake of September 11, and as relative enrollments in science, mathematics, and engineering continue to decline nationwide, perhaps it's time to consider a new approach.

Reference

1. National Center for Education Statistics, http://nces.ed.gov/programs/coe/2002/analyses/nontraditional/index.asp.

David Garrison
(garrison@uhcl.edu)
University of Houston–Clear Lake
Houston, Texas

Why no Einstein's laws?

Since my undergraduate days, I have been puzzled by the fact that we have Newton's laws of motion but only Einstein's theory of special relativity. We have finished celebrating the 100th anniversary of the publication of the theory of special relativity, and it seems to me that after a century of validation, it's time to rename it as more than just a theory.

I propose that we, as physicists, define a set of Einstein's laws, just as we have Newton's laws, Coulomb's law, or Faraday's law. I begin the discussion by offering the following three laws:

▶ The laws of physics are identical in

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Numerical analysis of simplified relic-birefringent gravitational waves

David Garrison and Rafael de la Torre

Physics Department, University of Houston Clear Lake, 2700 Bay Area Blvd, Houston, TX 77058, USA

E-mail: garrison@uhcl.edu

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Abstract

Some theories suggest that gravitational waves created in the early universe may be observable with future gravitational wave interferometers. As a result, identifying the characteristics of these gravitational waves and their corresponding power spectrums at different epochs has become an important area of study. The general solutions to these equations can become quite complex, making the task of obtaining analytical results a difficult one without simplifying assumptions. Using numerical techniques, a general solution to the birefringent gravitational wave equation is explored. This form of the gravitational wave equation is partly composed of a mode function that resembles the Coulomb wave equation from quantum mechanics, which has been explored computationally in the past. An attempt is then made to numerically solve these equations and the corresponding power spectrum for the present universe. Current/planned observatories such as LISA and Advanced LIGO can test these results.

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1. Introduction

Ever since Edwin Hubble discovered that the universe is expanding, there has been a concerted effort in the scientific community to understand the physical processes involved. Inevitably, study of the expanding universe usually leads to the investigation of the very early stages of expansion after the big bang. Included in these important epochs is the inflation stage, in which an extremely rapid expansion of the universe occurred over an infinitesimal amount of time. First proposed by Guth [1], the existence of such a stage helps solve 'problems' encountered when considering the standard big-bang model. However, the corresponding abstract theoretical elements involved with inflation raise many more questions for items such as quantum-gravitation, vacuum energy and the Higgs field/particle to name a few.

Several cosmological theories, such as inflation, suggest that the early universe produced gravitational waves. If such waves did result, then relics of gravitational radiation created during this stage should still be present in the current universe. The phenomena can be considered analogous to the CMB, where EM radiation from the surface of last scattering has remained and expanded with the universe until the present. As with the detection of the CMB, observation of relic gravitational waves would also provide direct evidence of the existence of the big bang and provide a test of several different cosmological theories. Detecting these relic waves would provide insight into the earliest frames of time after the big bang and begin to answer some of the many questions related to the physics of the early universe and its impact on the current epoch. Similar to the probes that detected the CMB, existing and planned observatories, such as LISA and LIGO, will attempt to detect relic gravitational waves. An important item required for the detectors is the expected relationship between amplitude and frequency for relic gravitational waves, given by a power spectrum.

The theory related to power spectra for standard relic waves has been extensively addressed in [2, 3]. A major assumption in these references is that the polarity of gravitational waves does not vary. However, recent work by the authors of [4, 5] shows that the left- and right-handed polarities of these waves may impact the nature of the early universe and should be considered further. As defined in [4], birefringent (BRF) gravitational waves exist due to cosmological birefringence and consist of left- and right-handed components that may have played a role in leptogenesis. This birefringence is believed to result from modifications of general relativity such as Chern–Simons gravity [6, 7]. Therefore, the detection of BRF waves would provide insight into the physics of the very early universe and alternative theories of gravity at the quantum scale. As with the standard waves, a power spectrum for birefringent waves can also be determined. Unlike the efforts in [2, 8], the BRF spectrum has never been expanded computationally in order to determine the expected signals where LISA and LIGO may observe these waves.

This paper documents the initial computation of the spectrum at the current epoch of the universe for the simplified form of BRF gravitational wave equations. The results presented describe the level of modification to the power spectrum for standard waves. To arrive at the simplified birefringent gravitational wave spectrum, the theory behind the general form of the relic gravitational wave spectrum and its associated mode functions is addressed in section 2. Section 3 focuses on relic gravitational wave theory by developing the general expressions in terms of birefringence and employing simplifying assumptions for this initial look at the spectrum. As a follow-on to this section, section 4 verifies that these equations reduce to those for standard relic gravitational waves when birefringence is ignored. In section 5, the methods used in [2, 8] are revisited to explain how the relic waves created during inflation are red-shifted to the current epoch. Once the necessary components of the theory are illustrated, details on the numerical approach are covered in section 6, including the applicable ranges of the key variables and the numerical approaches investigated and used to derive the modified power spectrum. Section 7 shows the resulting spectrum for the simplified BRF waves and section 8 discusses conclusions for the results obtained.

2. Relic gravitational wave spectrum

The starting point for the formulation of the power spectrum for general relic waves is the FRW metric given by

$$\mathrm{d}s^2 = -(1+2\varphi)\,\mathrm{d}t^2 + \omega_i\,\mathrm{d}x^i\,\mathrm{d}t + a(t)[((1+2\psi)\delta_{ij} + h_{ij})\,\mathrm{d}x^i\,\mathrm{d}x^j], \tag{1}$$

where the perturbation terms (φ, ψ, ω_i and h_{ij}) have been included. This metric is used since relic gravitational waves produced during inflation result in tensor perturbations (h_{ij}) to the spacetime metric. Ignoring the scalar and vector perturbations and changing the independent variable to conformal time (η) instead of cosmic time (t) reduces equation (1) to

$$\mathrm{d}s^2 = a^2(\eta)[\mathrm{d}\eta^2 - (\delta_{ij} + h_{ij})\,\mathrm{d}x^i\,\mathrm{d}x^j]. \tag{2}$$

The equation for the power spectrum can be deduced by treating the contracted tensor perturbations as eigenvalues of a quantum mechanical operator that operates on the vacuum state. This can be expressed as

$$\langle 0|\hat{\Omega}|0\rangle = \langle 0|h_{ij}(n,\eta)h^{ij}(n,\eta)|0\rangle = \left[\frac{C}{\pi}\right]^2 \frac{1}{2}\int_0^\infty n^2 \sum_p |h_p(\eta)|^2 \frac{\mathrm{d}n}{n}. \tag{3}$$

In equation (3), n refers to the dimensionless angular wave number and p refers to the left- and right-handed polarities of the gravitational waves. It can be shown from equation (3) that the mean-squared amplitude of the gravitational waves is

$$h^2(n,\eta) = \left[\frac{4l_{\mathrm{PL}}}{\sqrt{\pi}}n\right]^2 \frac{1}{2}\sum_{p=L,R} |h_p(\eta)|^2. \tag{4}$$

The square root of equation (4) will provide the root-mean-squared (RMS) amplitude of a gravitational wave for a specific wave number. An item of importance in equations (3) and (4) is the mode function, denoted by $h_p(\eta)$. This function is the major component of the gravitational wave spectrum, and its determination at a specific η near the end of inflation is the only item requiring computation in order to define the spectrum. Also note the role of polarity in the mode function. The separate polarities involved in the BRF equations should result in different RMS amplitudes for specific wave numbers when compared to the standard model. This should result in the anticipated modification to the standard power spectrum due to birefringent gravitational waves.

To complete the presentation of the power spectrum, some final equations for standard waves are shown. When the polarity is assumed equivalent [2], equation (4) becomes

$$h(n,\eta) = \left[\frac{4l_{\mathrm{PL}}}{\sqrt{\pi}}n\right]|h(\eta)|. \tag{5}$$

Using the relation $n_{\mathrm{H}} = 4\pi$ specified in [6], (5) becomes

$$h(n,\eta) = 8\sqrt{\pi}\,l_{\mathrm{PL}}\frac{n}{n_{\mathrm{H}}}|h(\eta)|. \tag{6}$$

The term n_{H} is the wave number that corresponds to a wavelength that is the size of the current Hubble radius. Reference [2] shows that (6) can be expressed in a convenient form shown to be

$$h(n,\eta) = 8\sqrt{\pi}\,l_{\mathrm{PL}}\frac{b}{l_o}\left(\frac{n}{n_{\mathrm{H}}}\right)^{(2+\beta)}. \tag{7}$$

The variable b is the power-law inflation parameter with -2 corresponding to the de Sitter universe and b is a constant in terms of β defined by

$$b = \frac{2^{[2+\beta]}}{|1+\beta|^{[1+\beta]}}. \tag{8}$$

l_0 is a constant that denotes an arbitrary Hubble radius during inflation. The beauty of (7) is that for $\eta \to 0$, it reduces the determination of the spectrum to a ratio of wave numbers. The exception to this is for the limiting case of a de Sitter universe. In this case, the spectrum is defined irrespective of the ratio. Although (7) simplifies the computation of the spectrum for certain scenarios, a general solution to the mode function and its components is required for cases that do not meet the condition of η noted above.

The mode function is described in (4) given by [5]

$$h_p(\eta) = \frac{g_p(\eta)}{a_p(\eta)}. \tag{9}$$

Equation (9) is composed of the gravitational wave equation $g_p(\eta)$ and effective scale factor $a_p(\eta)$ during inflation. This effective scale factor results from a correction to the standard scale factor $a(\eta)$ due to cosmological birefringence [5], given by

$$a_p = a(\eta)\sqrt{1 - \lambda_p 2\theta n\eta}. \tag{10}$$

The $\lambda_p\theta$ term in equation (10) is the birefringence parameter that accounts for this form of gravitational wave. Specifically, θ is composed of quantum-gravitational, scalar field and string theory terms and is defined in [4] and given by

$$\theta = -\frac{NH^2}{2\pi^2 M_{\mathrm{Pl}}^2}\sqrt{2\varepsilon}. \tag{11}$$

N and M_{pl} are composed of quantum-gravity and string theory terms, while ε is the slow-roll parameter. λ_p is simply defined as +1 and −1 for right-handed and left-handed waves, respectively. The scale factor during inflation is characterized by power-law inflation and is denoted as

$$a(\eta) = l_o|\eta|^{1+\beta} \quad -\infty \leqslant \eta \leqslant \eta_{iz}; \quad -2 \leqslant \beta \leqslant -1. \tag{12}$$

In equation (12), η_{iz} is the conformal time at the transition between inflation and the z-stage reheating epoch [8]. Values of β greater than the lower limit of −2 account for slow-roll inflation [9]. Equations (9)–(12) provide a straightforward approach to determine the denominator of the mode function once the key variables are defined. Therefore, the gravitational wave equation $g_p(\eta)$ is the variable in the mode function that requires special consideration.

3. Relic-BRF gravitational wave theory

The gravitational wave equation for BRF waves can be found in [5] and is given by

$$\frac{\mathrm{d}^2}{\mathrm{d}\eta^2} g_p + (n^2 - \mathrm{Veff}_p) g_p = 0. \tag{13}$$

This is simply the expression for a 1D harmonic oscillator in an effective potential, Veff_p. As with all 1D harmonic oscillators, the form of the effective potential is the key driver in shaping the form of the general solution. In the case of BRF gravitational waves, the general form of the effective potential is given by

$$\mathrm{Veff}_p = \frac{a_p''(\eta)}{a_p(\eta)}. \tag{14}$$

Taking equation (10) and substituting it into equation (14), we obtain a general effective potential of the form

$$\frac{a_p''(\eta)}{a_p(\eta)} = \frac{a''(\eta)}{a(\eta)} + \lambda_p \frac{2(1+\beta)}{\eta}\frac{n\theta}{(1-\lambda_p 2n\theta\eta)} + \frac{(n\theta)^2}{(1-\lambda_p 2n\theta\eta)^2}. \tag{15}$$

Using (12), the ratio of scale factor terms in (15) can be expressed as

$$\frac{a''(\eta)}{a(\eta)} = \frac{\beta(1+\beta)}{\eta^2}, \tag{16}$$

with the effective potential becoming

$$\frac{a_p''(\eta)}{a_p(\eta)} = \frac{\beta(1+\beta)}{\eta^2} + \lambda_p \frac{2(1+\beta)}{\eta} \frac{n\theta}{(1-\lambda_p 2n\theta\eta)} + \frac{(n\theta)^2}{(1-\lambda_p 2n\theta\eta)^2}. \tag{17}$$

For this initial look at the spectrum, it was determined that a simplified form of the BRF gravitational wave equation should be investigated. This was performed to obtain preliminary results for the spectrum and to refine the numerical approach ultimately used. Also as specified above, the effective potential shapes the general solution of the gravitational wave equation. Therefore, a simplified form of the potential leads to more typical solutions for the 1D harmonic oscillator. The simplification employed was to minimize the terms in the denominator of the form $(1 - \lambda_p 2n\theta\eta)$, by setting $n\theta|\eta| \ll 1$. Therefore, the effective potential simplifies to

$$\mathrm{Veff}_p = \frac{a_p''(\eta)}{a_p(\eta)} = \frac{\beta(1+\beta)}{\eta^2} + \lambda_p \frac{2(1+\beta)n\theta}{\eta} + (n\theta)^2. \tag{18}$$

Substituting equation (18) into (13) results in the ODE for simplified birefringent gravitational waves

$$\frac{\mathrm{d}^2}{\mathrm{d}\eta^2} g_p + \left(n^2 - \frac{\beta(1+\beta)}{\eta^2} - \lambda_p \frac{2(1+\beta)n\theta}{\eta} - (n\theta)^2\right) g_p = 0. \tag{19}$$

Note that when $\beta = -2$ and a left-handed wave is considered ($\lambda_p = -1$), (19) reduces to equation (19) in [4]. To obtain a general solution, a change of variable was performed with

$$z = 2\mathrm{i}n\eta\sqrt{1-\theta^2}. \tag{20}$$

Using equation (20), (19) is converted to an ODE of the form

$$\frac{\mathrm{d}^2}{\mathrm{d}z^2} g_p + \left(-\frac{1}{4} + \lambda_p \frac{|(1+\beta)\theta/\sqrt{\theta^2-1}|}{z} + \frac{\frac{1}{4} - \left|\beta + \frac{1}{2}\right|^2}{z}\right) g_p = 0. \tag{21}$$

Setting

$$\kappa_p = \lambda_p |(1+\beta)\theta/\sqrt{\theta^2-1}| \tag{22}$$

and

$$\mu = \beta + \tfrac{1}{2} \tag{23}$$

converts equation (21) into the Whittaker differential equation [10] given by

$$\frac{\mathrm{d}^2}{\mathrm{d}z^2} g_p + \left(-\frac{1}{4} + \frac{\kappa_p}{z} + \frac{\frac{1}{4} - \mu^2}{z}\right) g_p = 0. \tag{24}$$

Solutions to equation (24) are a linear combination of the Whittaker functions ($M_{\kappa_p \mu}$ and $W_{\kappa_p \mu}$)

$$M_{\kappa_p,\mu}\left(\mu + \tfrac{1}{2} - \kappa_p, 2\mu + 1, z\right) + W_{\kappa_p,\mu}\left(\mu + \tfrac{1}{2} - \kappa_p, 2\mu + 1, z\right). \tag{25}$$

Therefore, the general solution to equation (24) in terms of η is given by

$$\begin{aligned} g_p(\eta) = {} & C_{1B} M_{\kappa_p,\mu}(\beta + 1 - \kappa_p, 2\beta + 2, 2\mathrm{i}n\eta\sqrt{1-\theta^2}) \\ & + C_{2B} W_{\kappa_p,\mu}(\beta + 1 - \kappa_p, 2\beta + 2, 2\mathrm{i}n\eta\sqrt{1-\theta^2}). \end{aligned} \tag{26}$$

As described in [10], this solution can be expanded in terms of confluent hypergeometric series resulting in

$$g_p(\eta) = C_{1B}\,\mathrm{e}^{-\mathrm{i}n\eta\sqrt{1-\theta^2}}\left(2\mathrm{i}n\eta\sqrt{1-\theta^2}\right)^{1+\beta}\,{}_1F_1\left(\beta+1-\kappa_p; 2\beta+2; 2\mathrm{i}n\eta\sqrt{1-\theta^2}\right)$$
$$+ C_{2B}\,\mathrm{e}^{-\mathrm{i}n\eta\sqrt{1-\theta^2}}\left(2\mathrm{i}n\eta\sqrt{1-\theta^2}\right)^{1+\beta}\,{}_2F_0\left(\beta+1-\kappa_p, \tfrac{3}{2}-\left|\beta+\tfrac{1}{2}\right|-\kappa_p; -1/2\mathrm{i}n\eta\sqrt{1-\theta^2}\right). \quad (27)$$

Just as the effective potential shapes the form of the general solution, the behavior of this function at certain points defines the boundary conditions that can be used to determine the constants C_1 and C_2. Examination of equation (18) shows that for $n \ll \mathrm{Veff}(\eta \to 0)$, the effective potential becomes

$$\mathrm{Veff}_p \to \frac{\beta(1+\beta)}{\eta^2}, \quad (28)$$

with the general solution approaching

$$g_p(\eta) \to C_{p1}\eta^{1+\beta} + C_{p2}\eta^{-\beta}. \quad (29)$$

This corresponds to very small conformal times during the end of inflation, which is a proper assumption. For small values of η, the second term is much less than the first. This further reduces equation (29) to

$$g_p(\eta) \to C_{p1}\eta^{1+\beta}. \quad (30)$$

To make (27) match (30), the behavior of the confluent hypergeometric series requires that $C_2 = 0$, since $W_{\kappa_p\mu} \to \infty$ for small values of η. Therefore, the boundary conditions impose that the birefringent gravitational wave equation should be

$$g_p(\eta) = C_{1B}\,\mathrm{e}^{-\mathrm{i}n\eta\sqrt{1-\theta^2}}\left(2\mathrm{i}n\eta\sqrt{1-\theta^2}\right)^{1+\beta}\,{}_1F_1\left(\beta+1-\kappa_p; 2\beta+2; 2\mathrm{i}n\eta\sqrt{1-\theta^2}\right). \quad (31)$$

Inspection of (31) with $\eta \to 0$ shows that this equation does indeed reduce to the form of (30), given that ${}_1F_1 \to 1$ in this case [10].

4. Comparison between BRF and standard waves

In order to verify the simplified BRF gravitational wave equations, an effort was made to recover the equations for standard waves. In order to accomplish this, equations (18), (19), (22) and (31) were investigated with no birefringence ($\theta = 0$) and with constant polarity. These assumptions result in

$$\mathrm{Veff} = \frac{a''(\eta)}{a(\eta)} = \frac{\beta(1+\beta)}{\eta^2}, \quad (32)$$

$$\frac{\mathrm{d}^2}{\mathrm{d}\eta^2}g + \left(n^2 - \frac{\beta(1+\beta)}{\eta^2}\right)g = 0, \quad (33)$$

$$\kappa_p = 0, \quad (34)$$

$$g(\eta) = C_{1B}\,\mathrm{e}^{-\mathrm{i}n\eta}(2\mathrm{i}n\eta)^{1+\beta}\,{}_1F_1(\beta+1; 2\beta+2; 2\mathrm{i}n\eta). \quad (35)$$

Equations (32)–(35) were then compared to equations obtained for the standard equations in [2, 3, 8]. The first items inspected were the actual forms of the effective potential and the corresponding ODE. Comparison of the equations in these references with (32) and (33) above shows that they do match the standard model when birefringence is ignored. Equation (35) can be expressed in terms of the Bessel function by using the relation

$$ {}_1F_1\left(\mu+\tfrac{1}{2};2\mu+1;2\mathrm{i}z_j\right)=\frac{\Gamma(1+\mu)}{\left(\frac{1}{2}z_j\right)^{\mu}}\,\mathrm{e}^{iz}J_\mu(z_j), \tag{36} $$

which is defined in [10]. Converting (36) using the relation in (35), we obtain

$$ g(\eta)=C_{1B}\Gamma\left(\beta+\tfrac{3}{2}\right)2^{2\beta+\frac{3}{2}}\,\mathrm{i}^{1+\beta}\sqrt{n\eta}J_{(\beta+\frac{1}{2})}(n\eta). \tag{37} $$

The general solution to the standard waves is composed of Hankel functions [2] and is given by

$$ g(\eta)=C_{H1}\sqrt{n\eta}H^{(1)}_{(\beta+\frac{1}{2})}(n\eta)+C_{H2}\sqrt{n\eta}H^{(2)}_{(\beta+\frac{1}{2})}(n\eta). \tag{38} $$

Similar forms are shown in [5, 8]. The appropriate selection of constants C_{H1} and C_{H2} expresses (38) in the form of Bessel functions, namely

$$ g(\eta)=C_{1j}\sqrt{n\eta}J_{(\beta+\frac{1}{2})}(n\eta)+C_{2y}\sqrt{n\eta}Y_{(\beta+\frac{1}{2})}(n\eta). \tag{39} $$

The boundary conditions $n^2 \ll$ Veff for the ODE that defines the standard gravitational wave equation are identical to the conditions for the BRF gravitational wave. Therefore, the standard equation also resembles (30) above and $C_2=0$ in (39), leaving the solution to the standard wave as

$$ g(\eta)=C_{1j}\sqrt{n\eta}J_{(\beta+\frac{1}{2})}(n\eta). \tag{40} $$

From inspection, (40) is identical to (37) if the constants are related by

$$ C_{1j}=C_{1B}\Gamma\left(\beta+\tfrac{3}{2}\right)2^{\beta+\frac{1}{2}}2\mathrm{i}^{1+\beta}. \tag{41} $$

The equality of (37) and (40) to the same equations in [2, 3, 8] verifies that the general solution for the simplified BRF gravitational wave equations is correct and reduces to the standard equation when birefringence and polarity are ignored.

The final item that remains is the determination of the constants C_{1j} and C_{1B}. As $n\eta\to 0$ in the Bessel functions contained in (37) and (40), the limited form of the Bessel function becomes [10]

$$ J_{(\beta+\frac{1}{2})}(n\eta)\approx\frac{\left(\frac{1}{2}n\eta\right)^{(\beta+\frac{1}{2})}}{\Gamma\left(\beta+\frac{3}{2}\right)}. \tag{42} $$

Substituting (42) into (40) we obtain

$$ g(\eta)=\frac{C_{1j}n^{(1+\beta)}}{\Gamma\left(\beta+\frac{3}{2}\right)2^{(\beta+\frac{1}{2})}}\eta^{(1+\beta)}. \tag{43} $$

Equation (43) can be shown to contain the scale factor $a(\eta)$ expressed in (12) by replacing C_{1j} with

$$ C_{1j}=C_{3j}l_0. \tag{44} $$

Therefore, (43) becomes

$$ g(\eta)=\frac{C_{3j}n^{(1+\beta)}}{\Gamma\left(\beta+\frac{3}{2}\right)2^{(\beta+\frac{1}{2})}}a(\eta)=C_{4j}a(\eta). \tag{45} $$

Recalling the relationship between $g(\eta)$ and the mode function defined by (9) and the fact that the effective scale factor reduces to the standard scale factor when birefringence and polarity are ignored, the mode function for the standard gravitational waves becomes

$$ h(\eta)=\frac{C_{4j}a(\eta)}{a(\eta)}=C_{4j}. \tag{46} $$

This equation illustrates the constant behavior of the mode function when $n^2 \ll$ Veff, with the behavior matching that of (30). Using this fact along with the behavior of the spectrum in this regime, (46) can be combined with (6) and set equal to (7) to determine the constant C_{4j}. Specifically,

$$h(n,\eta) = 8\sqrt{\pi} l_{\mathrm{PL}} \frac{n}{n_{\mathrm{H}}} |C_{4j}| = 8\sqrt{\pi} l_{\mathrm{PL}} \frac{b}{lo} \left(\frac{n}{n_{\mathrm{H}}}\right)^{(2+\beta)} \tag{47}$$

results in

$$C_{4j} = \frac{b}{lo} \left(\frac{n}{n_{\mathrm{H}}}\right)^{(1+\beta)}. \tag{48}$$

Back substitution shows the constant in the Bessel function of the standard equation to be

$$C_{1j} = b\Gamma\left(\beta + \frac{3}{2}\right) 2^{(\beta+\frac{1}{2})} \left(\frac{1}{n_{\mathrm{H}}}\right)^{(1+\beta)}, \tag{49}$$

and the constant in the Whittaker function of the BRF equation is given by

$$C_{1B} = b[2\mathrm{i}n_{\mathrm{H}}]^{-(1+\beta)}. \tag{50}$$

5. Red-shift of the RMS amplitude

Once the gravitational wave equation (31) and the mode function (9) are determined for a specific n and η, the results can be placed into (4) to derive the RMS amplitude of the spectrum at this time during inflation. Upon determining this amplitude, it is still necessary to red-shift the result to the desired epoch of the universe. In this case, the goal of this paper is to determine the spectrum at the present time. In order to achieve this, the method contained in [2] for standard gravitational waves will be applied to the BRF waves. In general, cosmological red-shift depends on the nature of the scale factor from when a gravitational wave was emitted until the time the wave was observed and is given by the relation

$$1 + z = \frac{\nu_e}{\nu_0} = \frac{n_e}{n_0} = \frac{a_{\mathrm{now}}(\eta)}{a_{\mathrm{then}}(\eta)}. \tag{51}$$

The terms ν_0 and n_0 correspond to the wave frequency and wave number when it was observed and ν_e and n_e are the wave frequency and wave number when it was emitted. As can be seen from (51), the way the universe expanded after the big bang has an impact on the frequency of the observed waves at a given time. This behavior can be determined by accounting for the form of the scale factor at different 'breakpoints' in the evolution of the universe. These breakpoints correspond to transitions between different eras and are shown in figure 1 for the standard model. Each breakpoint in figure 1 corresponds to the wavelength that equals the Hubble radius at the transition between the specific eras. The wave number, n, is shown due to its relation to wavelength.

The only item left is determining the appropriate red-shift correction to a specific set of wavelengths for a given era. This method is performed by applying the correction to wavelengths that fit within the ranges of wavelengths for a chosen era. The only exception is for wavelengths that are larger than the current Hubble radius. These waves are not corrected for red-shift since they are outside of this distance. The corrections for the different eras are as follows.

For wavelengths that corresponding to different stages of the universe, the red-shift correction applied to (4) is given by [2, 8]

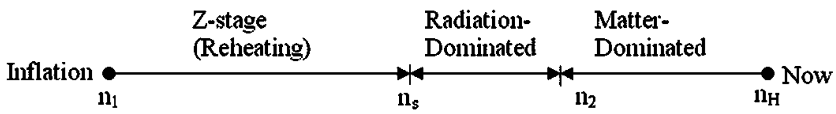

Figure 1. This figure expresses the red-shift corrections to the RMS amplitude at different stages of the universe. Not shown is the acceleration stage that begins after the matter-dominated era, as advocated by [8]. This stage will be addressed in a subsequent paper. Note that the lengths of the lines do not signify length of cosmic time for each era.

$$\left(\frac{n_{\mathrm{H}}}{n}\right)^2 \qquad \text{for} \quad n_{\mathrm{H}} \leqslant n \leqslant n_2, \tag{52}$$

$$\left(\frac{n_2}{n}\right)\left(\frac{n_{\mathrm{H}}}{n_2}\right)^2 \qquad \text{for} \quad n_2 \leqslant n \leqslant n_s, \tag{53}$$

$$\left(\frac{n_{\mathrm{H}}}{n}\right)^{1+\beta_S}\left(\frac{n_S}{n_{\mathrm{H}}}\right)^{\beta_S}\left(\frac{n_{\mathrm{H}}}{n_2}\right) \qquad \text{for} \quad n_s \leqslant n \leqslant n_1. \tag{54}$$

The term β_s is a specific power-law inflation parameter during the z-stage, which is highly dependent on the model used to characterize this epoch [8].

6. Numerical approach

Prior to investigating an adequate numerical approach to determine the power spectrum, the properties of key variables involved were defined. For the wave number, n, the direct relationship between wave number and frequency makes it convenient to specify the desired frequency in the numerical algorithms. Furthermore, the relation between these parameters and wavelength allows for the determination of limits that correspond to lengths of the eras illustrated in figure 1. A lower limit for frequency in these computations corresponds to super-Hubble horizon wavelengths. Since the spectrum is nearly constant in this regime, a convenient lower limit of 10^{-20} Hz was selected. For the higher limit, the relationship is expressed by [2]

$$b\frac{l_{\mathrm{pl}}}{l_0}\left[\frac{\nu}{\nu_{\mathrm{H}}}\right]^{2+\beta}. \tag{55}$$

This relation limits the upper frequency limit to $\leqslant 10^{10}$ Hz. The theoretical range for the power-law inflation parameter is $-2 \leqslant \beta \leqslant -1$. However, current theory [9] and even indirect WMAP observations [11] limit the upper value to ~ -1.9. Therefore, -2 and -1.9 were used in the computations to encompass the expected range of this parameter. This range is also important since values other than -2 correspond to the slow-roll approximation. The birefringence parameter, θ, was selected to correspond to linear solutions of the effective potential. According to [4], this corresponds to $\theta \leqslant 10^{-5}$ and basically supports the constraint for the simplified BRF waves. Values larger than this result in nonlinear effective potentials [5] and will not be treated in this paper. Keeping the specified constraint of $n\theta|\eta| \ll 1$, conformal time was selected to make this relation

$$n\theta|\eta| \to 10^{-4}. \tag{56}$$

To satisfy this relation, values of $|\eta| < 10^{-9}$ were selected.

The original goal for the numerical computation of BRF waves was to avoid the evolution of the general solution (31) and to solve the ODE for the 1D harmonic oscillator given by

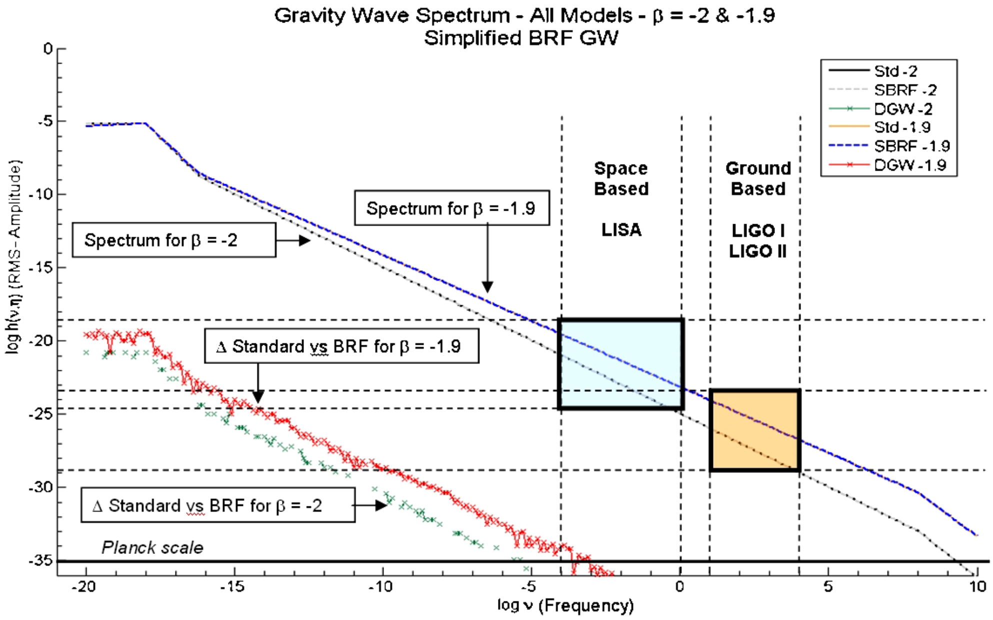

Figure 2. The BRF and standard power spectrums are shown and compared for $\beta = -2$ and -1.9. The expected amplitudes in the observation regions of LISA and LIGO are highlighted as well.

(This figure is in colour only in the electronic version)

(19). Various methods and approaches were initially investigated to attempt to solve this ODE, including the standard methods such as RK4, Taylor series and power series. Unfortunately, the extremely small values of $n\eta$ in the long wavelength region and the comparatively large step sizes required to evolve these methods from the initial values do not allow adequate numerical solutions. A brief look at more extensive approaches was also conducted. This included attempts at solving (21) using the methods discussed in [12]. Also, attempts were made to convert (21) into a Coulomb wave equation. Once in this form, methods outlined in [13] were attempted as well. The methods outlined in [12, 13] are promising and may eventually lead to numerical solutions of (21) with further modifications. Unfortunately, the preliminary attempts with these methods did not yield adequate results either. Therefore, a more direct approach was sought which involved the evolution of (31). Attempts are still planned to obtain a numerical solution to the ODEs in the long-term for this research.

Of the standard tools that exist, MATLAB was selected as the platform to perform this direct evolution given the tools and scripting capability that exist in the program. Given the complex nature of (31), the hypergeometric series functions present in MATLAB could not solve this equation. Special functions designed to solve these complex equations were imported from the MATLAB file exchange [14] and modified to fit the specific purpose of this research. In addition, the standard GW equations were determined with the built-in Bessel functions and compared to the results for the BRF waves. Once the numerical method to determine (31) was specified, the evolution approach was determined. First, (31) was determined using the functions described above. At each step, this solution was passed to (9) and the spectrum (4) was determined. After this result was obtained, the appropriate red-shift (52)–(54) was applied and the result at each step was stored in an array for plotting. As mentioned above, this process was also conducted for the standard waves by using (40).

7. Results

The power spectrum for the simplified BRF waves is shown in figure 2. The BRF and standard spectrums are shown for $\beta = -2$ and -1.9. In addition, the difference between the standard and BRF versions is also shown on this graph. As can be seen from figure 2, computational results show that the simplified BRF waves produce a spectrum that is not much different than the standard model. This is illustrated by the difference plot, which shows small differences that diminish beyond the Planck scale as frequency increases. In terms of observational opportunities, differences in the LISA range approach and exceed the Planck scale, implying that the spectra eventually converge.

8. Conclusions

Results from figure 2 indicate that the GW spectrum for simplified BRF gravitational waves is not significantly different than the standard GW spectrum at the present epoch. Therefore, differences between BRF and standard waves are not observable in the current universe for the constraint $n\theta|\eta| \ll 1$. Even though the differences are negligible, the fact that very similar solutions were obtained both in the analytic and numerical developments is encouraging and indicates that the equations for BRF theory are correctly formed. A conclusion related to the general form of the BRF wave equation is that an implicit limit of $|\eta| < 5 \times 10^6$ exists. This is obtained by examining the denominator of the effective potential in (15) for right-handed waves. The importance of this discovery is that several references, such as [1–3] also infer a conformal time near this value for the end of the inflation stage.

References

[1] Islam J 2001 *Introduction to Mathematical Cosmology* (Cambridge: Cambridge University Press)
[2] Grishchuk L P *et al* 2001 *Phys. Usp.* **44** 1–51
Grishchuk L P *et al* 2001 *Usp. Fiz. Nauk* **171** 3–59 (*Preprint* astro-ph/0008481)
[3] Baskaran D, Grishchuk L P and Polnarev A G 2006 *Phys. Rev.* D **74** 083008 (*Preprint* gr-qc/0605100)
[4] Alexander S, Peskin M and Sheikh-Jabbari M 2006 *Phys. Rev. Lett.* **96** 081301 (*Preprint* hep-th/0403069)
[5] Alexander S and Martin J 2005 *Phys. Rev.* D **71** 063526 (*Preprint* hep-th/0410230)
[6] Alexander S and Yunes N 2007 *Phys. Rev.* D **75** 124022 (*Preprint* 0704.0299)
[7] Smith T *et al* 2007 *Preprint* 0708.0001
[8] Zhang Y, Yuan Y, Zhao W and Chen Y 2005 *Class. Quantum Grav* **22** 1383–94 (*Preprint* astro-ph/0501329)
[9] Easther R, Greene B, Kinney W and Shiu G 2002 *Phys. Rev.* D **66** 023518
[10] Abramowitz M and Stegun I 1964 *Handbook of Mathematical Functions* (New York: Dover)
[11] WMAP http://map.gsfc.nasa.gov/
[12] Seaton M J 2002 *Comput. Phys. Commun.* **146** 225–49
[13] Michel N 2007 *Comput. Phys. Commun.* **176** 232–49 (*Preprint* physics/0702051)
[14] MATLAB File Exchange www.mathworks.com/matlabcentral/fileexchange

Gravitational Waves And The Evolution Of The Universe

David Garrison

University of Houston Clear Lake, Physics Department
2700 Bay Area Blvd., Houston, TX 77058

Abstract. As Cosmologists struggle to understand the evolution of the universe, an often overlooked element is the presence of gravitational radiation. During this presentation, I will show how gravitational waves may have had a significant impact on the evolution of our universe. The dominance of matter over antimatter, the formation of cosmic structures and the recently observed accelerated expansion of the universe may have all been caused by gravitational radiation. This hypothesis can be tested when the LISA mission attempts to detect gravitational waves from the early universe.

Keywords: Cosmology, Gravitational Radiation, Relativity
PACS: 47.75.+f, 95.30.Sf, 98.80.-k

INTRODUCTION

According to the Standard Model History of the Universe, electromagnetic radiation from the early universe was last scattered about 300,000 years after the big bang. Before this time, the universe was opaque and therefore, information from this period is not directly observable using electromagnetic radiation. Because of this, our knowledge of the first 300,000 years of universal evolution is derived by theory more than it is known from experimental observations. Although most theorists agree about what happened during most of the first 300,000 years, there is still some disagreement about what happened during the most critical part of cosmic evolution, the first fraction of a second. Part of this disagreement concerns the production of gravitational waves. While most theorists agree that quantum fluctuations, symmetry breaking and the rapid expansion of the early universe could have produced gravitational radiation, theorists tend to disagree as to if these waves had a large enough amplitude to have had any effect on the evolution on the universe or be observable using future gravitational wave detectors. Most theorists make the assumption that these waves are insignificant and therefore leave them out of their models for the evolution of the universe. In this presentation, I review several theories, which show how gravitational waves may have affected the evolution of the universe.

GRAVITATIONAL WAVES IN THE EARLY UNIVERSE

According to work by Grishchuk [5], the spectrum of gravitational waves from the early universe can be calculated by treating the system of quantum fluctuations in an expanding universe like a driven harmonic oscillator. Because the lowest allowed frequency is rapidly changing, this results in the parametric amplification of both scalar and tensor metric oscillations. The unique thing about this theory is that it does not rely on the assumption of a preset tensor/scalar ratio as is commonly used in cosmological theory. Grishchuk's theory therefore provides one of the only predictions for the spectrum of relic gravitational waves from the early universe. This theory also predicts that these relic gravitational waves should be observable with future gravitational wave interferometers such as LISA. So far the predictions of this theory are consistent with cosmic microwave background (CMB) observations. According to Grishchuk the spectrum of gravitational wave perturbations is given by

$$h(k,t) = 8\sqrt{\pi}\, l_{pl}\, |1+\beta|^{-(1+\beta)} k^{2+\beta} / l_0 . \tag{1}$$

Work by Alexander [1] uses gravitational waves to explain the asymmetry between matter and antimatter. This theory, called Gravi-leptogenesis, utilizes the three Sakharov Conditions: 1) baryon number is violated 2) CP is violated and 3) both violations are relevant when the universe is not in thermal equilibrium. This implies that the asymmetry in baryons may grow from an asymmetry in leptons. Therefore, Leptogenesis should lead to Baryogenesis. The Lepton number violation comes for a triangle anomaly, which relates fermion number current to a gravitational anomaly in the Standard Model.

$$\partial_\mu J_l^\mu = \frac{1}{16\pi^2} R\widehat{R} \tag{2}$$

The anomaly is a result of a difference in the number of left- and right-handed leptons, leading to a nonzero value for lepton current. This also results in birefringence in the polarization of left- and right-handed gravitational waves created in the early universe. To see how this affects the spectrum predicted by Grishchuk, see the paper by Garrison and de la Torre [4].

THE EFFECT OF GRAVITATIONAL WAVES ON OUR PRESENT UNIVERSE

Work by Kolb [6] uses gravitational waves to explain the recently observed accelerated expansion of the universe. He examines the "effective" scale factor resulting from both super-Hubble and sub-Hubble gravitational waves. He then calculates an "effective" deceleration parameter, which should correspond to the effect of these waves. According to Kolb, sub-Hubble gravitational waves cause a back-reaction, which results in an accelerated expansion without invoking some form of dark energy.

The author of this work feels that if these gravitational waves where strong enough to observer directly, cause matter—antimatter asymmetry and accelerate the expansion of the universe, it should have also had an impact on structure formation. Here, structure is defined as cosmic magnetic fields, density and temperature variations and secondary relic gravitational waves. The assumption is that gravitational waves in the early universe (around the time of nucleosynthesis) interacted with the primordial plasma field and resulted in Alfvén and magnetosonic modes [3]. These modes could then interact dynamically possibly resulting in turbulence and structure formation [8].

In order to test this theory the author has constructed a GRMHD computer code to model both the plasma field and the background space-time dynamically. Preliminary results show that isotropic gravitational waves acting on homogeneous plasma field (using a Minkowski background metric) results in pockets of increased density and therefore implies structure formation. While further work is needed, the ultimate test of the theories presented here will be the attempted observation of relic gravitational waves. If gravitational waves are found, there will be significant justification to revisit the part they play in our cosmological theories.

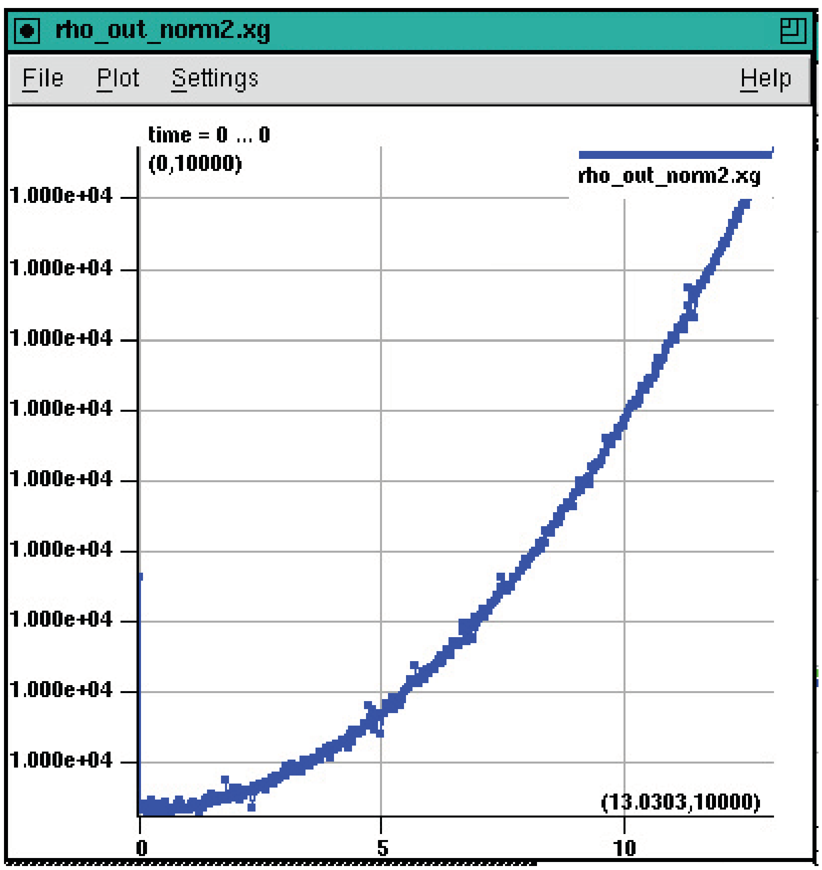

FIGURE 1. This figure shows the increase in density observed in an isotropic gravitational radiation field interacting with a homogeneous plasma field using a background Minkowski metric.

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REFERENCES

1. Alexander S and Martin J 2005 *Phys. Rev. D* **71** 063526
2. Allahverdi R and Drees M 2004 *Phys. Rev. D* **70** 123522 **[arXiv:hep-ph/0408289]**
3. Duez M D, Liu Y T, Shapiro S T and Stephens B C 2005 *Phys. Rev. D* **72** 024029
4. Garrison D and de la Torre R 2007 *Class. Quant. Grav.* **24** 5889
5. Grishchuk L P **arXiv:gr-qc/0707.3319**
6. Kolb E W, S. Matarrese and A.Riotto 2006 *New J. Phys.* **8**, 322 [**arXiv:astro-ph/0506534**]
7. Murayama H and Pierce A 2002 *Phys. Rev. Lett.* **89** 271601
8. Shebalin J V 2005 *Discrete & Continuous Dynamical Systems B* **5** 153-175

Numerical Cosmology: Building a Dynamical Universe

David Garrison

University of Houston Clear Lake, Physics Department
2700 Bay Area Blvd., Houston, TX 77058

Abstract. In this talk I discuss an often over-looked aspect of most cosmological models, dynamical interactions caused by gravitational waves. I begin by reviewing our current state of cosmological knowledge and gravitational waves. Then, I review work done to understand the nature of primordial magnetic fields. Finally, I combine the ideas of gravitational wave theory and plasma turbulence to develop a new theory of cosmic structure formation. Eventually, this work could help to explain the distribution of mass-energy in the observable universe as well as the anisotropies in the Cosmic Microwave Background without a heavy dependence on dark matter. This work seeks to explain how the dense, hot, turbulent plasma of protons, neutrons, electrons and neutrinos cooled in the presence of gravitational waves to form into structures and develop a statistical mechanics to describe this dynamical system.

Keywords: Cosmology, Gravitational Radiation, Plasma Physics
PACS: 47.75.+f, 95.30.Sf, 98.80.-k

INTRODUCTION

Our knowledge of how the universe evolved comes primarily from observations of large structures such as stars, galaxies, clusters and super-clusters of galaxies as well as from observations of the Cosmic Microwave Background (CMB). Based on these observations, the Standard Model of Cosmology was developed during the mid to late twentieth century. Some elements of this model include the existence of primordial metric perturbations and an early universe filled with a nearly homogenous and isotropic plasma field [16]. Many cosmological models relate density fluctuations and variations in the CMB to perturbations in the FRW metric at the time of recombination. These perturbations start off small and grow as a power-law with time as the competing forces of universal expansion and gravitational attraction affect their growth [16]. Work by Kodama and Sasaki [14], Sachs and Wolfe [23], and Mukhanov, Feldman and Brandenberger [16] all showed how metric perturbations could cause density perturbations in a hydrodynamic fluid. Unfortunately, they (and almost every author who followed them) approximated the plasma field as a hydrodynamic fluid instead of as a Magnetohydrodynamic (MHD) fluid. This approximation may have first appeared in order to simplify the problem to fit within the computational capacity of the day or because little was known about the dynamics of the magnetofluid and primordial magnetic fields. For whatever reason, interesting physics was lost because of this approximation. As a result, it became a common belief in cosmology that only scalar perturbations could significantly affect the fluid and form density fluctuations. This approximation quickly became a pillar of mainstream cosmological theory and therefore its validity was rarely questioned.

Magnetofluid vs. Hydrodynamic Fluid

The biggest difference between a hydrodynamic fluid and a magnetofluid is how they are affected by magnetic fields. It follows that if there were no magnetic fields in the early universe, the primordial plasma could be accurately approximated by a hydrodynamic system. However, if magnetic fields were present in the early universe then a magnetohydrodynamic system is needed to understand the evolution of the early universe. Unfortunately, the only thing that we currently know about magnetic fields in the early universe is that little is known about their existence or absence. There are no direct observations of primordial magnetic fields. Our only knowledge of magnetic fields in this epoch comes from theories that fail to agree on their amplitude. There are currently several dozen theories about the origin of cosmic magnetic fields [3,9]. The main reason that we believe that primordial magnetic fields existed is because they may have been needed to seed the large magnetic fields observed today. Most theories of cosmic magnetic field generation fall into one of three categories [3,4,9]: 1) Magnetic fields generated by phase transitions 2) Electromagnetic Perturbations expanded by inflation 3) Turbulent MHD resulting in charge and current asymmetries.

Primordial Magnetic Fields

Most models calculate the magnitude of primordial magnetic fields by starting with the observed strength of galactic or intergalactic magnetic fields and calculating how this field should have been amplified or diffused by external effects such as the galactic dynamo and expansion of the universe [3,9]. A major problem is that there doesn't appear to be a universal agreement of how efficiently a galactic dynamo could have strengthened seed magnetic fields. Estimates of the strength of these seed fields can vary by tens of orders of magnitude. Seed magnetic fields produced by Inflation are predicted to be somewhere between 10^{-11} G and 10^{-9} G on a scale of a few Mpc [3,9,11]. Magnetic seed fields generated by phase transitions are believed to be less than 10^{-23} G at galactic scales [3,9]. Some Turbulence theories imply that magnetic fields were not generated until after the first stars were formed therefore requiring no magnetic seed fields [3].

Given how little is understood about primordial magnetic fields and the general lack of agreement among theoretical predictions, it seems clear that the existence of primordial magnetic fields can neither be confirmed or ruled out. It appears that the best we can do is set an upper limit on the strength of primordial magnetic fields and utilize this limit as a starting point in developing models of cosmic structure formation involving magnetofluid dynamics. Observations of the CMB limit the intensity of the magnetic seed fields to 10^{-9} G [3,9,11,17].

AFFECT ON STRUCTURE FORMATION

Work by Duez [7], showed that gravitational waves can induce oscillatory modes in a plasma field if magnetic fields are present. According to Shebalin [24,26], sound waves also lead to magnetosonic and Alfven waves in the magnetofluid, resulting in an increased velocity of linear perturbations. This could lead to turbulence in the magnetofluid and induce the development of coherent structures. The assumption here is that gravitational waves in the early universe (sometime after t = 0.01 seconds) caused the Alfven and magnetosonic modes [7]. These modes then interacted dynamically, possibly resulting in turbulence and structure formation [24,26]. Here, structure is defined as cosmic magnetic fields, density and temperature variations and secondary relic gravitational waves.

In order to test this theory we are developing a General Relativistic Magneto-hydrodynamic (GRMHD) computer code to model both the plasma field and the background space-time dynamically. For preliminary tests the initial space-time was constructed in such a way as to mimic the conditions present around 3 minutes after the big bang. We choose to begin the simulation at t = 3 minutes because at that time the primordial plasma field appeared to look like a classical plasma field and the amplitude of the gravitational waves where moderate. Also, at this time many of the initial conditions needed for the simulation were well established by the Standard Model of Cosmology.

In order to complete the set of initial conditions, future experiments will also utilize explicit calculations of the viscosity and magnetic dissipation for the initial magnetofluid. These will help determine quantities, such as the dampening scale of the turbulent plasma. This requires further theoretical work, since no universally accepted values are available for this epoch. Based on the arguments above [3,4,9,12,15], the initial seed magnetic field should be less than or equal to 10^{-9} G. The initial study did not include any viscosity or dissipation. The purpose of this simulation was to see if the concept proposed here is sound. Future work will start around t = 0.01 seconds and include scalar perturbations and dark matter as well as tensor perturbations and magnetic fields.

Before running the experiment we thoroughly tested the code. The Duez paper [6] suggested four tests of a GRMHD code, however because of the limited scope of this experiment we felt that only the following two tests were necessary: Gravitational Wave-Induced MHD Waves and Consistency with the Standard Model of Cosmology. We did not include tests of Unmagnetized Relativistic Stars, Relativistic Bondi Flow, or Mikowski Spacetime MHD Tests such as shock tests because the spacetime that they are simulating lacks stars, black holes and supersonic flows. A future test of this structure formation theory may extend into the supersonic region and develop high-density pockets, which could make these tests necessary.

The first test that we performed involved generating Alfven and magnetosonic modes by gravitational waves and comparing the results against the semi-analytic predictions from the Duez paper [7]. We began by using the same initial conditions as we defined for t = 3 minutes. We then added monochromatic standing waves along the z-axis. The polarizations were varied between both the plus and cross polarizations and the direction of the magnetic field was also applied in a variety of directions. For every variation the test proved successful, the analytic and numerical results proved almost identical. We then removed the gravitational waves to see that the pressure of the virtual fluid did in fact balance the gravitational attraction of the fluid elements. After several thousand iterations, there was no apparent expansion or contraction of the spacetime.

For our second test they replaced the Minkowski space-time with a FRW space-time with parameters consistent with t = 3 minutes and tested that the variables evolved consistently based on the standard cosmological model during the radiation-dominated era. We set the initial scale factor to 2.8×10^{-9} and the initial Hubble Parameter to 7.6×10^{16} km/s/Mpc. This test again proved successful. At this point we added standing gravitational waves with a spectrum consistent to Grishchuk's predictions [10] with both plus and cross polarizations in all three spatial directions.

Simulations utilizing the FRW background metric showed that while gravitational waves and magnetic fields had little impact on the expansion rate of the space-time, they did have some effect on variations in density, pressure and fluid velocity. In analyzing the data, we looked closely at density variations in each run. Here, density variations are defined as the difference between the density at each point and the mean density of the system. We observed that in runs involving gravitational waves, the trough to crest density variations seemed to increase with time, reach a peak and then stabilize at some slightly lower constant value instead of increasing without limit. These variations tended to be larger in the runs utilizing both tensor perturbations and magnetic fields. This initial growth appears to be caused by the sudden introduction of gravitational waves into the homogeneous plasma field. A further analysis of this data showed that several areas with high and low density formed in the system and remained throughout the simulation. The amplitude of these variations was 10^{-10}, which implies a density fluctuation of about one part in ten trillion given a computational domain of two meters cubed. In today's measurements this corresponds to roughly twice the distance from the earth to the moon. Further work is needed to show how results of this code will match up with observations of the CMB. While the full extent of these fluctuations and their impact on structure formation requires further study, these results show that they are much more significant than density fluctuations generated by gravitational waves acting on a hydrodynamic fluid.

Vortices were also present in the data implying the existence of a turbulent system. This could lead to a dynamo effect that could strengthen the magnetic fields. These preliminary results show that isotropic gravitational waves acting on a homogeneous plasma field, using a FRW background metric, result in regions of increased and decreased density and therefore could lead to structure formation as the spacetime evolves. The work that is being proposed here will include a study of how structure formation depends on scalar perturbations and gravitational waves as well as dark matter, dissipation and magnetic fields in the initial plasma field.

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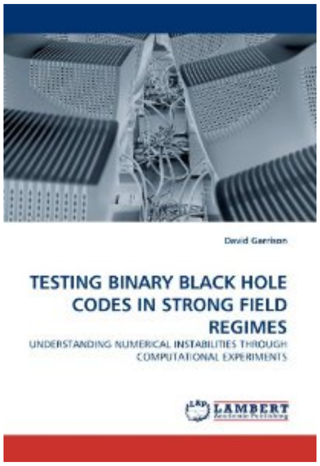
REFERENCES

1. Alexander S and Martin J 2005 *Phys. Rev. D* **71** 063526
2. Allahverdi R and Drees M 2004 *Phys. Rev. D* **70** 123522 (Preprint hep-ph/0408289)
3. Battaner E and Lesch H 2000 (Preprint astro-ph/0003370)
4. Dolgov A D 2001 (Preprint hep-ph/0110293)
5. Doroshkevich A G 1973 *Astrophys. Lett.* **14** 11
6. Duez M D, Liu Y T, Shapiro S T and Stephens B C 2005 *Phys. Rev. D* **72** 024028
7. Duez M D, Liu Y T, Shapiro S T and Stephens B C 2005 *Phys. Rev. D* **72** 024029
8. Garrison D and de la Torre R 2007 *Class. Quant. Grav.* **24** 5889
9. Grasso D and Rubinstein H R 2001 Phys. Rept. 348 163-266 (Preprint astro-ph/0009061)
10. Grishchuk L P 2006 *Phys. Rev. D* **74** 083008 (Preprint gr-qc/0605100**)**
11. Hoyle F 1951 IAU Symposium on the Motion of Gaseous Masses of Cosmical Dimensions: Problems of Cosmical Aerodynamics (Central Air Documents Office), p. 195
12. Jedamzik K, Katalinic V and Olinto A V 2000 *Phys. Rev. Lett* **85** 4 700-703
13. Jones B J T 1976 *Rev. Mod. Phys.* **48** 107-149
14. Kodama H and Sasaki M 1984 *Prog. Theor. Phys. Suppl.* **78** 1
15. Maroto A L 2001 (Preprint hep-ph/0111268)
16. Mukhanov V F, Feldman H A and Brandenberger R H 1992 *Phys. Reports* 215 5-6, 203-333
17. Murayama H and Pierce A 2002 *Phys. Rev. Lett.* **89** 271601
18. Ozernoi L M and Chernin A D 1968 *Sov. Astron.-AJ* **11**, 907
19. Ozernoi L M and Chernin A D 1968 *Sov. Astron.-AJ* **12**, 901
20. Ozernoi L M and Chibisov G V 1971 *Sov. Astron.-AJ* **14**, 615
21. Ozernoi L M and Chibisov G V 1971 *Astrophys. Lett.* **7**, 201
22. Ozernoi L M and Chibisov G V 1972 *Sov. Astron.-AJ* **15**, 923
23. Sachs R K and Wolfe A M 1967 *Astrophys. J.* 147,73-90
24. Shebalin J V 1989 *Physica D* **37**, 173-191
25. Shebalin J V 1997 *Phys. Lett. A* **226**, 1-6
26. Shebalin J V 2007 *Physics of Plasmas* **14**, 102301
27. Zel'dovich Ya B and Starobinshky A A 1972 *Sov. Phys. JETP* **34**, 1159



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David Garrison, Ph.D: Studied Physics at the Massachusetts Institute of Technology and The Pennsylvania State University. Associate Professor and Chair of Physics at the University of Houston ? Clear Lake and Associate Professor of Physics at the University of Houston. Founded the Physics Program at the University of Houston Clear Lake.

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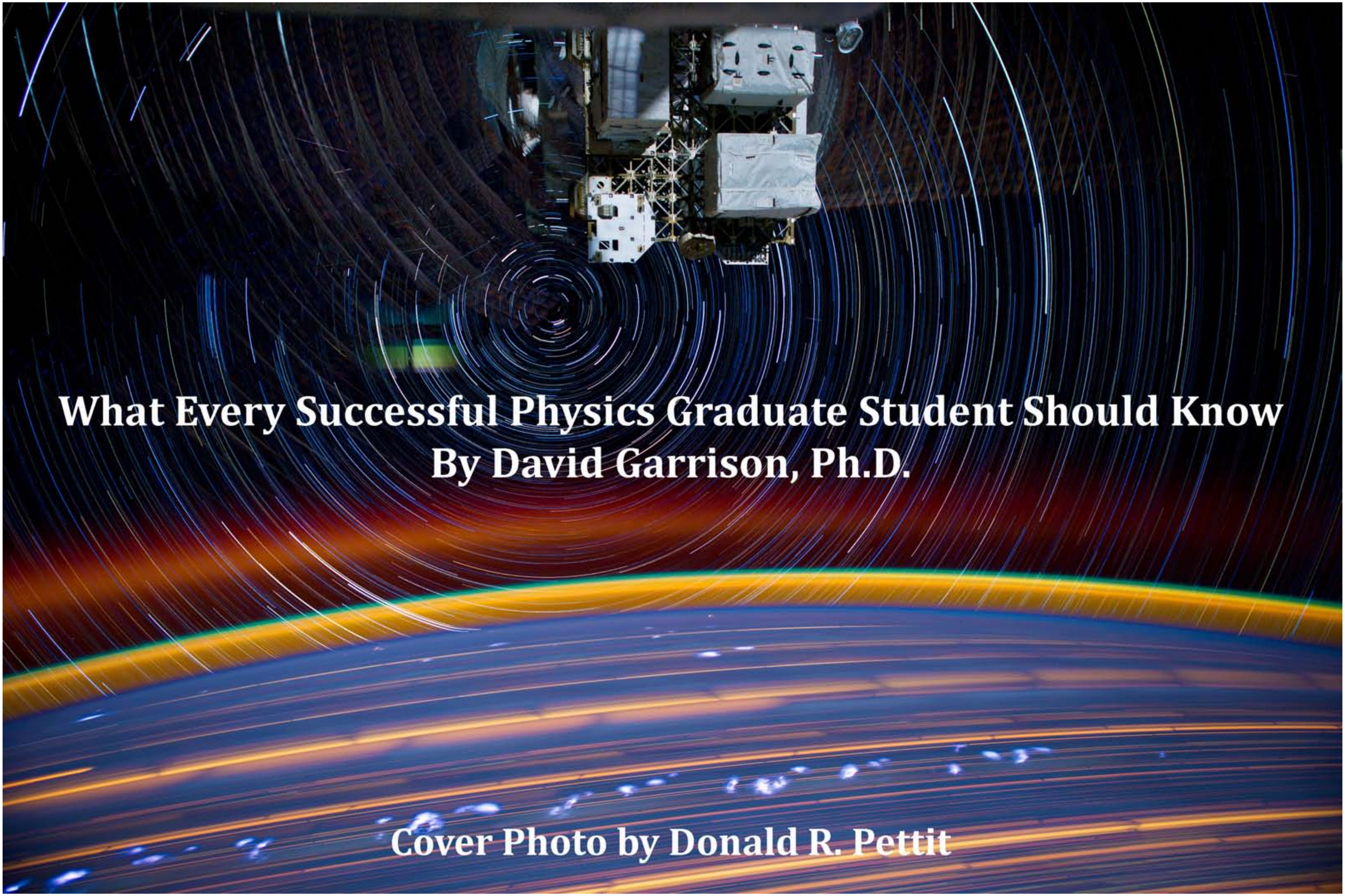
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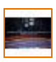

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Research Article

A Numerical Simulation of Chern-Simons Inflation

David Garrison and Christopher Underwood

Physics Department, University of Houston-Clear Lake, Houston, TX 77058, USA

Correspondence should be addressed to David Garrison; garrison@uhcl.edu

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We present results of numerical simulations of the Chern-Simons inflation model proposed by Alexander, Marciano, and Spergel. According to this model, inflation begins with a fermion condensate interacting with a gauge field. Crucial to the success of this mechanism is the assumption that the Chern-Simons interaction would drive energy from the initial random spectrum into a narrow band of frequencies at superhorizon scales. In this work, we numerically confirm this expectation. These gauge fields and currents, when combined with the Friedmann equations, were broken into a system of hyperbolic equations and numerically simulated. It was found in our simulation that, by including the effects of the chiral anomaly for the axial vector current, inflation can end satisfactorily after approximately 60 e-folds.

1. Introduction and Motivation

Our understanding of the early universe is based on the phenomenon of cosmic inflation [1]. It is well known that inflation resolves most of the problems of the standard big-bang scenario, such as the horizon problem. Although there are many successes of inflation, there are hundreds of scalar field models of inflation which have proven difficult to distinguish with data. Moreover, scalar field driven inflation is fraught with conceptual and technical issues. Recently Chen and Wang demonstrated that the primordial power spectrum in scalar field inflation has anomalous sensitivity to high energy physics [2]. These issues have motivated Alexander et al. [3] to provide an inflationary mechanism that is driven by an interaction between vector and spinor fields, otherwise known as Chern-Simons inflation. This is somewhat similar in concept to the vector field inflation model proposed by Ford in which the vector field self-couples in order to form an effective scalar field [4]. For an overview of Chern-Simons modified gravity, see the paper by Alexander and Yunes [5].

Alexander et al. propose a model in which the early universe is dominated by a gauge field that interacts with a fermion current. This interaction results in an equation of state with consistently negative pressure, the condition needed for inflation [3]. In this model, the gauge field begins as a random, white noise spectrum; the authors assume that this evolves into a spectrum of superhorizon modes. Even though gauge fields and currents dilute with the expansion of space, their interaction energy is found to provide enough negative pressure to fuel an exponential expansion of spacetime. Because of the complexity of the differential equations, they were not able to show this evolution analytically. Also, in the final published version of their paper, Alexander et al. focus on the interaction between the fermion charge density and the temporal part of the gauge field. This is most likely because they thought the spacial part of the fermion current would not be significant enough to maintain the energy density needed for inflation. We show that while the current density does drop off quickly with volume, it can still give rise to a significant energy density.

This code attempts to achieve an end to inflation by modeling the Adler-Bell-Jackiw (ABJ) chiral anomaly [6], which is a small quantum mechanical violation of the conservation of axial-vector current. This violation occurs due to the tunneling of fermions from one vacuum to another. It is by this means that the gauge field converts to leptons during inflation. If the current decreases enough during inflation, the negative pressure generated during inflation should dwindle and inflation should end.

Another goal of this project is to establish the robustness of the model. One criticism of inflation is that specific theories can focus too much on formalism and lack a clear connection to physical processes that actually could have occurred [7]. Therefore, we aim to strengthen the physical interpretation of an inflationary theory while assessing its accuracy. For this purpose, we use a new code based on the Cactus framework to simulate the early universe.

In Section 2, we provide necessary mathematical background. In Section 3, we describe the analytical and computational methods used to simulate the specific inflationary theory discussed in Section 2 [3]. In Section 4, we present the results of the simulation, and in Section 5, we discuss the results and future research directions.

2. Chern-Simons Inflation

Because scalar field models are widely found and difficult to distinguish from one another, Alexander et al. suggest an alternate model in which a gauge field interacts with fermions in the early universe to produce an effective scalar field that generates inflation [3].

In this gauge field model, we have an energy density

$$\rho = \frac{E^2 + B^2}{2a^4} + |A \cdot \mathcal{J}|, \tag{1}$$

where the gauge field has both an electric field-like term, $E \equiv \dot{A}$, and a magnetic field-like term, $B \equiv \nabla \times A$ term. Because the gauge field of interest existed before the electroweak phase transition, it should be considered a hypercharged electromagnetic field. We can therefore see that this energy density has a hypercharged electromagnetic component, which scales as a^{-4}, as well as a gauge field-fermion interaction. The electromagnetic terms effectively serve as a source of perturbations in the field density which later forms the basis of structure formation but does not have a significant impact on the energy density. As shown in [3], if the second term dominates over the first term, it is possible for inflation to occur. This will give us an energy density $\rho \approx |A \cdot \mathcal{J}|$ and pressure $P \approx -|A \cdot \mathcal{J}|$, corresponding to an equation of state $w = -1$, which is sufficient to cause inflation.

We will consider the equation of motion of the gauge field in this case. Its action is as follows:

$$\begin{aligned} S = \int_{M_4} d^4x \sqrt{-g} \Bigg(& \frac{M_P^2 R}{8\pi} - \frac{1}{2}\partial_\mu \theta \partial^\mu \theta + \xi R \theta^2 \\ & - \frac{1}{4} \operatorname{Tr}\left[F_{\alpha\beta} F^{\alpha\beta}\right] + \frac{\theta}{4M_*} \operatorname{Tr}\left[F_{\alpha\beta} F^{\alpha\beta}\right] \\ & + q \operatorname{Tr}\left[A_\mu \mathcal{J}_5^\mu\right] \Bigg). \end{aligned} \tag{2}$$

By varying this action with respect to the gauge field, we find the equation of motion. The gauge field's equation of motion, in terms of Fourier modes, is then [3] as follows:

$$\ddot{A}_h + k^2 A_h = -hkA_h \frac{\dot{\theta}}{M_*} + a^4 \mathcal{J}_h, \tag{3}$$

where h refers to the different helicities, M_* is the mass scale identified with the UV cut-off scale of the effective field theory, and θ is responsible for CP violation. The fermion currents are

$$\sqrt{2}\mathcal{J}_h = \mathcal{J}_1 + hi\mathcal{J}_2. \tag{4}$$

Alexander et al. assume that the fermion currents have a background solution in which they scale as J_0/a. Since they are being suppressed by a factor of a, we can define a set of constants J_h where $J_h = \mathcal{J}_h/a$ [3]. The equation of motion for the gauge field is now as follows:

$$\ddot{A}_h + k^2 A_h = -hkA_h \frac{\dot{\theta}}{M_*} + a^3 J_h. \tag{5}$$

According to the solutions for the gauge field [3], a value of $k < \dot{\theta}/M_*$, corresponding to long-wavelength modes, will result in its exponential growth. However, the presence of short wavelength modes, $k > \dot{\theta}/M_*$, will result in continued linear growth due to back reaction of the gravitational field.

We model the flow of current with the ABJ anomaly. It was shown by Adler [6] that the axial-vector current is not conserved in quantum field theory. This anomaly arises through perturbation theory and the analysis of triangle diagrams with a gauge-invariant regularization procedure. During inflation, the anomaly causes the gauge field to decay into fermions.

The divergence of the axial fermion current in the ABJ anomaly is defined by

$$\nabla_\mu \mathcal{J}_5^\mu = \frac{1}{32\pi^2} F_{\alpha\beta} F_{\mu\nu} \epsilon^{\alpha\beta\mu\nu}. \tag{6}$$

We assume that the spacial components of the current act like a charge density, J^0, which moves with a velocity, v^i:

$$J^i = J^0 v^i. \tag{7}$$

For this simulation, we assume the velocity to be constant and only model the changes in current through the charge density. We therefore derive the time rate of change of the charge density for the ABJ anomaly to be

$$\partial_0 J^0 = \frac{\vec{E} \cdot \vec{B}}{4\pi^2 a^2} - \partial_i J^i - 2HJ^0. \tag{8}$$

In order to maintain an initial current density of approximately $10^{-20} M_p^3$, the initial charge density and current velocity were chosen to be

$$J^0 = 10^{-10} M_p^3, \qquad \left|v^i\right| = 10^{-10}. \tag{9}$$

The choice of these two numbers is arbitrary as long as the velocity is not relativistic, and they multiply to something on the order of $10^{-20}M_p^3$.

The θ field is determined by

$$\ddot{\theta} + 3H\dot{\theta} + 2m^2\theta = \frac{\vec{E}\cdot\vec{B}}{4a^3 M_*}, \tag{10}$$

where m is on the order of the GUT energy scale. Assuming that $m \approx H$ and that the right hand side of (10) becomes negligible during inflation, the solution to (10) is $\theta(t) = -\theta_0 e^{-Ht}$ [3]. Our simulation does not rely on this simplifying assumption, and we allow θ to be determined dynamically.

Because the universe was essentially a plasma before last scattering, we look to plasma physics for an analogy of how our system should behave. In particular, we consider magnetohydrodynamics (MHD), the study of electrically conducting fluids. Here in the Chern-Simons system, the gauge field is considered analogous to the field part of the MHD equations, while the velocity terms are considered constant and the density is free to vary like in a compressible MHD system. When fluids in motion are electrically conducting, currents in the fluid produce magnetic fields that induce forces and thus change the dynamics of the system when it becomes turbulent [8]. This kind of turbulence is analogous to the dynamical system changes that could be capable of generating inflationary behavior. Computer codes that simulate MHD use the equations of fluid dynamics, along with Maxwells equations, to analyze the dynamics of a plasma system. Simulations such as these are commonly known to lead to what is referred to as an "inverse energy cascade." In a hydrodynamic turbulent system, as a system evolves in time, energy tends to "cascade" from the longest wavelength modes to the shortest wavelength modes as turbulent eddies get smaller and smaller. In MHD systems, the reverse happens. Energy cascades inversely from high frequency modes to low frequency modes.

Utilizing the coupled partial differential equations that describe the very early universe could allow us to see the resulting exponential increase and then "leveling off" of the scale factor in agreement with current cosmological models. Additionally, a simulation of this type will allow us to see directly the physical effects of fine-tuning the initial conditions for these coupled differential equations. We can input the equations of motion for the fields and currents that are interacting to generate inflation, along with the Friedmann equations, which describe the expansion of space, in order to create a system similar to the MHD equations. Here the Friedmann equations will allow us to relate the evolving pressure and density of the system to the evolution of the scale factor.

3. Methods and Equations

For the numerical calculation, we use natural units but later evaluate the data in terms of SI units so that the results can be easily compared to the established values. In this simulation, we allow the gauge field to vary, so the most relevant equation from [3] is the equation of motion for the gauge field, A:

$$\ddot{A} - \nabla^2 A + \frac{\dot{\theta}}{M_*}(\nabla\times A) - a^4\mathcal{J}_i = 0. \tag{11}$$

In comoving coordinates, this equation becomes

$$a(t)\frac{d^2A}{dt^2} + \frac{da}{dt}\frac{dA}{dt} = Ja(t)^3 + \frac{1}{a(t)}\nabla^2 A - a(t)^2\frac{\dot{\theta}}{M_*}\nabla\times A. \tag{12}$$

In order to use this in our code, we separated the equations of motion for the gauge field, ABJ chiral anomaly, Chern-Simons term, and the Friedman equations into a system of first order in time differential equations. Consider

$$\begin{aligned}
\frac{dA}{dt} &= \frac{Z}{a},\\
\frac{dZ}{dt} &= Ja^3 + \frac{\nabla^2 A}{a} - a^2\frac{\dot{\theta}}{M_*}(\nabla\times A),\\
\frac{dJ^0}{dt} &= \frac{\vec{E}\cdot\vec{B}}{4\pi^2 a^2} - \partial_i J^i - 2HJ^0,\\
\frac{dD}{dt} &= \frac{\vec{E}\cdot\vec{B}}{4a^3 M_*^2} - 3HD - 2\frac{m^2}{M_*}\theta,\\
\frac{d\theta}{dt} &= DM_*,\\
\frac{da}{dt} &= aH,\\
\frac{dH}{dt} &= \frac{8\pi}{3}\frac{\overline{\rho}}{a} - H^2.
\end{aligned} \tag{13}$$

The average energy density and pressure are calculated as $\overline{\rho} = (1/N)\sum_{k=1}^{N}|A_k\cdot\mathcal{J}_k|$ and $\overline{P} = -(1/N)\sum_{k=1}^{N}|A_k\cdot\mathcal{J}_k|$. Here N represents the total number of grid points in the computational domain. The scale factor and Hubble parameter therefore depend on the average energy density and not the local field dynamics.

The initial gauge field was composed of a random (white noise) spectrum. In order to generate the initial gauge field, we used a random number generator to create a random spectrum with amplitude up to the calculated maximum amplitude, A_0, in each direction. The magnitude of the gauge

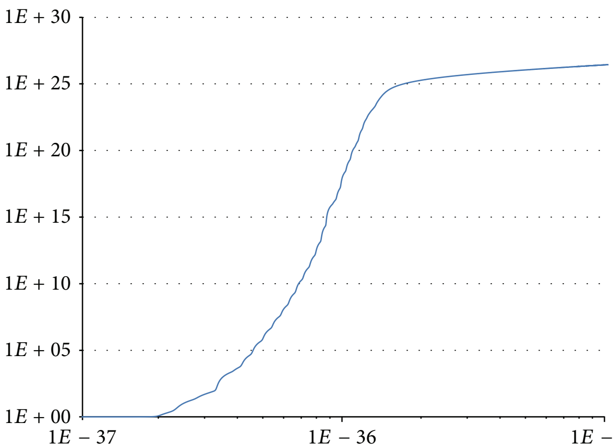

Figure 1: The scale factor for the inflationary period (log-log scale).

field was then held equal to the initial amplitude A_0. The initial value for the other variables is given as follows:

$$\begin{aligned}
\left|A_0\right| &= 3.36566 \times 10^{-5} M_P, \\
J^0 &= 10^{-10} M_P^3, \\
\vec{v} &= 10^{-10}\left(\hat{x} + \hat{y} + \hat{z}\right), \\
\frac{\dot{\theta}_0}{M_*} &= 2.18 \times 10^{-5} M_P, \\
a_0 &= 1.0, \\
H_0 &= \sqrt{\frac{8\pi}{3}\left|A_0 \cdot J\right|}, \\
Z_0 &= H_0 a_0 \times \text{random number}\,(-1, 1), \\
m &= 4.0 \times 10^{-6} M_P, \\
M_* &= 4.0 \times 10^{-6} M_P.
\end{aligned} \tag{14}$$

The code was then run on the University of Houston Texas Learning and Computation Centers Xanadu cluster using a variety of time steps, grid sizes, and resolutions in order to obtain consistent results. We ran the code using resolutions ranging from 34^3 to 132^3 grid points and grid sizes ranging from 10^4 to 10^7 units cubed. These grid sizes correspond to the size of the horizon throughout the simulation. We adjusted the Courant ratio from a low of 0.001 to a high of 0.9 during several data runs. These runs used anywhere from 8 to 48 processors and the runs lasted anywhere from 2 hours to 7 days. We also ran the code using three different differencing schemes including 2nd order finite differencing, 4th order finite differencing, and Fourier spectral differencing.

Because the initial units were entered as Planck units, we assumed that the physical grid (horizon) size corresponded to Planck lengths and the timing output could be interpreted as Planck time. The output was analyzed using several tools including ygraph and Pro Fit (http://www.quansoft.com/).

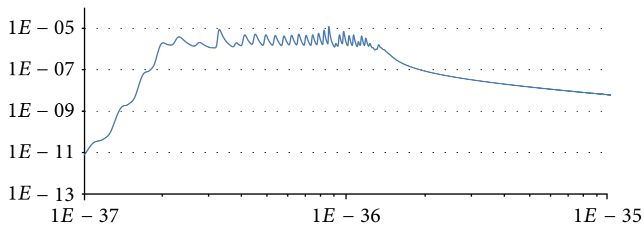

Figure 2: The Hubble parameter throughout the inflationary period (log-log scale).

4. Results

Using the definition that inflation is active during regions where $\ddot{a} > 0$, we saw that inflation consistently began at around 2.0×10^{-37} s and lasted until 1.5×10^{-36} s before settling into a linear progression as shown in Figure 1. The values for m and M_* that produced the best results were $4.0 \times 10^{-6} M_p$ for both parameters. In order to achieve at least 60 e-folds of inflation, the initial gauge field parameter, A_0, necessary was $3.36566 \times 10^{-5} M_p$. The code was highly sensitive to this number and even a deviation of $10^{-10} M_p$ in either direction caused the scale factor to go infinite or level off too soon. For example, using an initial gauge field parameter of $3.3658 \times 10^{-5} M_p$ results in the scale factor leveling off around 10^{22} instead of 10^{27}. These parameters were tuned using a grid size of 10^6 Planck lengths. When the code was run using these parameters on a grid size of 10^5 Planck lengths, no inflation occurred at all, and when it was run using a grid size of 10^7 Planck lengths, the scale factor leveled off at about 10^3 most likely because of the reduced effective resolution for the larger grid size.

The Hubble parameter in Figure 2 rose sharply from 1.0×10^{-37} to 2.0×10^{-37} s before undergoing an oscillatory behavior. The oscillations increased in frequency and persisted until 1.4×10^{-36} s where they settled into an exponential decline. These oscillations seem to be the result of oscillations in the θ term. The behavior of the charge density in Figure 3(a) is the opposite of that of the scale factor. It reached as low as $10^{-60} M_p^3$ before leveling off. Notice that although the charge density drops off quickly, as a^{-3}, it still has a significant impact on the energy density because of the high growth rate of the gauge field. The magnitude of the gauge field (Figure 3(b)) rose sharply during inflation before leveling off at around $10^{50} M_p$. This implies that the gauge field grew like a^2 not as a^1 throughout most of the inflation period. There also appears to be a period at the beginning of the simulation when the gauge field grew as fast or faster than the charge density declined, resulting in a constant or growing energy density and therefore a constant or growing Hubble parameter. Because of the variations in the growth rates of the gauge field and fermion current, the inflation event ends naturally instead of continuing indefinitely.

The power spectrum (Figure 4) of the gauge field is initially random, but it flattens out before the onset of inflation, with lower frequency modes becoming dominant.

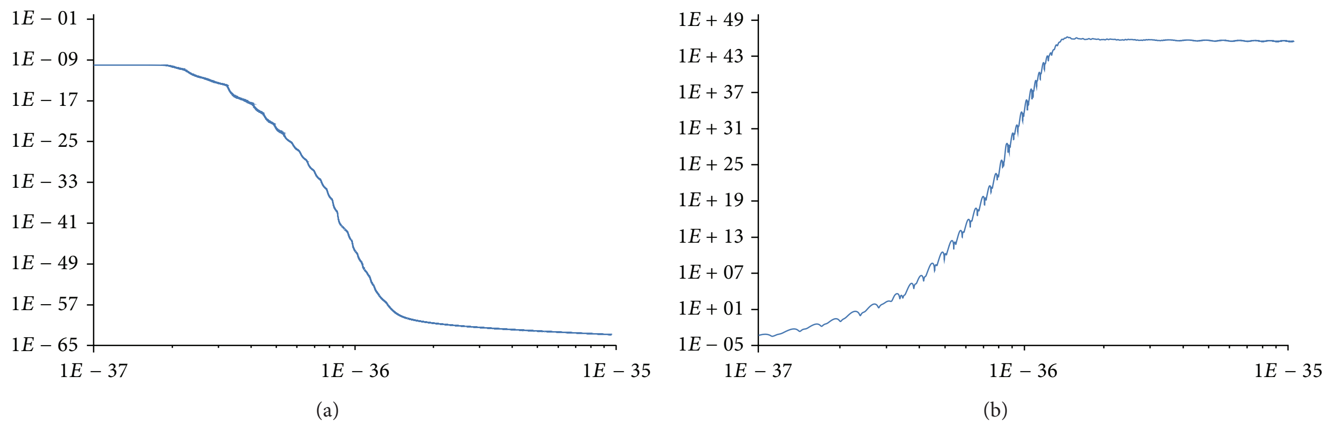

FIGURE 3: The (a) charge density and (b) magnitude of the gauge field throughout inflation (log-log scales).

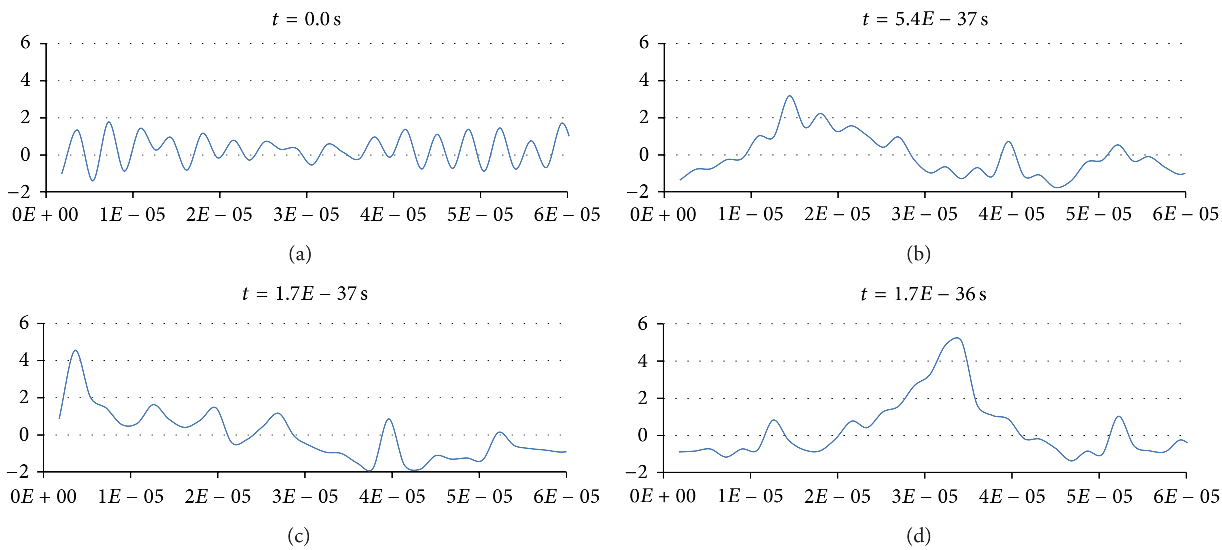

FIGURE 4: Power spectral density for the gauge field throughout inflation. The vertical axis is the log of the deviation from the mean. The horizontal axis is frequency in Plank units.

In the middle of the inflationary period, the spectrum starts to become concentrated in higher frequency modes before accumulating into wide band of midrange frequencies from 2.0×10^{-5} to $5.0 \times 10^{-5} t_p^{-1}$ at the end of inflation. This wide band power spectrum persists throughout the postinflation era.

5. Discussion and Conclusions

The simulation presented here clearly supports much of the hypotheses proposed by Alexander et al.: the evolution equations given drive energy into a narrow band of modes and cause the universe to expand exponentially. Though the theory does not predict an initial start time for inflation, our value of about $t_i = 10^{-37}$ s is consistent with the time predicted by the most general models of inflation [9]. This suggests some universality in the initial conditions required for inflation, regardless of the model; in the future, we can study this question analytically for this model.

The power spectrum in Figure 4 supports the hypothesis that an initially random gauge field spectrum becomes concentrated in low frequencies during inflation. This analysis allows us to see the progression from an almost completely random spectrum near the beginning to the energy being concentrated in a narrow band of low-frequency modes during the inflation event. In addition to the dominance of low-frequency modes, the higher modes are suppressed during much of inflation. This reflects the behavior predicted in [3]. The dominance of low-frequency modes has subsided, and we are mostly left with lower amplitude random noise behind a flatter power spectrum, indicating that the end of inflation is near.

It is interesting that exponential growth does not occur for horizon sizes that are too small. This could be due to the unavailability of very long wavelength (low frequency) modes for the gauge field. In the future, accurate measurements of these frequencies could allow us to verify that they are, in fact, superhorizon modes. A more detailed study of the effect of grid resolution on the dynamics of the system could lead to some interesting revelations about the role of low and high-frequency modes in the system. By understanding the spectral dependence on the dynamics of the system, we can better understand how our choice of initial conditions affects the system. We can then better determine what initial conditions lead to the universe which we observe today. Other future work on this project will be to incorporate the product of the charge density and temporal part of the gauge field into the energy density to determine if they also have a significant impact on inflation and the dynamics of the system.

The results presented here only work for the grid size and grid resolutions discussed. This speaks to the level of fine tuning necessary in this model to get the required 60 e-folds of inflation. The value of $4.0 \times 10^{-6} M_p$ for m is approximately the GUT scale for string theory. Increasing the initial gauge field had by far the most effect of the scale factor. Since the plot of the charge density closely resembles a mirror image of the scale factor, the Hubble parameter term in (8) is likely responsible for most of the decrease in charge density, as well as energy density, and the anomalous behavior of the axial current likely had little effect. Typical models have inflation taking place from approximately 10^{-37} to 10^{-32} s. The inflation described by this simulation starts at about 10^{-37} s and ends at roughly 10^{-36} s which is far quicker than what most models predict. This may be resolved by the right choice of initial parameters with sufficiently high resolution.

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References

[1] A. H. Guth, "Inflationary universe: a possible solution to the horizon and flatness problems," *Physical Review D*, vol. 23, no. 2, pp. 347–356, 1981.

[2] X. Chen and Y. Wang, "Anomalous high energy dependence in inflationary density perturbations," *High Energy Physics*. http://arxiv.org/abs/1207.0100.

[3] S. Alexander, A. Marciano, and D. Spergel, "Chern-Simons inflation and baryogenesis," *Journal of Cosmology and Astroparticle Physics*, vol. 2013, 2013.

[4] L. H. Ford, "Inflation driven by a vector field," *Phyical Review D*, vol. 40, no. 4, pp. 967–972, 1989.

[5] S. Alexander and N. Yunes, "Chern-Simons modified general relativity," *Physics Reports*, vol. 480, no. 1-2, pp. 1–55, 2009.

[6] S. Adler, *Physical Review*, vol. 77, 1968.

[7] W. H. Kinney, "TASI Lectures on Inflation," http://adsabs.harvard.edu/abs/2009arXiv0902.1529K.

[8] J. V. Shebalin, "Broken ergodicity in two-dimensional homogeneous magnetohydrodynamic turbulence," *Physics of Plasmas*, vol. 17, no. 9, Article ID 092303, 2010.

[9] S. Weinberg, *Cosmology*, Oxford University Press, Oxford, UK, 1st edition, 2008.

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Research Article

Numerical Relativity as a Tool for Studying the Early Universe

David Garrison

Physics Department, University of Houston Clear Lake, Houston, TX 77058, USA

Correspondence should be addressed to David Garrison; garrison@uhcl.edu

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Numerical simulations are becoming a more effective tool for conducting detailed investigations into the evolution of our universe. In this paper, we show how the framework of numerical relativity can be used for studying cosmological models. The author is working to develop a large-scale simulation of the dynamical processes in the early universe. These take into account interactions of dark matter, scalar perturbations, gravitational waves, magnetic fields, and turbulent plasma. The code described in this report is a GRMHD code based on the Cactus framework and is structured to utilize one of several different differencing methods chosen at run-time. It is being developed and tested on the University of Houston's Maxwell cluster.

1. Introduction

Our knowledge of how the universe evolved comes primarily from observations of large structures such as stars, galaxies, clusters, and super-clusters of galaxies as well as from observations of the cosmic microwave background (CMB) radiation. Based on these observations, the standard model of cosmology was developed during the mid to late twentieth century. Some elements of this model include the existence of primordial metric perturbations, magnetic fields, and an early universe filled with nearly homogenous and isotropic plasma [1]. The perturbed Friedmann-Robertson-Walker (FRW) metric, which describes the spacetime curvature of the early universe, takes the following form:

$$ds^2 = -\left(1+2\phi\right)dt^2 + \omega_i dt dx^i + a(t)^2\left[\left(\left(1+2\psi\right)\delta_{ij} + h_{ij}\right)dx^i dx^j\right]. \tag{1}$$

Here $a(t)$ is the scale factor and ϕ, ψ, ω_i, and h_{ij} are the scalar, vector, and tensor perturbation terms. Many cosmological models relate density fluctuations and variations in the CMB to perturbations in the FRW metric at the time of recombination. These perturbations start off small and grow as a power-law with time as the competing forces of universal expansion and gravitational attraction affect their growth [1]. Work by Kodama and Sasaki [2], Sachs and Wolfe [3], and Mukhanov et al. [1] all showed analytically how metric perturbations could cause density perturbations in a hydrodynamic fluid.

Recently, beyond the standard model cosmological theories, [4] has suggested that primordial fluids and fields are potential sources of observable gravitational waves. This realization opens up exciting new possibilities, making primordial gravitational radiation an important source of information about the early universe. Taken together, this leads to the idea that there was a dynamical interaction between matter, electromagnetic, and gravitational fields in the early universe that affected the evolution of our universe. Signatures of these interactions may still be observable today. The objective of this paper is to show how the tools of numerical relativity can be used to study such an interaction and to introduce a computer code written for this purpose.

This project uses the framework of numerical relativity to develop a computational laboratory to study the evolution of the early universe. The initial focus of this work is on deriving the spectrum of gravitational waves produced by relativistic turbulence in the early universe. Future work may involve a more advanced study of how this gravitational wave spectrum is affected by the presence of dark matter or a preexisting primordial gravitational wave field. Numerical relativity has been used for years to study the collisions of compact objects such as black holes and neutron stars and to predict the spectrum of the gravitational waves produced by their interactions. We propose to use this tool to provide detailed studies of cosmological events that may also one day be observable using either gravitational or conventional astronomy. In cosmology, numerical simulations are capable of providing more detail than the analytic calculations that have been performed to date. For example, a modern general relativistic magnetohydrodynamic (GRMHD) code is capable of performing such simulations by evolving both the spacetime and plasma field dynamically and can therefore represent chaotic processes such as turbulence more accurately than analytic calculations. This paper is a summary of the techniques used to develop such a simulation.

2. Development of Initial Conditions

Every numerical simulation consists of three parts: initial data, numerical evolution, and data analysis. In this section, we will focus on the initial data needed for cosmological studies.

2.1. Background and Hypotheses. Several different mechanisms for producing primordial gravitational waves have been identified and studied by researchers. These include quantum fluctuations during inflation, bubble wall motion, and collisions during phase transitions, cosmological magnetic fields, oscillating classical fields during reheating, cosmological defects, and plasma turbulence [4–14]. We assume that the early universe was in a metastable state during a first order phase transition. The false vacuum was separated from the true vacuum by a potential barrier or a scalar field. Quantum tunneling occurred across the barrier in finite regions of space resulting in true vacuum bubbles inside the false vacuum phase. As the universe expanded and cooled, the energy difference between the false vacuum and true vacuum got larger, making the phase transition more probable. Eventually, the probability of nucleating one critical bubble per Hubble time became high enough to cause the phase transition to begin. This defined the transition temperature, which is believed to be about 1 TeV [4]. The nucleated bubbles expanded and collided, eventually filling the whole universe. The collision of two or more of these bubbles broke spherical symmetry and released some of their energy as gravitational waves. Since the expansion of the bubbles was accompanied by macroscopic motions in the cosmic matter field, the collision of these bubbles also resulted in the anisotropic stirring of the field. This caused turbulent motions which provided a primary source of gravitational waves for this research.

2.1.1.Primordial Magnetic Fields. Magnetic fields are believed to have played a large part in the dynamics of the universe's evolution. Little is known about the existence of magnetic fields in the early universe. There are no direct observations of primordial magnetic fields. Theories also disagree on the amplitude of primordial magnetic fields. There are currently several dozen theories about the origin of cosmic magnetic fields [15, 16]. The main reason that we believe that primordial magnetic fields existed is because they may have been needed to seed the large magnetic fields observed today. Most theories of cosmic magnetic field generation fall into one of three categories [15–17]: (1) magnetic fields generated by phase transitions; (2) electromagnetic perturbations expanded by inflation; and (3) turbulent magnetofluid resulting in charge and current asymmetries.

Most models calculate the magnitude of primordial magnetic fields by starting with the observed strength of galactic or intergalactic magnetic fields and calculating how this field should have been amplified or diffused by external effects such as the galactic dynamo and expansion of the universe [15, 16]. A major problem is that there does not appear to be a universal agreement of how efficiently a galactic dynamo could have strengthened seed magnetic fields. Estimates of the strength of these seed fields can vary by tens of orders of magnitude. Seed magnetic fields produced during inflation are predicted to have a current strength somewhere between 10^{-11} G and 10^{-9} G on a scale of a few Mpc [15, 16, 18]. Magnetic seed fields generated by phase transitions are believed to be less than 10^{-23} G at galactic scales [15, 16]. Some turbulence theories imply that magnetic fields were not generated until after the first stars were formed therefore requiring no magnetic seed fields [15].

Given how little is understood about primordial magnetic fields and the general lack of agreement among theoretical predictions, it seems clear that the existence of primordial magnetic fields can neither be confirmed or ruled out. It seems that the best we can do is set an upper limit on the strength of primordial magnetic fields and utilize this limit as a starting point in developing models of cosmic turbulence. Observations of the CMB limit the intensity of the magnetic seed fields to a current upper limit of 10^{-9} G [15, 16, 18, 19].

It is well known that gravitational waves can interact with a magnetofluid in the presence of a magnetic field. Work by Duez et al. [20] showed how gravitational waves can induce oscillatory modes in a plasma field if magnetic fields are present. Work by Kahniashvili and others [4, 9–13] has shown how a turbulent plasma can yield gravitational waves. The result may be a highly nonlinear interaction as energy is transferred from the fluid to the gravitational waves and back.

2.1.2. Turbulence in the Early Universe. Turbulence provides a particularly interesting GW source because it is not well understood analytically. This turbulence is a natural result of dynamics of the early universe resulting from bubble wall collisions and other chaotic events during the first order phase transitions. Analytic work done to date [4, 5, 12–14] summarizes the dynamics of the phase transitions using two quantities, α and β. α is traditionally defined as the ratio of false vacuum energy and plasma thermal energy density. This provides a measure of the transition strength. If α is much less than one, the transition is very weak. If α is larger than unity, the transition is very strongly first order. β is the rate of variation of the nucleation rate at the transition time. It fixes the time scale of the phase transition once the transition has begun. After a time interval β^{-1}, the whole universe is converted to a true vacuum phase. Therefore the turbulent stirring should only last β^{-1}.

Table 1: Consistency of standard model of cosmology parameters test results.

	t	T	$\rho\epsilon$	H	a
Initial	10^{-6}	4.120×10^{13}	1.091×10^{23}	2.401×10^{26}	1.0
Final	8.629×10^{1}	4.446×10^{9}	1.480×10^{7}	2.792×10^{18}	9.289×10^{3}
Final/initial	8.629×10^{7}	1.079×10^{-4}	1.357×10^{-16}	1.163×10^{-8}	9.289×10^{3}
t^{a}	8.629×10^{7}	8.586×10^{7}	8.586×10^{7}	8.601×10^{7}	8.629×10^{7}
T^{a}	1.077×10^{-4}	1.079×10^{-4}	1.079×10^{-4}	1.078×10^{-4}	1.077×10^{-4}
$\rho\varepsilon^{a}$	1.343×10^{-16}	1.357×10^{-16}	1.357×10^{-16}	1.352×10^{-16}	1.343×10^{-16}
H^{a}	1.159×10^{-8}	1.165×10^{-8}	1.165×10^{-8}	1.163×10^{-8}	1.159×10^{-8}
a^{a}	9.289×10^{3}	9.266×10^{3}	9.266×10^{3}	9.274×10^{3}	9.289×10^{3}
t^{b}	0.0	4.338×10^{5}	4.338×10^{7}	2.824×10^{5}	-2.980×10^{-7}
T^{b}	2.716×10^{-7}	0.0	-5.833×10^{-16}	9.506×10^{-8}	2.716×10^{-7}
$\rho\varepsilon^{b}$	1.361×10^{-18}	2.933×10^{-27}	0.0	4.773×10^{-19}	1.361×10^{-18}
H^{b}	3.804×10^{-11}	-2.051×10^{-11}	-2.051×10^{-11}	0.0	3.804×10^{-11}
a^{b}	1.637×10^{-11}	2.338×10^{1}	2.338×10^{1}	1.521×10^{1}	0.0
t^{c}	3.351×10^{-3}				
T^{c}		1.678×10^{-3}			
$\rho\varepsilon^{c}$			6.686×10^{-3}		
H^{c}				3.357×10^{-3}	
a^{c}					1.678×10^{-3}

[a]Final/initial for each column parameter calculated based on the Friedman equations.
[b]Ratio predicted by Friedman equations (analytic) − ratio calculated by the GRMHD code (numerical).
[c]Average error: (numerical − analytic)/numerical averaged among all nonzero columns.

Table 2: Initial states for one-dimensional MHD tests[a].

Test	Left state	Right state	Grid	t_{final}
Fast shock ($\mu = 0.2$[b])	$u^i = (25.0, 0.0, 0.0)$ $B^i/\sqrt{4\pi} = (20.0, 25.02, 0.0)$ $P = 1.0$, $\rho_0 = 1.0$	$u^i = (1.091, 0.3923, 0.00)$ $B^i/\sqrt{4\pi} = (20.0, 49.0, 0.0)$ $P = 367.5$, $\rho_0 = 25.48$	$n = 40$	2.5
Slow shock ($\mu = 0.5$[b])	$u^i = (1.53, 0.0, 0.0)$ $B^i/\sqrt{4\pi} = (10.0, 18.28, 0.0)$ $P = 10.0$, $\rho_0 = 1.0$	$u^i = (0.9571, -0.6822, 0.00)$ $B^i/\sqrt{4\pi} = (10.0, 14.49, 0.0)$ $P = 55.36$, $\rho_0 = 3.323$	$n = 200$	2.0
Switch-off fast rarefaction	$u^i = (-2.0, 0.0, 0.0)$ $B^i/\sqrt{4\pi} = (2.0, 0.0, 0.0)$ $P = 1.0$, $\rho_0 = 0.1$	$u^i = (-0.212, -0.590, 0.0)$ $B^i/\sqrt{4\pi} = (2.0, 4.71, 0.0)$ $P = 10.0$, $\rho_0 = 0.562$	$n = 150$	1.0
Switch-on slow rarefaction	$u^i = (-0.765, -1.386, 0.0)$ $B^i/\sqrt{4\pi} = (1.0, 1.022, 0.0)$ $P = 0.1$, $\rho_0 = 1.78 \times 10^{-3}$	$u^i = (0.0, 0.0, 0.0)$ $B^i/\sqrt{4\pi} = (1.0, 0.0, 0.0)$ $P = 1.0$, $\rho_0 = 0.01$	$n = 150$	2.0
Alfvén wave[c] ($\mu = 0.626$[b])	$u^i = (0.0, 0.0, 0.0)$ $B^i/\sqrt{4\pi} = (3.0, 3.0, 0.0)$ $P = 1.0$, $\rho_0 = 1.0$	$u^i = (3.70, 5.76, 0.00)$ $B^i/\sqrt{4\pi} = (3.0, -6.857, 0.0)$ $P = 1.0$, $\rho_0 = 1.0$	$n = 200$	2.0
Shock tube 1	$u^i = (0.0, 0.0, 0.0)$ $B^i/\sqrt{4\pi} = (1.0, 0.0, 0.0)$ $P = 1000.0$, $\rho_0 = 1.0$	$u^i = (0.0, 0.0, 0.0)$ $B^i/\sqrt{4\pi} = (1.0, 0.0, 0.0)$ $P = 1.0$, $\rho_0 = 0.1$	$n = 200$	1.0
Shock tube 2	$u^i = (0.0, 0.0, 0.0)$ $B^i/\sqrt{4\pi} = (0.0, 20.0, 0.0)$ $P = 30.0$, $\rho_0 = 1.0$	$u^i = (0.0, 0.0, 0.0)$ $B^i/\sqrt{4\pi} = (0.0, 0.0, 0.0)$ $P = 1.0$, $\rho_0 = 0.1$	$n = 200$	1.0
Collision	$u^i = (5.0, 0.0, 0.0)$ $B^i/\sqrt{4\pi} = (10.0, 10.0, 0.0)$ $P = 1.0$, $\rho_0 = 1.0$	$u^i = (-5.0, 0.0, 0.0)$ $B^i/\sqrt{4\pi} = (10.0, -10.0, 0.0)$ $P = 1.0$, $\rho_0 = 1.0$	$n = 200$	1.22

[a]In all cases, the gas satisfies the Γ-law EOS with $\Gamma = 4/3$. For the first 7 tests, the left state refers to $x < 0$ and the right state $x > 0$.
[b]μ is the speed at which the wave travels.
[c]For the nonlinear Alfvén wave, the left and right states are joined by a continuous function separated by 0.5 units.

The amount of gravitational waves emitted by bubble collisions and turbulence generated in the plasma are also determined from two quantities, κ and v_b. κ is the fraction of vacuum energy transferred into fluid kinetic energy and v_b is the velocity of bubble wall expansion. Bubble walls can propagate via two modes, detonation and deflagration [4, 5, 12–14]. For detonation, the bubble walls are thin compared to the radius and they propagate faster than the speed of sound. This results in

$$v_b(\alpha) = \frac{1/\sqrt{3} + (\alpha^2 + 2\alpha/3)^{1/2}}{1+\alpha},$$
$$\kappa(\alpha) = \frac{1}{1+0.715\alpha}\left[0.715\alpha + \frac{4}{27}\sqrt{\frac{3\alpha}{2}}\right]. \quad (2)$$

If the bubbles propagate by deflagration, the walls are thick and have a lower energy density. It is currently believed that for a relativistic plasma, the deflagration expansion mode is unstable so only the detonation modes will result.

The number density of turbulent eddies within a Hubble radius should depend on v_b and β. The characteristic velocity perturbation of the turbulent fluid for the largest eddies at the stirring scale is given by

$$v_0 = \sqrt{\frac{3\kappa\alpha}{4+3\kappa\alpha}}. \quad (3)$$

For $\kappa\alpha \approx 1$, which corresponds to a strongly first order phase transition, v_0 is about 0.65 at the time of the electroweak phase transition. We later use v_0 as the maximum velocity of fluid elements in our studies. This velocity is randomized in amplitude and direction in order to simulate the initial conditions for turbulence.

2.2. Computational Model. In order to study the interaction of the plasma field and the background spacetime dynamically (or separately) our team has written and is testing/improving a GRMHD code implemented using the Cactus framework [21]. We now describe the basic variables and equations that constitute this model.

2.2.1. The Spacetime Evolution Model. The spacetime metric can be written as

$$ds^2 = -N^2 dt^2 + \gamma_{ij}(\vec{x},t)\left(dx^i + N^i dt\right)\left(dx^j + N^j dt\right). \quad (4)$$

Here N is the lapse, N^i is the shift vector, and γ_{ij} is the spatial 3-metric [22, 23]. For this work, 3-metric and its "time-derivative," the extrinsic curvature, "K_{ij}" will be evolved using a strongly hyperbolic version of the BSSN formulation of numerical relativity [24].

2.2.2. The General Relativistic Magnetohydrodynamic Model. The fluid and electromagnetic fields of the GRMHD equations are developed from several well-known equations [25]. They include the conservation of particle number, the continuity equation, the conservation of energy-momentum, the magnetic constraint equation, and the magnetic induction equation. For a system consisting of a perfect fluid and an electromagnetic field, the ideal MHD stress-energy tensor is given by

$$T^{\mu\nu} = \left(\rho_0 h + b^2\right)u^\mu u^\nu + \left(P + \frac{b^2}{2}\right)g^{\mu\nu} - b^\mu b^\nu,$$
$$h = 1 + \epsilon + \frac{P}{\rho_0},$$
$$b^\mu = \frac{1}{\sqrt{4\pi}}B^\mu_{(u)}, \quad (5)$$
$$B^0_{(u)} = \frac{1}{\alpha}u_i B^i,$$
$$B^i_{(u)} = \frac{1}{u^0}\left(\frac{B^i}{\alpha} + B^0_{(u)}u^i\right).$$

Here, P is the fluid pressure, ρ_0 is density, B^i is magnetic field, u^μ is four-velocity, h is the enthalpy, ϵ is specific internal energy, and b^2 is the magnitude of the magnetic vector field squared. The addition of viscosity modifies the MHD stress-energy tensor by incorporating the viscous stress tensor:

$$T^{\mu\nu} = \left(\rho_0 h + b^2 + Q\right)u^\mu u^\nu + \left(P + \frac{b^2}{2}\right)g^{\mu\nu} - b^\mu b^\nu + \Sigma^{\mu\nu}. \quad (6)$$

Here Q is artificial bulk viscosity and $\Sigma^{\mu\nu}$ is the viscous stress tensor for artificial shear viscosity. Artificial viscosity is used here as a way of handling shocks although we are working on integrating more advanced HRSC techniques. Our viscosity terms [26] are described and defined below and are only meant to be used when the divergence of the fluid flow is negative:

$$Q = I_n \Delta l \partial_k V^k \left(k_q \Delta l \partial_k V^k - k_l C_s\right),$$
$$\Sigma^i_j = I_n \Delta l \left(k_q \Delta l \partial_k V^k - k_l C_s\right)\mathrm{Sym}\left(\delta_j V^i - \frac{\partial_k V^k}{3}\delta^i_j\right), \quad (7)$$
$$I_n = \left(\rho + \rho\epsilon + \left(P + Q + b^2\right)\right)N.$$

In these equations V^i is the fluid velocity, C_s is the local speed of sound, Δl is the minimum covariant zone length, and k_q and k_l are constants multiplying the quadratic and linear contributions, respectively. The $\mathrm{Sym}(\cdots)$ function in the shear viscosity equation is a symmetry operation.

Dark matter can be added to the system using a two-fluid approach where the stress energy tensor for dark matter is added directly to the stress energy tensor for the magnetofluid, therefore, completing the right-hand side of Einstein's equation.

2.2.3. Initial Conditions: Plasma Field. In order to get a more accurate picture of the primordial gravitational wave spectrum, we directly simulate the turbulent primordial universe with the most realistic initial conditions possible.

These should include not only a plasma field with a realistic EOS, they should also include elements such as magnetic fields, dark matter, and possibly even gravitational waves produced by other sources.

The study will begin at $t > 10^{-6}$ seconds after the Big Bang near the beginning of the Hadron epoch, when the primordial plasma field began to look like relativistic plasma and the strong force could be safely ignored. At this point the Debye length is about 10^{-16} m so even a small computational domain should demonstrate the dynamics of the plasma. The plasma at this time was composed mainly of electrons, positrons, neutrinos, and photons. Many of the initial conditions at this epoch are well known or can be fairly easily calculated using the available literature [27]. In addition, given that most cosmological models agree that over 80% of the matter in the universe is composed of dark matter, our cosmological simulations can also include some nonmagnetized "dark" fluid. We can take this into account by adding a second pressureless nonmagnetized fluid to our initial plasma field.

The initial matter field will be taken to be homogenous and turbulent. We introduce turbulence into the system by randomly varying the initial velocities of the fluid elements up to the magnitude of v_0, (3). In addition, we will be working to better establish the initial conditions resulting from the first order EWPT. Based on arguments in previous work [15–17, 28, 29], the initial magnetic field during this epoch should be less than or equal to 10^{17} G.

2.2.4. Initial Conditions: Spacetime. For this computational study the initial spacetime is constructed in such a way as to mimic the conditions present during the Hadron epoch ($t > 10^{-6}$ seconds). I choose to begin the simulation during the Hadron epoch because at that time the primordial plasma field appeared to look like a relativistic plasma field that could be modeled using a GRMHD code as opposed to a quark gluon plasma field. At this time the strong force could be safely ignored as electromagnetic effects would dominate the plasma's dynamic motions. Also, at this time any EWPT would be complete.

Although initial calculations will use a fixed spacetime background, where the background metric is not evolved, we may find it necessary to dynamically model the turbulent/spacetime interactions in order to fully understand the physics of the early universe. To do this, we need good initial conditions for the curvature of space during this epoch.

The Robertson-Walker (R-W) spacetime metric for a flat universe can be written as

$$ds^2 = -dt^2 + a^2(t)\,\overline{g}_{ij}dx^i dx^j, \tag{8}$$

where t is the time-like coordinate, $\overline{g}_{ij}$ is the maximally symmetric three-dimensional space metric, and $a(t)$ is the scale factor. For calculating the initial spacetime, conformal time, $\tau = -(1/a(t)H(t))$ is often used instead of cosmic time, $t = t_0 a^2$, to simplify the equations. Therefore,

$$ds^2 = a^2(\tau)\,g_{\mu\nu}dx^\mu dx^\nu. \tag{9}$$

Here, the scale factor and Hubble parameter can be calculated based on the temperature and mass-energy density of the early universe relative to today. In order to add gravitational waves, the metric $g_{\mu\nu}$ is broken into two components: $\widetilde{g}_{\mu\nu}$ the background metric plus a perturbation $h_{\mu\nu}$. The metric can be written as

$$g_{\mu\nu} = \widetilde{g}_{\mu\nu} + h_{\mu\nu}. \tag{10}$$

The background metric may take any form. It is also assumed that any perturbations are linear. For this study, a R-W metric is presumed. Initial perturbations may or may not be used for numerical experiments within this study. This metric may involve scalar, (ϕ, ψ) vector (ω_i), and tensor (h_{ij}) perturbations, (1). The tensor perturbations are symmetric and transverse-traceless so $\partial_i h^{ij} = 0$ and $\delta^{ij}h_{ij} = 0$. The initial amplitude and spectrum of any of these fluctuations depend on the theory used to explain the generation of perturbations from inflation. Note that by comparing (4) and (1), it can be shown that scalar (ϕ) and vector (ω_i) perturbations can be related to the chosen lapse and shift in the same way that scalar (ψ) and tensor (h_{ij}) perturbations can relate to the three-metric and extrinsic curvature. Because the focus here is on tensor perturbations, a geodesic slicing is used so the lapse, N, is set to unity and the shift vector, N^i, is set to zero. Since there are no singularities in either the proposed study or the tests described in Section 3, geodesic slicing should be sufficient for this work. Later, if scalar perturbations are included, they can be added by modifying the lapse, as well as the three-metric and extrinsic curvature.

The process of generating tensor perturbations or gravitational waves from quantum fluctuations during inflation is similar to the process of generating scalar or vector perturbations. For example, work by Grishchuk [30–32] gives a basis for calculating the spectrum and amplitude of these waves for different slow-roll parameters.

The possibility of all polarizations is included using $h^+_{ij}, h^\times_{ij}, h^L_{ij}$, and h^R_{ij}. Here, h^+_{ij} and $h^\times_{ij}$ are the plus and cross-polarizations, respectively, and h^L_{ij} and h^R_{ij} are the left and right rotating polarizations defined by

$$h^L_{ij} = \frac{1}{\sqrt{2}}\left(h^+_{ij} - ih^\times_{ij}\right), \qquad h^R_{ij} = \frac{1}{\sqrt{2}}\left(h^+_{ij} + ih^\times_{ij}\right). \tag{11}$$

According to work by Alexander and Martin [33], rotating polarizations should dominate in the early universe and satisfy the equations:

$$\Box h^L_{ij} = -2i\theta \dot{h}'^L_{ij}, \qquad \Box h^R_{ij} = +2i\theta \dot{h}'^R_{ij}. \tag{12}$$

Here, the dot denotes a time-like derivative with respect to τ and the prime denotes a spatial derivative along the gravitational wave's direction of propagation. If Alexander's θ value is set to zero, the unpolarized gravitational wave signature is recovered [34]. For this work, rotational polarizations may have the added benefit of introducing extra vorticity into the homogeneous plasma. This may result in an increased magnetic field due to the dynamo effect. During inflation, a nonzero θ term results in a decrease in the amplitude of h^L and an amplification of h^R and, therefore, cosmological birefringence.

Initial gravitational wave spectra from sources such as bubble collisions or phase transitions can be added linearly. Therefore, the initial gravitational wave spectrum can correspond to those predicted by supersymmetry, loop quantum gravity, string theory, deformed special relativity, variable speed of light theories, or many other theoretical models in order to provide potential tests of theoretical physics once the system is evolved with the turbulent matter field.

2.2.5. Numerical Evolutions. The development of a stable and accurate GRMHD code has been a work in progress for the past several years. We now have a new GRMHD code in the testing and improvement stage. This code is designed to perform spacetime evolutions using either 2nd order finite, 4th order finite, or Fourier pseudospectral differencing methods with magnetohydrodynamic and pressure-less matter fields as well as various boundary and gauge conditions. The code can evolve the matter field independently of the spacetime in cases where a fully dynamic spacetime is not needed so the spacetime metric does not have to be evolved.

We utilize the Cactus framework to develop this code. We developed an arrangement for Cactus that contains the GRMHD initial data, analysis, and evolution thorns. This code handles the physics, while Cactus does the IO and parallelization. The code is structured so that all the differencing is done outside of the main loops. This allows us to choose between several differencing techniques such as finite differencing or Fourier spectral differencing at runtime. We also used the Cactus method of lines routines to supply the time integrators. The spacetime (LHS of Einstein's equations) can be evolved using a strongly hyperbolic form of the BSSN equations as defined by Brown et al. [24]. The matter field (RHS of Einstein's equations) is evolved by the form of the GRMHD equations as defined by Duez et al. [23] with divergence cleaning and artificial viscosity. Periodic boundary conditions are also used so that the simulation domain can accurately represent a homogenous slice of a much larger universe.

In addition to developing an accurate GRMHD evolution code, it is important to extrapolate the data so that it can be compared to cosmological observations. Gravitational waves can be calculated directly from the stress-energy tensor using its quadrupole moments. By doing this, the spectrum and relative amplitude of primordial gravitational waves created as a result of the turbulence in the matter field can be determined. Eventually, these results can be compared to stochastic gravitational wave data from GW observatories and observations of the cosmic microwave background.

There are many challenges to evolving the numerical code. First, there are the standard difficulties of dealing with a nonlinear code. Speed and accuracy are the most important issues. Also, there are additional challenges because the GRMHD code utilizes a nonlinear primitive variable solver to recover elements of the stress-energy tensor from the MHD evolution variables, shock capturing techniques, and a technique called divergence cleaning to maintain physical values for the *B*-field. Optimizing and improving these solvers are essential to developing a fast, accurate, and stable code.

Before running the experiments we thoroughly tested the code. The Duez et al. paper [23] suggested four tests of a GRMHD code; however, because of the limited scope of this study I felt that only the following tests are necessary: gravitational wave-induced MHD waves, Minkowski spacetime MHD tests, such as shock tests and consistency with the standard model of cosmology. I will not include tests of unmagnetized relativistic stars or relativistic Bondi flow in this paper because the spacetime that they are simulating lacks stars and black holes.

This code is being developed and run on a variety of computing resources including: UHCL's Athena cluster, University of Houston's Maxwell cluster, and University of Texas' Ranger cluster via the XSEDE network.

2.2.6. Data Analysis. The data analysis part of this project will focus around determining the gravitational wave spectrum from the simulation. A Fourier analysis of the quadrupole moments of the stress-energy tensor should yield the spectrum of gravitational waves produced by the turbulent matter field. Much of the data analysis work consists of the addition and fine tuning of new analysis routines in the code.

Visualization of Cactus-generated data is done using a variety of open-source software such as VisIt, xgraph, ygraph, and gnuplot. Each requires implementation scripts to be written. These scripts will tell the visualization program how to read the Cactus-generated data files. Modifications of the data include fast Fourier transforms (FFT) for spectral analysis.

As these numerical experiments are being performed, the output is analyzed. The effects of variations in the density, temperature, magnetic field, and initial turbulence will be studied in the output data. A Fourier analysis of the perturbed quadrupole moments will be performed in order to extract the spectrum of gravitational waves. This spectrum will then be extrapolated to give the current observable values. The result will be several templates of GW spectra resulting from different initial conditions.

3. Testing the Code

The first test that we performed involved generating Alfvén and magnetosonic modes by gravitational waves and comparing the results against the semianalytic solutions from the Duez et al. paper [20]. This semianalytic solution is only valid for a time much less than the dynamical collapse time of

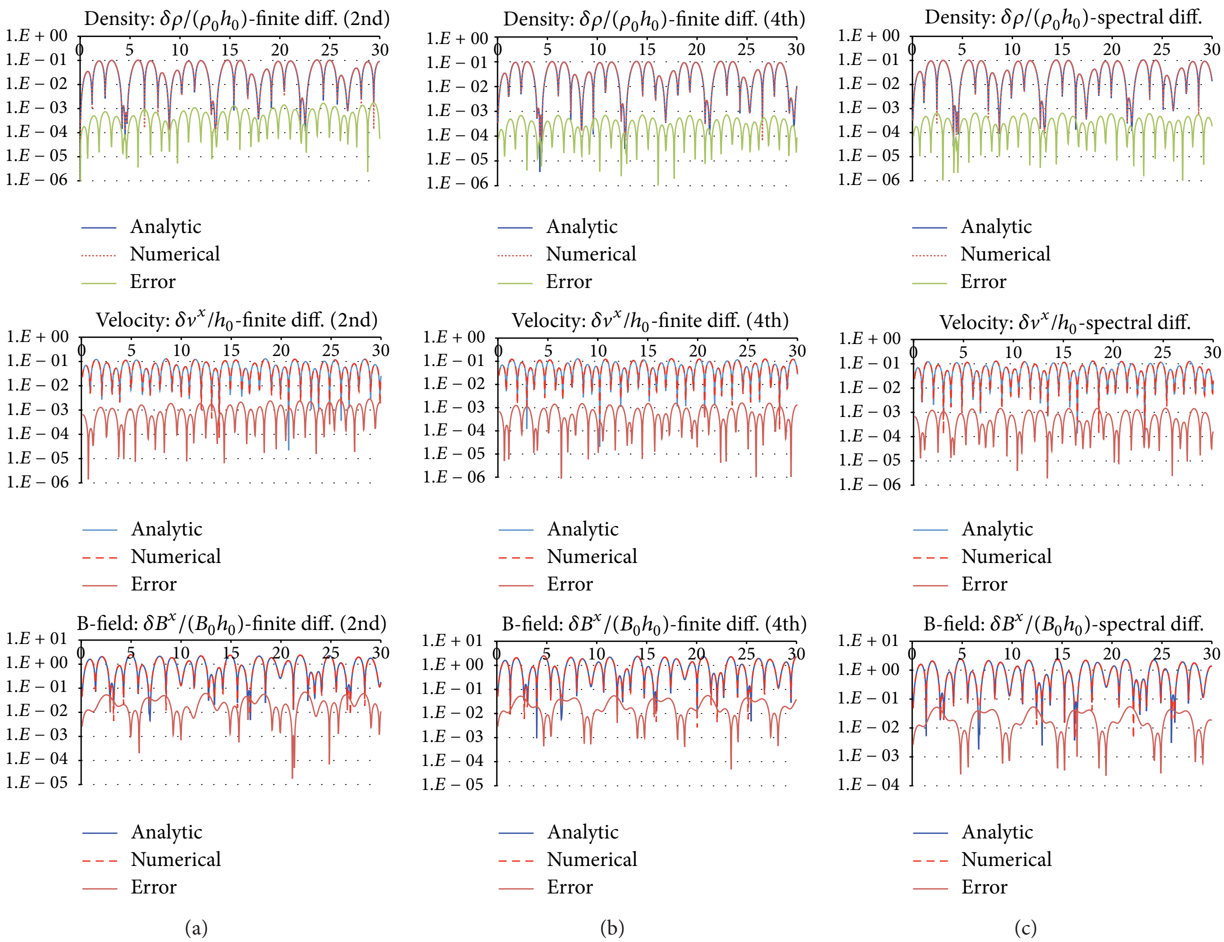

FIGURE 1: Gravitational wave-induced MHD waves test results. The left column used 2nd order finite differencing, the middle column used 4th order finite differencing, and the right column used Fourier spectral differencing. Density is displayed here by calculating $\delta\rho/(\rho h_0)$, velocity is displayed here by calculating $\delta v^x/h_0$, and B-field is displayed here by calculating $\delta B^x/(B_0 h_0)$ as in the Duez et al. paper [23]. Time is shown on the x-axis. Because the physical size of the grid is 2 units, a time of 30 units represents 15 crossing times.

the unperturbed fluid. We began by using the same initial conditions as defined by Duez et al. 's general example [23]:

$$\begin{gathered}
h_+(t,z) = h_{+0}\sin(kz)\cos(kt),\\
h_\times(t,z) = h_{\times 0}\sin(kz)\cos(kt),\\
P(0,z) = 1.29\times 10^{-9}, \qquad \rho_0(0,z) = 2.78\times 10^{-9},\\
v^i(0,z) = 0, \qquad B^i(0,z) = (1.09, 8.26, 14.4)\times 10^{-5},\\
h_{+0} = h_{\times 0} = 1.18\times 10^{-4},
\end{gathered} \tag{13}$$

where k is the wave number and we assume the fluid is unperturbed at $t = 0$. Results are shown in Figure 1. The test was performed using second order, fourth order, and Fourier spectral differencing as a one-dimensional problem. The results shown used 200 grid points for the second order differencing, 50 grid points for the fourth order differencing, and 32 grid points for the spectral differencing. Additional tests were performed where the initial conditions were varied. For every variation the test proved successful, the analytic and numerical results proved almost identical to within a few percent. Runs were also conducted with 100, 25, and 16 grid points for the second order, fourth order, and spectral differencing, respectively, in order to test for convergence. As shown in Figure 1, the main source of errors in this test was phase errors between the analytic and numerical solutions. This made calculating convergence difficult. We were able to calculate convergence of the results at each time by dividing the L2 norm of the errors of the low resolution runs by that of the high resolution runs. The result was an oscillating pattern with a mean, after 5 crossing times, of around 2.4 for the 2nd order finite differencing, 4.67 for the 4th order finite differencing, and 2.7 for the Fourier Spectral differencing. A major factor affecting the convergence rate may be the larger time steps taken in the low resolution runs. Although we cannot show that the overall convergence rate matches that of the differencing method, we can show that the code does converge for each differencing method.

For our second test we utilized a FRW spacetime that contained parameters (temperature, energy density, Hubble parameter, and scale factor) based with those accepted for the

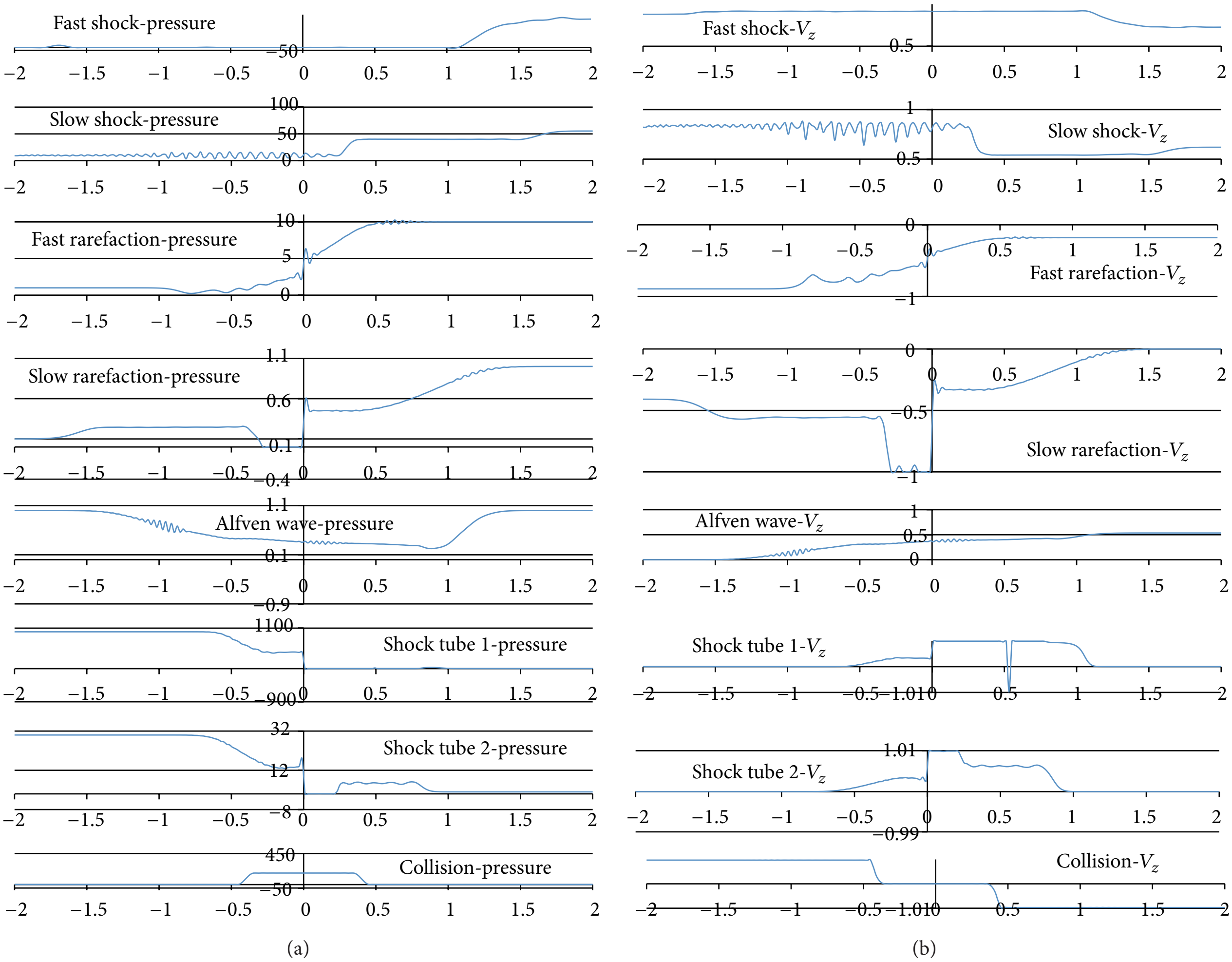

FIGURE 2: Shock test results shown using second order finite differencing and artificial viscosity at t_{final} time. The pressure profiles are shown on the left and the z component of velocity profiles are shown on the right.

universe at $t = 10^{-6}$ s. The goal of the test was to determine if it evolved consistently with the Friedmann equations. We set the initial scale factor $a = 6.6 \times 10^{-14}$, the initial Hubble parameter $H = 1.4 \times 10^{26}$ km/s/Mpc, the initial temperature $T = 4.1 \times 10^{13}$ K, and the initial energy density $\rho_0\epsilon = 1.1 \times 10^{23}$ J/m^3. The system evolved until around $t = 86$ s and the final value of these parameters was found at the end of the simulation. The code's calculated change in each parameter was then compared to the values predicted from the Friedmann equations in order to determine how well the code's results matched the analytic solution. The final time, 86 s, corresponded to physical age of the simulated universe after seven days of computing time and was not chosen to have any particular relationship to the physical size of the domain. There were no structures or inhomogeneities in the system so spacial resolution was not important in this test. This test proved successful with the errors of less than one percent as shown in Table 1.

At this point we are prepared to add standing gravitational waves with a spectrum consistent to Grishchuk's predictions [30–32]. The gravitational waves were given random phases in order to avoid large nodes and antinodes. We then ran simulations with spacetime perturbations and large (10^{17} Gauss) magnetic fields. These simulations showed that spacetime perturbations and magnetic fields had no significant impact on the expansion rate of the spacetime and therefore adding them should still result in a simulation consistent with cosmological theory to within the same error as found in Table 1.

Finally, we conducted shock tests using similar initial conditions to Duez et al. [23] and Komissarov [35] as shown in Table 2. The results shown are based on runs utilizing the second order finite differencing method. The fourth order finite differencing method gives similar results, as expected, although the fourth order tests were conducted using a lower resolution grid. These tests could not be completed with our Fourier spectral differencing method because the suggested shock tests are not periodic in nature. Future work may involve testing all three differencing methods using a periodic shock test, but the current results suggest that this may not be a worthwhile effort until HRSC techniques can be incorporated into the code.

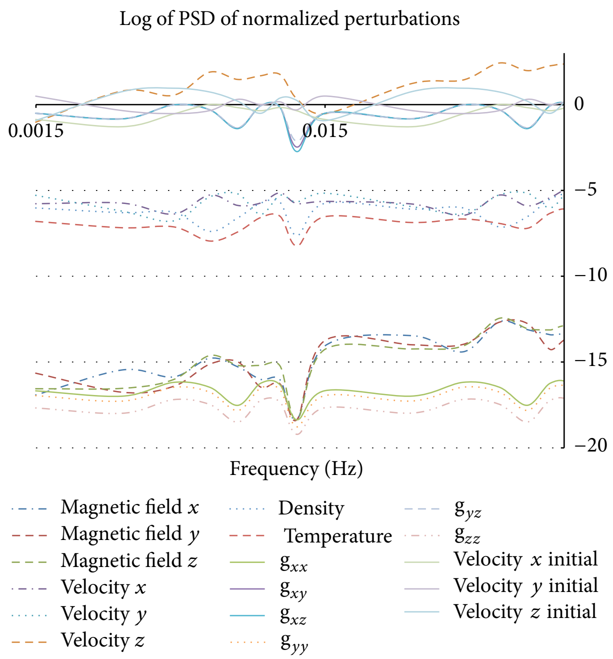

FIGURE 3: Logarithms of the power spectral densities of several quantities after a turbulent relativistic plasma were evolved using the GRMHD code from 10^{-6} s to around 3.5×10^{-5} s. The perturbations were normalized using the mean amplitude of each quantity before the PSD was calculated.

Overall, the artificial viscosity methods used in this code seemed to produce less accurate results than the high resolution shock capturing methods used by Duez et al. [23] and Komissarov [35]. *Fast and Slow Shocks*: the shock fronts for both of these cases were more distorted than the results of Duez et al. [23] and Komissarov [35]. Also, the fast shock appeared to move slower than the slow shock which does not seem to agree with the standard results. *Switch-on/off Rarefaction*: while the switch-off (fast rarefaction) seemed to agree with the published results the switch-on (slow rarefaction) appeared distorted at the shock front. *Alfvén Wave*: our Alfvén wave results seemed to agree with the published results except for the extra dip for $z < 0$. *Shock Tubes 1 and 2*: shock tube tests also produced distorted shock fronts, particularly for $z > 0$. *Collision*: the collision test produced the best results when compared to the established results.

4. Preliminary Results

In order to present a relevant proof of concept on the use of GRMHD in cosmology, we evolve a turbulent plasma field, with conditions similar to the universe when it was 10^{-6} s old. We use similar conditions as outlined in Section 2.2.3 and the consistency of standard model of cosmology parameters test with an initial uniform magnetic field of 10^{15} G. No initial gravitational waves or dark matter was included in the system. We also introduced turbulence with a random initial velocity of 0.65.

The data presented in Figure 3 correspond to evolving the initial conditions stated above to around 3.5×10^{-5} s. Before calculating the PSDs of each of the quantities, they were normalized by dividing the perturbation amplitude by the mean value of the quantity. The results where plotted logarithmically for a frequency range from 0.0015 Hz to 0.12 Hz. Although the simulation was run to 3.5×10^{-5} s, the normalized PSDs did not seem to vary much after about a hundred iterations. The normalized PSDs of the relevant parameters were plotted on a logarithmic scale for a frequency range relevant to a potential space based gravitational wave interferometer such as eLISA. The results show that for strong uniform initial magnetic fields, noticeable perturbations are generated in the spacetime metric, density, temperature, and magnetic field terms which are different from the perturbations in the velocity field. Perturbations in the metric are the most interesting of these results because they correspond to gravitational waves. These were vanishingly small for magnetic fields less than or equal to 10^{12} G. Much more work is needed to more fully understand the dynamics of the interaction between GRMHD turbulence and gravitational waves, but the results so far clearly show that gravitational wave generation from primordial turbulence is possible.

5. Discussion

We now have several parameters to work with in developing numerical experiments. Assuming the expansion properties of the background spacetime and composition of the matter field are fixed, we can alter the metric perturbations (scalar and tensor), initial magnetic field strength, and the turbulence of the initial matter field. By altering these properties, we can perform a variety of numerical experiments to determine the effects of scalar perturbations and gravitational waves on structure formation, limits on primordial magnetic fields, properties of gravitational waves formed by turbulent plasma, the dynamics of a turbulent plasma in an expanding universe, and other interesting scientific properties.

One of the most interesting of these experiments involves the interaction between gravitational waves and the primordial plasma. Work by Duez et al. [20] showed that gravitational waves can induce oscillatory modes in a plasma. According to Shebalin [36–38], large-scale coherent structures grow naturally out of MHD turbulence. Here, structure is defined as strengthening magnetic fields, permanent density and temperature variations, and secondary relic gravitational waves. One can assume that spacetime perturbations in the early universe (sometime after $t = 10^{-6}$ seconds) interacted with the primordial plasma and resulted in Alfvén and magnetosonic modes [20]. These modes then interacted dynamically, possibly resulting in turbulence and structure formation [36–38]. Using the techniques of numerical relativity, we can test this assumption.

Conflict of Interests

The author declares that there is no conflict of interests regarding the publication of this paper.

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References

[1] V. F. Mukhanov, H. A. Feldman, and R. H. Brandenberger, "Theory of cosmological perturbations," *Physics Report*, vol. 215, no. 5-6, pp. 203–333, 1992.

[2] H. Kodama and M. Sasaki, "Cosmological perturbation theory," *Progress of Theoretical and Experimental Physics Supplement*, vol. 78, pp. 1–66, 1984.

[3] R. K. Sachs and A. M. Wolfe, "Perturbations of a cosmological model and angular variations of the microwave background," *The Astrophysical Journal*, vol. 147, pp. 73–90, 1967.

[4] T. Kahniashvili, A. Kosowsky, G. Gogoberidze, and Y. Maravin, "Detectability of gravitational waves from phase transitions," *Physical Review D*, vol. 78, no. 4, Article ID 043003, 2008.

[5] C. Caprini, R. Durrer, and D. Physical Review, "Gravitational waves from stochastic relativistic sources: primordial turbulence and magnetic fields," vol. 74, Article ID 063521, 2006.

[6] C. Caprini, R. Durrer, and G. Servant, "The stochastic gravitational wave background from turbulence and magnetic fields generated by a first-order phase transition," *Journal of Cosmology and Astroparticle Physics*, vol. 2009, article 024, 2009.

[7] A. D. Dolgov, D. Grasso, and A. Nicolis, "Relic backgrounds of gravitational waves from cosmic turbulence," *Physical Review D*, vol. 66, Article ID 103505, 2002.

[8] G. Gogoberidze, T. Kahniashvili, and A. Kosowsky, "The spectrum of gravitational radiation from primordial turbulence," *Physical Review D*, vol. 76, Article ID 083002, 2007.

[9] T. Kahniashvili, "Gravitational radiation from primordial helical turbulence," submitted, http://arxiv.org/abs/astro-ph/0508459.

[10] T. Kahniashvili, G. Gogoberidze, and B. Ratra, "Polarized cosmological gravitational waves from primordial helical turbulence," *Physical Review Letters*, vol. 95, no. 15, Article ID 151301, 2005.

[11] T. Kahniashvili and B. Ratra, "CMB anisotropies due to cosmological magnetosonic waves," *Physical Review D*, vol. 75, Article ID 023002, 2007.

[12] T. Kahniashvili, L. Campanelli, G. Gogoberidze, Y. Maravin, and B. Ratra, "Gravitational radiation from primordial helical inverse cascade magnetohydrodynamic turbulence," *Physical Review D*, vol. 78, Article ID 123006, 2008, Erratum-ibid. D, vol. 79, Article ID 109901, 2009.

[13] T. Kahniashvili, L. Kisslinger, and T. Stevens, "Gravitational radiation generated by cosmological phase transition magnetic fields," *Physical Review D*, vol. 81, Article ID 023004, 2010.

[14] A. Nicolis, "Relic gravitational waves from colliding bubbles and cosmic turbulence," *Classical and Quantum Gravity*, vol. 21, no. 4, p. L27, 2004.

[15] E. Battaner and H. Lesch, "On the physics of primordial magnetic fields," submitted, http://arxiv.org/abs/astro-ph/0003370.

[16] D. Grasso and H. R. Rubinstein, "Magnetic fields in the early Universe," *Physics Reports*, vol. 348, no. 3, pp. 163–266, 2001.

[17] A. D. Dolgov, "Generation of magnetic fields in cosmology," in *From Integrable Models to Gauge Theories*, V. G. Gurzadyan and A. G. Sedrakian, Eds., pp. 143–154, 2002.

[18] F. Hoyle, "The Origin of the rotations of the galaxies," in *Problems of Cosmical Aerodynamics, Proceedings of the Symposium on the Motion of Gaseous Masses of Cosmical Dimensions*, pp. 195–197, Central Air Documents Office, Paris, France, 1949.

[19] H. Murayama and A. Pierce, "Realistic dirac leptogenesis," *Physical Review Letters*, vol. 89, Article ID 271601, 2002.

[20] M. D. Duez, Y. T. Liu, S. T. Shapiro, and B. C. Stephens, "Excitation of magnetohydrodynamic modes with gravitational waves: a testbed for numerical codes," *Physical Review D*, vol. 72, Article ID 024029, 2005.

[21] D. Garrison, "Did gravitational waves affect the evolution of the universe?" submitted, http://arxiv.org/abs/0808.1764.

[22] T. W. Baumgarte and S. L. Shapiro, "Numerical integration of Einstein's field equations," *Physical Review D*, vol. 59, Article ID 024007, 1999.

[23] M. D. Duez, Y. T. Liu, S. T. Shapiro, and B. C. Stephens, "Relativistic magnetohydrodynamics in dynamical spacetimes: numerical methods and tests," *Physical Review D*, vol. 72, Article ID 024028, 2005.

[24] J. D. Brown, P. Diener, S. E. Field et al., "Numerical simulations with a first-order BSSN formulation of Einstein's field equations," *Physical Review D*, vol. 85, Article ID 084004, 2012.

[25] C.F. Gammie, J. C. McKinney, and G. Tóth, "HARM: a numerical scheme for general relativistic magnetohydrodynamics," *The Astrophysical Journal*, vol. 589, no. 1, pp. 444–457, 2003.

[26] P. Anninos, P. C. Fragile, and J. D. Salmonson, "*COSMOS++*: relativistic magnetohydrodynamics on unstructured grids with local adaptive refinement," *Astrophysical Journal Letters*, vol. 635, no. 1 I, pp. 723–740, 2005.

[27] J. N. Islam, *An Introduction to Mathematical Cosmology*, Cambridge University Press, Cambridge, UK, 1992.

[28] K. Jedamzik, V. Katalinić, and A. V. Olinto, "Limit on primordial small-scale magnetic fields from cosmic microwave background distortions," *Physical Review Letters*, vol. 85, no. 4, pp. 700–703, 2000.

[29] A. L. Maroto, "Cosmological magnetic fields induced by metric perturbations after inflation," submitted, http://arxiv.org/abs/hep-ph/0111268.

[30] L. P. Grishchuk, "The detectability of relic (squeezed) gravitational waves by laser interferometers," submitted, http://arxiv.org/abs/gr–qc/9810055.

[31] L. P. Grishchuk, "Relic gravitational waves and their detection," *Lecture Notes in Physics*, vol. 562, pp. 167–194, 2001.

[32] L. P. Grishchuk, "Gravitational wave astronomy: in anticipation of first sources to be detected," *Physics-Uspekhi*, vol. 44, no. 1, p. 1, 2001, Uspekhi Fizicheskikh Nauk, vol. 171, no. 3, 2001.

[33] S. Alexander and J. Martin, “Birefringent gravitational waves and the consistency check of inflation,” *Physical Review D*, vol. 71, Article ID 063526, 2005.

[34] D. Garrison and R. de La Torre, “Numerical analysis of simplified relic-birefringent gravitational waves,” *Classical and Quantum Gravity*, vol. 24, no. 23, pp. 5889–5899, 2007.

[35] S. S. Komissarov, “On the properties of Alfvén waves in relativistic magnetohydrodynamics,” *Physics Letters A*, vol. 232, no. 6, pp. 435–442, 1997.

[36] J. V. Shebalin, “The statistical mechanics of idealhomogeneous turbulence,” NASA TP-2002-210783, 2002.

[37] J. V. Shebalin, “Theory and Simulation of real and ideal magnetohydrodynamic turbulence,” *Discrete & Continuous Dynamical Systems B*, vol. 5, pp. 153–175, 2005.

[38] J. V. Shebalin, “Broken symmetries and magnetic dynamos,” *Physics of Plasmas*, vol. 14, no. 10, Article ID 102301, 2007.

Gauge Field Turbulence as a Cause of Inflation in Chern-Simons Modified Gravity

David Garrison[1]

University of Houston-Clear Lake, 2700 Bay Area Blvd., Houston, TX, USA
(E-mail: garrison@uhcl.edu)

Abstract. In this paper, we study the dynamics of the Chern-Simons Inflation Model proposed by Alexander, Marciano and Spergel. According to this model, inflation begins when a fermion current interacts with a turbulent gauge field in a space larger than some critical size. This mechanism appears to work by driving energy from the initial random spectrum into a narrow band of frequencies, similar to the inverse energy cascade seen in MHD turbulence. In this work we focus on the dynamics of the interaction using phase diagrams and a thorough analysis of the evolution equations. We show that in this model inflation is caused by an over-damped harmonic oscillator driving waves in the gauge field at their resonance frequency.

Keywords: Turbulance modeling, Cosmology, Chern-Simons Modified Gravity, Simulation, Chaotic simulation.

1 Introduction

According to accepted cosmological theory, the early universe went through a period of inflation where it's size increased by at least 60 e-folds in a small fraction of a second [9]. There is a wealth of observational data providing evidence that inflation occurred [1]. In addition, Inflation is needed to satisfy several fundamental problems in cosmology such as the flatness and horizon problems. Unfortunately, most theories of inflation involve the existence of a scalar field and are difficult to distinguish by observation or experiment. Also, there are still many unanswered questions about where the scalar field came from or why it disappeared after inflation ended. Recently, Alexander et al. [3] suggested a new theory of cosmic inflation based on Chern-Simons modified gravity [4] Unlike scalar field theories of inflation, the theory proposed by Alexander et al. utilizes the interaction between a gauge field and fermion current to drive inflation and does not depend on the existence of a scalar field. This is not the only theory of inflation derived from a vector field interaction [6] but it is unique in that it involves elements that are known to exist in practice and not just in theory.

The Chern-Simons Inflation theory works by suggesting that the energy density from the interaction between the gauge field and fermion current behaves like vacuum energy. This is possible in Chern-Simons modified gravity. The gauge field starts with a random white noise spectrum but then the energy is transported to a few low frequency modes. In the early version of the paper by Alexander et al, the spatial parts of the gauge field and fermion current where used to derive the energy density. They later changed that and based the energy density on the temporal parts of the gauge field and fermion current. This author believes that the motivation for this change may have been the belief that the spatial part of the fermion current dropped to zero too quickly to be effective in driving inflation. We find this to not be the case. We also find that the temporal part of the gauge field and fermion current may not be sufficient to drive a 60 e-fold increase in scale factor.

Our code utilizes the Adler-Bell-Jackiw (ABJ) chiral anomaly [2,5] to model the decrease in fermion current associated with changes in the scale factor and gauge field. This is a small quantum mechanical violation of the conservation of axial-vector current. This violation occurs due to tunneling of fermions from one vacuum to another and is partially responsible for the gentle ending of the inflation event. It is the means by which the gauge field converts to leptons during inflation resulting in lepto-genesis. As the current decreases during inflation, the negative pressure driving inflation should decrease as well unless the decrease in current is offset by an increase in the gauge field.

The overall goal of the study presented here is to understand the dynamics of the system and strengthen our physical interpretation of the theory presented here. The author's previous paper on the Numerical Simulation of Chern-Simons Inflation [7] served to prove the feasibility of the theory. Additional work is being planned to more thoroughly study the version of the theory involving the temporal part of the gauge field and fermion current both alone and in conjunction with the spatial part. In the following sections, we will describe in more detail what we believe is the most promising model of Chern-Simons Inflation as well as the results of computer simulations of this model. In the final section, we will discuss these results and how they may be used in future research.

2 Model and Simulations

The code utilized in these simulations is based on the Cactus framework [8] used for Numerical Relativity research. While Cactus is an extremely sophisticated code containing millions of lines of code, all the physics is contained in code written by the author. This code has been thoroughly tested and the results are self-consistent and reliable.

The inflation model developed by Alexander, Marciano and Spergel utilizes a gauge field which interacts with fermions in the early universe to produce an effective scalar field that generates inflation [3]. See the recent article by Garrison and Underwood for a complete description of how the numerical equations for this model are derived [7].

For the numerical calculation, we use natural units but later evaluate the data in terms of SI units so that the results can be easily compared to the established values. In order to use this model in our code, we separated the equations of motion for the gauge field, ABJ chiral anomaly, Chern-Simons term and the Friedman equations into a system of first order in time differential equations.

$$\frac{d\boldsymbol{A}}{dt} = \frac{\boldsymbol{Z}}{a} \tag{1}$$

$$\frac{d\boldsymbol{Z}}{dt} = \boldsymbol{J}a^3 + \nabla^2 \boldsymbol{A}/a - a^2 \frac{\dot{\theta}}{M_*}\boldsymbol{B} \tag{2}$$

$$\frac{dJ^0}{dt} = \frac{\boldsymbol{E}\cdot\boldsymbol{B}}{4\pi^2 a^2} - \boldsymbol{\nabla}\cdot\boldsymbol{J} - 2HJ^0 \tag{3}$$

$$\frac{dD}{dt} = \frac{\boldsymbol{E}\cdot\boldsymbol{B}}{4a^3 M_*^2} - 3HD - 2\frac{m^2}{M_*}\theta \tag{4}$$

$$\frac{d\theta}{dt} = DM_* \tag{5}$$

$$\frac{da}{dt} = aH \tag{6}$$

$$\frac{dH}{dt} = \frac{8\pi}{3}\bar{\rho}/a - H^2 \tag{7}$$

Here the gauge field is represented with $\boldsymbol{A}$, the current is $\boldsymbol{J}$, a is the scale factor and H is the Hubble parameter. Current is assumed to depend simply on the charge density according to the equation $\boldsymbol{J} = J^0\boldsymbol{v}$. $\boldsymbol{E}$ represents the hyper charged electric field, $\boldsymbol{E} \equiv \dot{\boldsymbol{A}}$. $\boldsymbol{B}$ is the hyper charged magnetic field, $\boldsymbol{B} \equiv \nabla \times \boldsymbol{A}$ term. M_* is the mass scale identified with the UV cut-off scale of the effective field theory and θ is responsible for CP violation. m is on the order of the GUT energy scale. Finally, The average energy density is calculated as $\bar{\rho} = \frac{1}{N}\sum_{k=1}^{N} \frac{E_k^2+B_k^2}{2a^4} + |\boldsymbol{A}_k \cdot \boldsymbol{J}_k/a|$. Here N represents the total number of grid points in the computational domain. The scale factor and Hubble parameter therefore depend on the average energy density and not the local field dynamics.

The initial gauge field was composed of a random (white noise) spectrum. In order to generate the initial gauge field, we used a random number generator to create a random spectrum with amplitude up to the calculated maximum amplitude, $|\boldsymbol{A}|$, in each direction. The magnitude of the gauge field was then held equal to the initial amplitude $|\boldsymbol{A}|$. The initial values for the variables used in this study are given below.

$$|\boldsymbol{A}| = 1.0 \times 10^{-5} M_P \tag{8}$$

$$J^0 = 10^{-10} M_P^3 \tag{9}$$

$$\boldsymbol{v} = 10^{-10}(\hat{x} + \hat{y} + \hat{z}) \tag{10}$$

$$\frac{\dot{\theta}}{M_*} = 2.18 \times 10^{-5} M_P \tag{11}$$

$$a = 1.0 \tag{12}$$

$$H = \sqrt{\frac{8\pi}{3}|\boldsymbol{A}\cdot\boldsymbol{J}|} \tag{13}$$

$$\boldsymbol{Z} = Ha \times random\ number(-1,1) \tag{14}$$

$$m = 4.15 \times 10^{-6} M_P \tag{15}$$

$$M_* = 4.15 \times 10^{-6} M_P \tag{16}$$

The code was then run on the University of Houston′s Maxwell cluster using a variety of time-steps, grid sizes and resolutions in order to obtain consistent results. A fourth order finite differencing scheme was used to test convergence for high and low resolution simulations. Because the initial units were entered as Planck units, we assumed that the physical grid (horizon) size corresponded to Planck lengths and the timing output could be interpreted as Planck time.

3 Results

The previous article by Garrison and Underwood [7] focused on demonstrating the feasibility of the model and verifying that the apparent inverse energy cascade occurred as predicted. Previous data have shown that this is an interesting chaotic system which is highly dependent on initial conditions but numerically stable for a large range of initial data. As in the previous paper, Figure 1 shows the life-cycle of the evolution as our virtual universe experiences inflation. This is demonstrated by the scale factor and Hubble parameter.

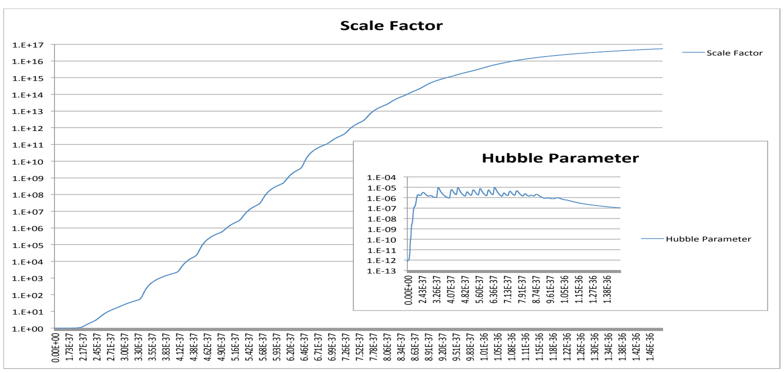

Fig. 1. The scale factor and Hubble Parameter for the inflationary period (log scale).

Figure 2 shows how the gauge field increases and charge density decreases with time. The net result of this is that the dot product of the gauge field and charge density yields a nearly constant energy density (and therefore Hubble parameter) until inflation ends. The gauge field evolution equation is essentially an inhomogenous wave equation driven by the $\frac{\dot{\theta}}{M_*}\boldsymbol{B}$ term and the $\boldsymbol{J}a^3$ term. Understanding how inflation occurs is directly connected to the dynamics of these two terms. Charge density falls off as roughly a^{-2} making the second term simply increase proportional to the scale factor and therefore lack the dynamics needed to significantly effect the gauge field evolution. The first term however is much more dynamic and could explain why inflation begins and ends. Also, given our initial conditions, the first term is $\sim 10^{-5}\boldsymbol{B}$ while the second term is $\sim 10^{-20}$ so the first term should normally dominate since $\boldsymbol{B}$ starts around 10^{-9} and increases as quickly as the gauge field.

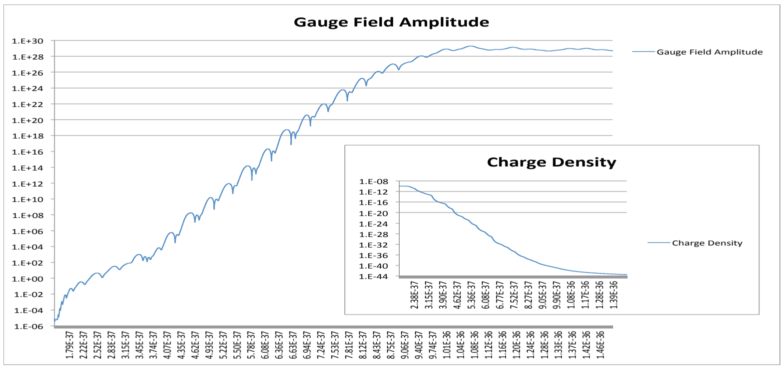

Fig. 2. The Gauge Field Amplitude and Charge Density (log scale).

Without the θ term Chern Simons modified gravity reduces to ordinary General Relativity and the effective vacuum energy disappears. Much of the gauge field dynamics is therefore the result of the θ term and it's time derivatives. The phase diagram in Figure 3 shows that this term acts like a dampened driven harmonic oscillator. The frequency of this system is $\omega = \sqrt{2}m$ the dampening term is $\gamma = \frac{3}{2}H$ and the driving term is F $= \frac{\boldsymbol{E}\cdot\boldsymbol{B}}{4a^3M_*}$. Given our initial conditions, $\omega \approx 10^{-6}$, $\gamma \approx 10^{-12} \rightarrow 10^{-5}$ and F is insignificant because $\boldsymbol{E}\cdot\boldsymbol{B}$ is unmeasurably small. This is therefore an under-damped harmonic oscillator that transitions into an over-damped harmonic oscillator as the Hubble parameter increases. The θ term vanishes quickly after γ exceeds ω and the gauge field's rate of growth slows while current continues to decrease at a constant rate resulting in a decreasing energy density and an end to inflation. Maintaining the Chern Simons term, $\frac{\dot{\theta}}{M_*}$, for as long as possible appears to be essential to the inflation process.

In Figure 4, we see the spectrum of the gauge field as a function of time. Notice that the initial gauge field starts off with an evenly distributed spectrum and then sometime later the spectrum peaks at low frequencies to resemble an inverse energy cascade. Later the peak of the power spectrum moves to higher frequencies as the Chern Simons term decays. The peak follows the changing frequency of the Chern Simons term to maintain resonance until it decays to zero and inflation ends.

4 Conclusions

An important result of this study is that we now know why inflation only appears to occur when the computational grid is sufficiently large. Our analysis of the θ term's dynamics show that it's natural oscillatory frequency is on the order of 10^{-6}. This corresponds to a grid size of about 10^6 units. If the

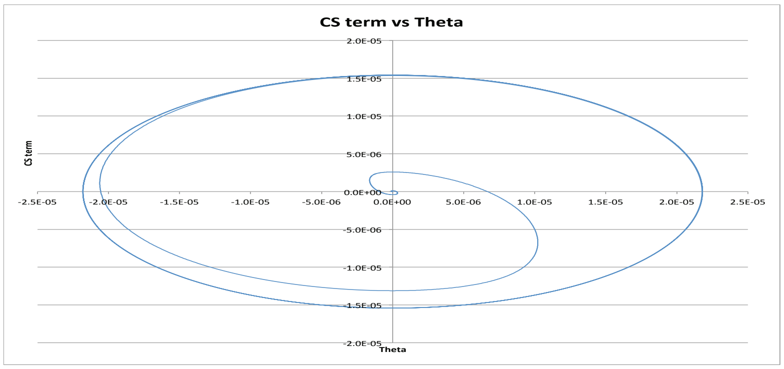

Fig. 3. Phase diagram of the θ and $\frac{\dot{\theta}}{M_*}$ terms.

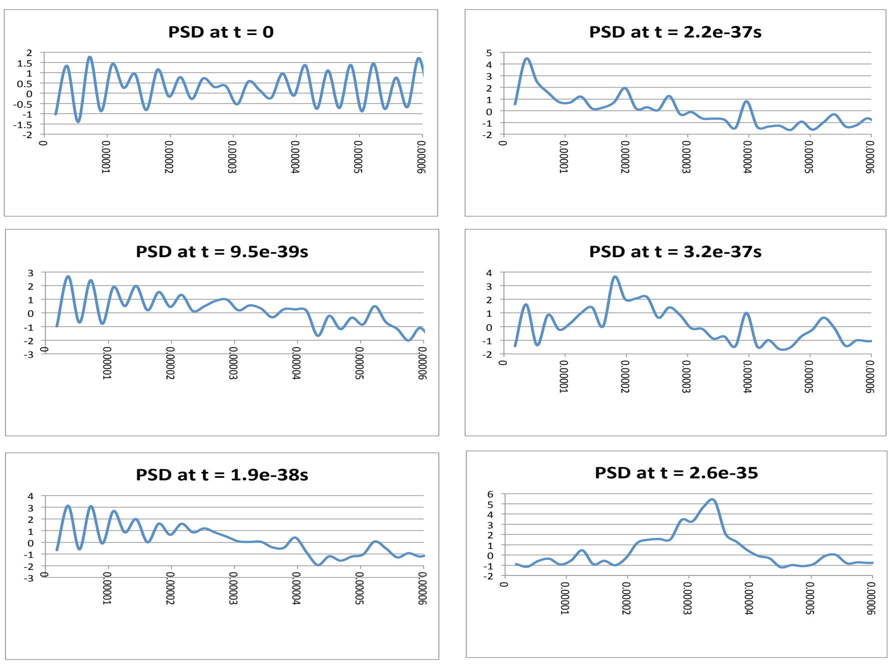

Fig. 4. Power Spectral Density of the gauge field at various times. The vertical axis is the log of the deviation from the mean. The horizontal axis is frequency in Plank units.

computational grid is smaller than this minimum, the gauge field cannot come into resonance with the driver θ and explode in amplitude.

Information from this study may also be useful in better determining what initial conditions led to inflation in our universe. By varying the initial conditions, the forcing term, dampening term and frequency of θ may be altered to extend our simulated inflation and better conform to observation.

References

1.P. A. R. Ade *et al.* [BICEP2 Collaboration]. BICEP2 I: Detection Of B-mode Polarization at Degree Angular Scales. arXiv:1403.3985 [astro-ph.CO], 2014.

2.S. Adler. Axial-Vector Vertex in Spinor Electrodynamics. *Physical Review*, 177, 1969.

3.S. Alexander, A. Marciano, and D. Spergel. Chern-Simons inflation and ba,ryogenesis. *Journal of Cosmology and Astroparticle Physics*, 2013, 2013

4.S. Alexander and N. Yunes. Chern-Simons modified general relativity. *Physics Reports*, 480,1-2:1–55, 2009.

5.J. S. Bell and R. A. Jackiw. PCAC puzzle: $\pi^0 \rightarrow \gamma\gamma$ in the σ-model. em IL Nuovo Cimento, 60A,4, 1969.

6.L. H. Ford. Inflation driven by a vector field. *Physical Review D*, 40,4:967–972, 1989.

7.D. Garrison and C. Underwood. A Numerical Simulation of Chern-Simons Inflation. *Advances in Astronomy*, 2013: 207218, 2013.

8.T. Goodale, G. Allen, G. Lanfermann, J. Massó, T. Radke, E. Seidel and J. Shalf. The Cactus Framework and Toolkit: Design and Applications, Vector and Parallel Processing – VECPAR' 2002, 5th International Converence, Lecture Notes in Computer Science, Berlin: Springer, 2003. ¡http://edoc.mpg.de/3341¿

9.A. H. Guth. Inflationary universe: a possible solution to the horizon and flatness problems. *Physical Review D*, 23,2:347–356, 1981.

Email: garrison@uhcl.edu, nguyenp@uhcl.edu

Many studies in numerical relativity and high-energy astrophysics depend on the dynamics of relativistic plasmas. These include phenomena such as primordial turbulence, neutron stars, active galactic nuclei, and accretion disks near black holes [1]-[8]. Unfortunately, we do not know if the results of these studies are accurate because of approximations such as the use of nonrelativistic fluid dynamics and the lack of a standard model to describe the dynamics of relativistic turbulence. In particular, very little is understood about the turbulent dynamics of a relativistic plasma or its effect on the evolution of magnetic fields. This can only effectively be studied through direct numerical simulation of the relativistic magnetofluid.

In the following report we will first discuss what is currently known about the dynamics of nonrelativistic MHD systems. We introduce the standard incompressible and compressible nonrelativistic MHD evolution equations as well as the ideal invariants for those systems. In Section 4, we will introduce the relativistic MHD equations and the relativistic equivalents of the nonrelativistic ideal MHD invariants. We then describe our numerical experiment and present our results for a relativistic MHD code. We conclude by discussing the similarities and differences between the different systems.

2. Nonrelativistic Incompressible MHD

Work by Shebalin [9]-[14], on ideal homogeneous incompressible MHD turbulence best demonstrates how the dynamics of a magnetofluid can differ from that of a hydrodynamic fluid. Plasma can be accurately modeled as a fluid made up of charged particles that are therefore affected by magnetic fields as well as particle-particle interactions. Because of this, the magnetic field becomes a dynamic variable in addition to density, pressure and the velocity of particles. For example, In MHD turbulence, an equipartition occurs and we expect kinetic and magnetic energy fluctuations to become roughly equal. Shebalin modeled the magnetofluid as a homogenous system where the same statistics are considered valid everywhere in the computational domain. He utilized periodic boundary conditions and spectral methods in order to study how the dynamics of different scales interacted without the addition of boundary errors. Much of his work focused on an ideal MHD system, where the magnetic and fluid dissipation terms were excluded. Below are the evolution equations used by Shebalin to describe the incompressible MHD system.

$$\nabla \cdot \boldsymbol{v} = 0 \tag{1a}$$

$$\rho \frac{\partial \boldsymbol{v}}{\partial t} = -\rho\left(\boldsymbol{v} \cdot \nabla v\right) - \nabla p - \frac{1}{4\pi}\boldsymbol{B} \times \left(\nabla \times \boldsymbol{B}\right) \tag{1b}$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times \left(\boldsymbol{v} \times \boldsymbol{B}\right). \tag{1c}$$

By varying the mean magnetic field (B_0) and angular velocity (Ω_0) of the system, Shebalin was able to define five different cases with different invariants as shown in **Table 1**. In such a system there could be as many as 3 ideal invariants; energy (E), and the psuedoscalars cross helicity (H_C) and magnetic helicity (H_M). In addition, the invariant parallel helicity, $H_P = H_C - \sigma H_M \quad \left(\sigma = \Omega_0 / B_0\right)$, can be formed from a linear combination of cross and magnetic helicity. In a hydrodynamic fluid the ideal invariants are only energy and kinetic helicity.

For an incompressible fluid $u(k, t)$ is the Fourier coefficient of turbulent velocity and $b(k, t)$ is the Fourier coefficient of the turbulent magnetic field. The energy, cross helicity and magnetic helicity can be expressed in terms of these as:

$$E = \frac{1}{2N^3}\sum_k \left[\left|u(k)\right|^2 + \left|b(k)\right|^2\right] \tag{2a}$$

$$H_C = \frac{1}{2N^3}\sum_k u(k) \cdot b^*(k) \tag{2b}$$

$$H_M = \frac{1}{2N^3}\sum_k \frac{i}{k^2} k \cdot b(k) \times b^*(k). \tag{2c}$$

A cubic computational domain with N grid points in each direction is assumed. The statistical mechanics of the system is defined by the Gaussian canonical probability density function (PDF):

$$D = \frac{1}{Z}\exp\left(-\alpha E - \beta H_C - \gamma H_M\right) \tag{3a}$$

Table 1. Invariants for ideal incompressible MHD.

Case	Mean field	Angular velocity	Invariants
I	0	0	E, H_C, H_M
II	$B_0 \neq 0$	0	E, H_C
III	0	$\Omega_0 \neq 0$	E, H_M
IV	$B_0 \neq 0$	$\Omega_0 = \sigma B_0$	E, H_P
V	$B_0 \neq 0$	$\Omega_0 \neq 0 \quad (B_0 \times \Omega_0 \neq 0)$	E

$$Z = \int_\Gamma \exp\left(-\alpha E - \beta H_C - \gamma H_M\right) \mathrm{d}\Gamma \tag{3b}$$

$$\hat{\Phi} = \int_\Gamma \Phi D \mathrm{d}\Gamma, \quad \bar{\Phi} = \frac{1}{T}\int_0^T \Phi \mathrm{d}t. \tag{3c}$$

where Z is the partition function and $\mathrm{d}\Gamma$ is the phase space volume. $\hat{\Phi}$ shows how to calculate the ensemble averages using the PDF while $\bar{\Phi}$ is the time average. If $\hat{\Phi} = \bar{\Phi}$, the system is said to be ergodic but if $\hat{\Phi} \neq \bar{\Phi}$, it is non-ergodic. Here α, β and γ are inverse temperatures. The ensemble average magnetic energy ($\hat{E}_M$) is always greater than or equal to ensemble average kinetic energy ($\hat{E}_K$), and the inverse temperature terms can be found as a function of $\hat{E}_M = \phi$.

$$\alpha = \frac{2N^3\phi}{\phi\left(\hat{E} - \phi\right) - \hat{H}_C^2} \tag{4a}$$

$$\beta = -2\frac{\hat{H}_C}{\phi}\alpha \tag{4b}$$

$$\gamma = -\frac{2\phi - \hat{E}}{\hat{H}_M}\alpha \tag{4c}$$

Phase portraits resulting from computer simulations of Shebalin's five cases show that coherent structures formed in many systems where the magnetofluid was experiencing turbulence [9]-[14]. Coherent structure occurs when time-averaged physical variables in MHD turbulence have large mean values, rather than the zero mean values expected from theoretical ensemble predictions. MHD turbulence thus has broken ergodicity, which can be explained by finding the eigenmodes of the system. One out of the four eigenvalues associated with each of the lowest wavenumbers will be very much smaller than the others; the eigenvariables associated with these very small eigenvalues grow to have very large energies compared to other eigenvariables; when this happens, an almost force-free state occurs in which large-energy eigenmodes are quasistationary while low-energy eigenmodes remain turbulent; thus, the predicted ergodicity has been dynamically broken. This is observed to occur even in dissipative systems because broken ergodicity in MHD turbulence manifests itself at the smallest wavenumbers (largest length scales) where dissipation is negligible, resulting in the ideal spectrum. In the case of ideal hydrodynamic turbulence, broken ergodicity can occur in a finite model system, but only at the largest wavenumbers (smallest scales). When dissipation is added, the large wavenumber modes are most affected and their energy quickly decays away, so that broken ergodicity plays no role in decaying hydrodynamic turbulence.

3. Nonrelativistic Compressible MHD

Compressible MHD systems have not been studied as much as incompressible systems so here we will focus primarily on their invariants. We will assume that both incompressible and compressible systems share the same statistical mechanics and dynamics whenever the same invariants apply. In a nonrelativistic compressible MHD system; Energy and the Incompressible form of Cross Helicity are always conserved for a nondissipative system [15]-[17] (see **Table 2**). Compressible Cross Helicity, $\tilde{H}_C = \rho H_C$, is not an ideal invariant in compressible MHD [15]. In the absence of a mean magnetic field and dissipation, Magnetic Helicity is also conserved [18]-[31]. The authors were unable to identify any literature showing the relationship between net angular velocity and ideal compressible MHD invariants.

Given that our relativistic system is by default a compressible system, we naively expect to see that the same ideal invariants will apply for the relativistic system as the nonrelativistic compressible system. The equations for ideal compressible MHD are similar to those of the incompressible system with the exception of the first equation.

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot \left(\rho \boldsymbol{v}\right) \tag{5a}$$

Table 2. Invariants for ideal compressible MHD.

Case	Mean field	Invariants
I	0	E, H_C, H_M
II	$B_0 \neq 0$	E, H_C

$$\rho\frac{\partial \boldsymbol{v}}{\partial t} = -\rho(\boldsymbol{v}\cdot\nabla v) - \nabla p - \frac{1}{4\pi}\boldsymbol{B}\times(\nabla\times\boldsymbol{B}) \tag{5b}$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla\times(\boldsymbol{v}\times\boldsymbol{B}). \tag{5c}$$

4. Relativistic MHD Systems

The fluid and electromagnetic components of the relativistic MHD equations are developed from several well-known equations [32]. They include the conservation of particle number, the continuity equation, the conservation of energy-momentum, the magnetic constraint equation and the magnetic induction equation. For a system consisting of a perfect fluid and an electromagnetic field, the ideal MHD stress-energy tensor is given by

$$T^{\mu\nu} = (\rho_0 h + b^2)u^\mu u^\nu + \left(P + \frac{b^2}{2}\right)g^{\mu\nu} - b^\mu b^\nu \tag{6a}$$

$$P = \epsilon\rho_0(\tilde{\Gamma} - 1) \tag{6b}$$

$$h = 1 + \epsilon + \frac{P}{\rho_0} \tag{6c}$$

$$b^\mu = \frac{1}{\sqrt{4\pi}}B^\mu_{(u)} \tag{6d}$$

$$B^0_{(u)} = \frac{1}{\alpha}u_i B^i \tag{6e}$$

$$B^i_{(u)} = \frac{1}{u^0}\left(\frac{B^i}{\alpha} + B^0_{(u)}u^i\right). \tag{6f}$$

Here, P is the fluid pressure, ρ_0 is density, B^i is magnetic field, u^μ is four-velocity, h is the enthalpy, ε is specific internal energy, and b^2 is the magnitude of the magnetic vector field squared. We define pressure in terms of the energy density using the $\tilde{\Gamma}$ law equation of state with, $\tilde{\Gamma} = \frac{5}{3}$. $P = (\tilde{\Gamma} - 1)\rho\epsilon$ at most energies and $P \propto \rho^{\tilde{\Gamma}}$ at extremely low energies. The evolution equations where given by Duez as [32]:

$$\partial_t \rho_* = -\partial_j(\rho_* v^j) \tag{7a}$$

$$\partial_t \tilde{\tau} = -\partial_i\left(\alpha^2\sqrt{\gamma}T^{0i} - \rho_* v^i\right) + s \tag{7b}$$

$$\partial_t \tilde{S}_i = -\partial_j\left(\alpha\sqrt{\gamma}T^j_i\right) - \frac{1}{2}\alpha\sqrt{\gamma}T^{\alpha\beta}g_{\alpha\beta,i} \tag{7c}$$

$$\partial_t \tilde{B}^i = -\partial_j\left(v^j\tilde{B}^i - v^i\tilde{B}^j\right). \tag{7d}$$

Here, ρ_* is conserved mass density, $\tilde{\tau}$ relates to energy density, $\tilde{S}_i$ is momentum density, $\tilde{B}^i$ is related to the magnetic field and s is the source term. γ_{ij} is the three metric and α is a lapse term related to the time evolution of the simulation. The determinate of the three metric and lapse are both set to unity because we are using the Minkowski metric and Geodesic slicing conditions.

$$\rho_* = \alpha\sqrt{\gamma}\rho_0 u^0 \tag{8a}$$

$$\tilde{\tau} = \alpha^2\sqrt{\gamma}T^{00} - \rho_* \tag{8b}$$

$$\tilde{S}_i = \alpha\sqrt{\gamma}T_i^0 = \left(\rho_* h + \alpha u^0\sqrt{\gamma}b^2\right)u_i - \alpha\sqrt{\gamma}b^0 b_i \tag{8c}$$

$$\tilde{B}^j = \sqrt{\gamma}B^j \tag{8d}$$

Notice that unlike the nonrelativistic system, we use the stress-energy tensor within the evolution equations so that 4-momentum conservation is built into the system. This results in a set of equations that look very different from that of the nonrelativistic system. According to work by Yoshida [33] [34], in addition to 4-momentum, relativistic systems are expected to conserve a quantity called Relativistic Helicity. It is defined below using the canonical 4-momentum density, $\mathcal{P}$, of the system.

$$\kappa = \left(\mathcal{P}\cdot(\nabla\times\mathcal{P}), \mathcal{P}_0(\nabla\times\mathcal{P}) + \mathcal{P}\times\left(\nabla\mathcal{P}_0 + \partial_0\mathcal{P}\right)\right) \tag{9}$$

Here the canonical 4-momentum density $\mathcal{P} = \left(\mathcal{P}_0, \mathcal{P}\right)$ is a combination of mechanical and electromagnetic momentum densities. The conservation of Relativistic Helicity is then effectively, $\int\partial_\mu\kappa^\mu \mathrm{d}^3x = 0$. The canonical 4-momentum can be expressed as the sum of mechanical and electromagnetic momentum, $\mathcal{P}_\mu = P_\mu + e\mathcal{P}_\mu$. If we ignore the electromagnetic fields, we recover a relativistic version of Cross Helicity Density, κ_C. If we set the particle's mechanical momentum to zero, we recover a relativistic version of Magnetic Helicity Density, κ_M.

5. Methodology

For this numerical experiment, we calculate Energy Density (E), Relativistic Helicity Density (κ), Cross Helicity Density (κ_C), and Magnetic Helicity Density (κ_M), numerically using the code described later in this section. These variables are defined as shown below.

$$E = \int T^{00}(\boldsymbol{x})\mathrm{d}^3x \tag{10a}$$

$$P_0 = \rho_* h u_0 - P \tag{10b}$$

$$P_i = \rho_* h u_i \tag{10c}$$

$$\kappa = \left(\tilde{S}\cdot\left(\nabla\times\tilde{S}\right), (\tau+\rho_*)\left(\nabla\times\tilde{S}\right) + \tilde{S}\times\left(\nabla(\tau+\rho_*) + \partial_0\tilde{S}\right)\right) \tag{10d}$$

$$\kappa_C = \left(P\cdot B, P_0 B - P\times\mathcal{E}\right) \tag{10e}$$

$$\kappa_M = \left(\mathcal{A}\cdot\mathcal{B}, \mathcal{A}_0\mathcal{B} - \mathcal{A}\times\mathcal{E}\right) \tag{10f}$$

Here the magnetic field is related to the vector potential by the equation, $\mathcal{B} = \nabla\times\mathcal{A}$. The electric field is defined using the MHD conditions, $\mathcal{E} = \mathcal{B}\times v$. We can test to see if the Helicities are invariant by comparing numerically calculated time derivatives of κ^0 to their predicted value at each time-step using the equation $\partial_0\kappa^0 + \partial_i\kappa^i = 0$. We normalize the result using the L2 norm of the calculated divergence so all results are on the same relative scale. We then integrate the result over the volume of our computational domain. If the normalized error is dominated by the truncation and round-off errors, we can assume that the system is invariant. For the normalized error in energy we simply look at the difference in energy at two different time levels divided by the total energy at that time level.

$$Error_\kappa = \frac{\int\left[\left(\kappa^0(t) - \kappa^0(t-\Delta t)\right)/\Delta t + \partial_i\kappa^i(t)\right]\mathrm{d}^3x}{\int\left\|\partial_i\kappa^i\right\|\mathrm{d}^3x} \tag{11a}$$

$$Error_E = \frac{E(t) - E(t-\Delta t)}{E(t)} \tag{11b}$$

In order to study the invariants of the relativistic MHD equations, we used a code called FixedCosmo which was originally written by one of us [4] to study the dynamics of primordial plasma turbulence. This code was developed using the open source Cactus framework (www.cactuscode.org). Cactus was originally developed to perform numerical relativistic simulations of colliding black holes but it's modular design has since allowed it to be used for a variety of Physics, Engineering and Computer Science applications. It is currently being maintained by the Center for Computation and Technology at Louisiana Sate University. Cactus codes are composed of a flesh (which provides the framework) and the thorns (which provide the physics). FixedCosmo is a collection of thorns. It uses the form of the Relativistic MHD equations described by Duez [32] and is written in a combination of F77, F90, C and C++. This code is parallelized and capable of using several different differencing methods such as second order finite differencing, fourth order finite differencing and spectral differencing. Although the code is capable of utilizing artificial viscosity and HRSC, neither was used for this project.

Because the objective of this study is to test the ideal relativistic MHD system, we complete a series of runs in a "high-energy" regime. The parameters used approximate that of the early universe around the electroweak scale. This is done so we can apply the results to any relativistic MHD system. **Table 3** shows a matrix of the test runs.

Each data run utilized Fourier spectral differencing on a grid with 64 × 64 × 64 internal data points. We ran these simulations for about 7500 iterations or over 10^{-9} s of physical time. The electron oscillation time for the "high energy" regime is about 1.1×10^{-34} s so the simulations appear to have run long enough to witness the full dynamics of the system. The simulation domains where all set to 4 m × 4 m × 4 m. Also, the code utilizes geometerized units ($c = G = \hbar = 1$) so parameters where translated from SI units to units of length for the use of the calculations and then back to SI units for the output. Time is therefore translated into seconds by dividing the output time by the speed of light.

6. Results

Truncation errors were found by doubling the resolution and measuring the change in the observed total errors. By assuming that the Euler Method, used to calculate $\partial_0\kappa^0$, is first order and that the numerical errors and variations from exactly conserved values are additive, the truncation errors can be calculated from

$$\left|E_{truncation}\right| = 2\left(\left|E_{LR}\right| - \left|E_{HR}\right|\right). \tag{12}$$

If the truncation errors are within an order of magnitude of the normalized errors, we can conclude that the system is invariant. We also found it impossible to completely eliminate the mean magnetic field and mean angular momentum in all cases. A mean magnetic field (on the order of 1% of the maximum field) remained in every case. Also, each case seemed to have a small angular velocity, also less than 1% of the fluid velocities within the simulation. The authors feel that these residual quantities where not enough to significantly disrupt the system and could be safely ignored.

Table 3. High energy numerical simulations.

Variables	Case 1	Case 2	Case 3	Case 4	Case 5
Max velocity (c)	0.25	0.25	0.25	0.25	0.25
Ω_x (c)	0	0	0	0	0
Ω_y (c)	0	0	0	0	0
Ω_z (c)	0	0	0.35	0.35	0.35
Init temperature (K)	2.8e15	2.8e15	2.8e15	2.8e15	2.8e15
Init density (kg/m^3)	9.7e29	9.7e29	9.7e29	9.7e29	9.7e29
Max magnetic field (G)	1.0e13	1.0e13	1.0e13	1.0e13	1.0e13
B_x (G)	0	2.0e13	0	0	2.0e13
B_y (G)	0	0	0	0	0
B_z (G)	0	0	0	2.0e13	0

Table 4. High energy simulation results.

Mean magnitude of errors	E	κ	κ_C	κ_M
Case 1	1.8e−9	2.8e−14	9.6e−5	1.0e−2
Case 2	1.8e−9	2.8e−14	9.7e−5	2.8e−2
Case 3	8.1e−10	0.0	6.6e−5	7.1e−3
Case 4	7.7e−10	0.0	6.0e−5	1.9e−2
Case 5	7.8e−10	0.0	6.6e−5	1.8e−2
Truncation errors	2.1e−9	2.2e−14	2.9e−5	2.0e−3

The results in **Table 4** were calculated by averaging the absolute values of normalized errors. As one can see, Energy and Relativistic Helicity appear to be conserved in every case given that the normalized error appears to be dominated by truncation errors for both. Cross Helicity may be conserved in every case since the calculated truncation error appears to be within an order of normalized errors in every case. Magnetic Helicity does not appear to be conserved in any of the cases. Normalized Errors for Cross Helicity Conservation appear smaller in cases where a large mean angular velocity is present. Deviations in Magnetic Helicity Conservation are smallest in the absence of a large mean magnetic field.

7. Discussion

Our results show that in the high-energy Relativistic MHD regime only Energy and Relativistic Helicity are clearly conserved. We are not able to conclusively prove Cross Helicity conservation. Magnetic Helicity conservation is questionable in this system. This is not an unexpected result but it does raise several interesting questions which lie beyond the scope of this article. Does the potential lack of Cross and Magnetic Helicity Conservation effect the dynamics of the relativistic system when it comes to phenomena such as inverse Energy Cascade or the Kolmogorov Energy Spectrum? How do magnetic dynamos in relativistic MHD systems function? Are there any other overlooked dynamics in relativistic MHD systems? These are all questions which we hope to address in future numerical studies.

Conflicts of Interests

The authors declare that there is no conflict of interests regarding the publication of this article.

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References

[1] Caprini, C. and Durrer, R. (2006) *Physical Review D*, **74**, Article ID: 063521.

[2] Caprini, C., Durrer, R. and Servant, G. (2009) *Journal of Cosmology and Astroparticle Physics*, **912**, 24. http://dx.doi.org/10.1088/1475-7516/2009/12/024

[3] Cho, J. (2006) *Journal of the Korean Physical Society*, **49**, 4.

[4] Garrison, D. (2014) *Journal of Gravity*, **2014**, Article ID: 407197.

[5] Inoue, T., Asano, K. and Ioka, K. (2011) *Astrophysical Journal*, **734**, 77. http://dx.doi.org/10.1088/0004-637X/734/2/77

[6] Melatos, A. and Peralta, C. (2010) *Astrophysical Journal*, **709**, 77. http://dx.doi.org/10.1088/0004-637X/709/1/77

[7] Zhang, W., MacFadyen, A. and Wang, P. (2009) Three-Dimensional Relativistic MHD Simulations of the Kelvin-Helmholtz Instability: Magnetic Field Amplification by a Turbulent Dynamo.

[8] Zrake, J. and MacFadyen, A. (2011) Numerical Simulations of Driven Relativistic MHD Turbulence.

[9] Shebalin, J.V. and Montgomery, D. (1988) *Journal of Plasma Physics*, **39**, 339-367. http://dx.doi.org/10.1017/S0022377800013076

[10] Shebalin, J.V. (2002) The Statistical Mechanics of Ideal Homogeneous Turbulence. NASA TP-2002-210783.

[11] Shebalin, J.V. (2005) *Discrete & Continuous Dynamical Systems B*, **5**, 153-175. http://dx.doi.org/10.3934/dcdsb.2005.5.153

[12] Shebalin, J.V. (2007) *Physics of Plasmas*, **14**, Article ID: 102301. http://dx.doi.org/10.1063/1.2780138

[13] Shebalin, J.V. (2011) *Geophysical and Astrophysical Fluid Dynamics*, **107**, 411-466. http://dx.doi.org/10.1080/03091929.2011.589385

[14] Shebalin, J.V. (2012) *Geophysical and Astrophysical Fluid Dynamics*, **107**, 353-375. http://dx.doi.org/10.1080/03091929.2012.689299

[15] Banerjee, S. (2014) Compressible Turbulence in Space and Astrophysical Plasmas: Analytical Approach and *in Situ* Data Analysis for the Solar Wind. Dissertation, Université Paris Sud (Paris XI), Paris.

[16] Marsch, E. and Mangeney, A. (1987) *Journal of Geophysical Research*, **92**, 7363-7367. http://dx.doi.org/10.1029/JA092iA07p07363

[17] Yokoi, N. (2013) *Geophysical & Astrophysical Fluid Dynamics*, **107**, 114-184. http://dx.doi.org/10.1080/03091929.2012.754022

[18] Biskamp, D. (2003) Magnetohydrodynamic Turbulence. Cambridge University Press, Cambridge. http://dx.doi.org/10.1017/CBO9780511535222

[19] Cho, J. (2005) *The Astrophysical Journal*, **621**, 324-327. http://dx.doi.org/10.1086/427493

[20] Dolgov, A.D., Grasso, D. and Nicolis, A. (2002) *Physical Review D*, **66**, Article ID: 103505. http://dx.doi.org/10.1103/PhysRevD.66.103505 http://arxiv.org/abs/astro-ph/0206461

[21] Ghosh, S., Stribling, W.T., Goldstein, M.L. and Matthaeus, W.H. (1995) The Evolution of Magnetic Helicity in Compressible Magnetohydrodynamics with a Mean Magnetic Field. In: Ashour-Abdalla, M., Chang, T. and Dusenbery, P., Eds., *Space Plasmas*: *Coupling between Small and Medium Scale Processes*, American Geophysical Union, Washington DC.

[22] Gogoberidze, G., Kahniashvili, T. and Kosowsky, A. (2007) *Physical Review D*, **76**, Article ID: 083002. http://dx.doi.org/10.1103/PhysRevD.76.083002 http://arxiv.org/abs/0705.1733

[23] Islam, J.N. (1992) An Introduction to Mathematical Cosmology. Cambridge University Press, Cambridge.

[24] Kahniashvili, T. (2005) Gravitational Radiation from Primordial Helical Turbulence. http://arxiv.org/abs/astro-ph/0508459

[25] Kahniashvili, T., Gogoberidze, G. and Ratra, B. (2005) *Physical Review Letters*, **95**, Article ID: 151301. http://arxiv.org/abs/astro-ph/0505628 http://dx.doi.org/10.1103/PhysRevLett.95.151301

[26] Kahniashvili, T. and Ratra, B. (2007) *Physical Review D*, **75**, Article ID: 023002. http://arxiv.org/abs/astro-ph/0611247 http://dx.doi.org/10.1103/PhysRevD.75.023002

[27] Kahniashvili, T., Kosowsky, A., Gogoberidze, G. and Maravin, Y. (2008) *Physical Review D*, **78**, Article ID: 043003. http://arxiv.org/abs/0806.0293 http://dx.doi.org/10.1103/PhysRevD.78.043003

[28] Kahniashvili, T., Campanelli, L., Gogoberidze, G., Maravin, Y. and Ratra, B. (2008) *Physical Review D*, **78**, Article ID: 123006. http://dx.doi.org/10.1103/PhysRevD.78.123006 http://arxiv.org/abs/0809.1899

[29] Kahniashvili, T., Kisslinger, L. and Stevens, T. (2010) *Physical Review D*, **81**, Article ID: 023004. http://arxiv.org/abs/0905.0643 http://dx.doi.org/10.1103/PhysRevD.81.023004

[30] Kisslinger, L.S. (2004) *Modern Physics Letters A*, **19**, 1179-1186. http://arxiv.org/abs/hep-ph/0402001 http://dx.doi.org/10.1142/S0217732304014537

[31] Nicolis, A. (2004) *Classical and Quantum Gravity*, **21**, L27-L33. http://arxiv.org/abs/gr-qc/0303084 http://dx.doi.org/10.1088/0264-9381/21/4/L05

[32] Duez, M.D., Liu, Y.T., Shapiro, S.T. and Stephens, B.C. (2005) *Physical Review D*, **72**, Article ID: 024028. http://arxiv.org/abs/astro-ph/0503420v2

http://dx.doi.org/10.1103/PhysRevD.72.024028

[33] Yoshida, Z., Kawazura, Y. and Yokoyama, T. (2014) *Journal of Mathematical Physics*, **55**, Article ID: 043101. http://dx.doi.org/10.1063/1.4872236

[34] Kawazura, Y., Yoshida, Z. and Fukumoto, Y. (2014) *Journal of Physics A*: *Mathematical and Theoretical*, **47**, Article ID: 465501. http://dx.doi.org/10.1088/1751-8113/47/46/465501

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Using Gravitational Waves to Put Limits on Primordial Magnetic Fields

By David Garrison

University of Houston Clear Lake, United States

Abstract- We describe a technique for using simulated tensor perturbations in order to place upper limits on the intensity of magnetic fields in the early universe. As an example, we apply this technique to the beginning of primordial nucleosynthesis. We determined that any magnetic seed fields that existed before that time were still in the process of being amplified. In the future, we plan to apply this technique to a wider range of initial magnetic fields and cosmological epochs.

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I. Introduction

Magnetic fields are believed to have played a large part in the dynamics of the evolution of our universe. However, little is known about the existence of magnetic fields when the universe was very young. There are no direct observations of primordial magnetic fields. Theories also disagree on the amplitude of primordial magnetic fields. There are currently several dozen theories about the origin of cosmic magnetic fields [2, 18]. The main reason that we believe that primordial magnetic fields existed is because they may have been needed to seed the large magnetic fields observed today. Most theories of cosmic magnetic field generation fall into one of three categories [2, 12, 18]: 1) magnetic fields generated by phase transitions; 2) electromagnetic perturbations expanded by inflation; and 3) turbulent magnetofluid resulting in charge and current asymmetries. Once generated, these seed magnetic fields were amplified by a dynamo however, we don't know when or how this dynamo did it's work.

Most models calculate the magnitude of primordial magnetic fields by starting with the observed strength of galactic or intergalactic magnetic fields and calculating how this field should have been amplified or diffused by external effects such as the magnetic dynamo and expansion of the universe [2, 18]. A major problem is that there doesn't appear to be a universal agreement of how efficiently a dynamo could have strengthened seed magnetic fields or when the strengthening occurred. Estimates of the strength of these seed fields can vary by tens of orders of magnitude. In the absence of amplification mechanisms, the frozen-in condition of magnetic field lines tells us that [2, 18].

$$\vec{B}_0 = \vec{B}a^2. \qquad (1)$$

Author: Physics Department, University of Houston Clear Lake, Houston, Texas 77058. e-mail: Garrison@UHCL.edu

Here $\vec{B}_0$ is the present magnetic field where the scale factor is unity and $\vec{B}$ is the magnetic field when the scale factor was a. Once amplification and diffusion are taken into account, this relationship can be used to calculate the amplitude of magnetic seed fields. Seed magnetic fields produced during Inflation are predicted to have a current strength somewhere between 10^{-11} G and 10^{-9} G on a scale of a few Mpc [2, 18, 26]. Magnetic seed fields generated by phase transitions are believed to be less than 10^{-23} G at galactic scales [2, 18]. Some turbulence theories imply that magnetic fields were not generated until after the first stars were formed therefore requiring no magnetic seed fields [2].

Given how little is understood about primordial magnetic fields and the general lack of agreement among theoretical predictions, it seems clear that the existence of primordial magnetic fields can neither be confirmed or ruled out. It seems that the best we can do is set an upper limit on the strength of primordial magnetic fields and utilize this limit as a starting point in developing models of cosmic turbulence. Observations of the CMB limit the intensity of the magnetic seed fields to a current upper limit of 10^{-9} G [2, 18, 26, 38].

It is well known that gravitational waves can interact with a magnetofluid in the presence of a magnetic field. Work by Duez et al [15] showed how gravitational waves can induce oscillatory modes in a plasma field if magnetic fields are present. Work by Kahniashvili and others [30, 31, 32, 34, 35, 36] have shown how a turbulent plasma can yield gravitational waves. The result may be a highly nonlinear interaction as energy is transferred from the fluid to the gravitational waves and back resulting in potentially significant density perturbations. Magnetic fields are the glue that bind the gravitational waves to the plasma field. The objective of this work is to utilize the interaction between gravitational waves and the primordial magnetofluid in order to put limits on the strength of magnetic fields that could have existed in the early universe.

II. Primordial Gravitational Wave Amplitudes

According to Boyle, Primordial Gravitational Waves develop primarily from tensor perturbations expanded by the inflation event [3, 4]. The process is similar to that of scalar perturbations and the two are related by a tensor/scalar ratio

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$$r = \Delta_t^2/\Delta_s^2. \quad (2)$$

Here the Δ terms refer to the primordial power spectrums. As a function of horizon exit time, τ_{out} and wavenumber, k,

$$\Delta_t^2(k,\tau_{out}) = 64\pi G\frac{k^3}{2\pi^2}|h_k(\tau_{out})|^2 \approx 8(\frac{H_*}{2\pi M_{pl}})^2, \quad (3)$$

$$\Delta_s^2(k,\tau_{out}) \approx \frac{1}{2\epsilon_*}(\frac{H_*}{2\pi M_{pl}})^2, \quad (4)$$

$$r(k) \equiv \Delta_t^2(k,\tau_{out})/\Delta_s^2(k,\tau_{out}) \approx 16\epsilon_*. \quad (5)$$

$M_{pl} = (8\pi G)^{-1/2}$ is the "reduced Planck mass" and ϵ is the slow roll parameter. Also the asterisk (*) terms denote the value of the parameters when the tensor perturbation exits the horizon. The wavenumber is commonly defined as k $= a_* H_*$ at the horizon exit.

Once the tensor mode enters the horizon, k≫aH, the strain amplitude of the gravitational waves can be defined as

$$h_k = \frac{1}{a\sqrt{2k}}. \quad (6)$$

Unfortunately, because there is not a consistent dimensionless definition of the Hubble Parameter, this method does not allow for an easy way to calculate the amplitude of gravitational waves in the early universe. We therefore turn to Grishchuk's work [19, 20]. Grishchuk believed that gravitational waves were generated by ination and amplified by a process called parametric amplification. Starting with the idea that the gravitational wave power spectrum is deduced by treating contracted tensor perturbations as eigenvalues of a quantum mechanical operator that works on the vacuum state we see that

$$\langle 0|\hat{\Omega}|0\rangle = \langle 0|h_{ij}(n,\eta)h^{ij}(n,\eta)|0\rangle = \frac{\mathcal{C}^2}{2\pi^2}\int_0^\infty n^2\sum_{p=1,2}|h_p(\eta)|^2\frac{dn}{n}. \quad (7)$$

Here, n refers to a dimensionless angular wave number, p refers to the left and right handed polarizations of the gravitational waves and $\eta = \int\frac{dt}{a(t)}$ is the conformal time.

The constant $\mathcal{C}$ should be taken as $\mathcal{C}=\sqrt{16\pi}l_{pl}$. It can be shown that the mean-square amplitude of the gravitational wave is

$$h^2(n,\eta) = [\frac{4l_{pl}}{\sqrt{\pi}}n]^2\sum_{p=1,2}|h_p(\eta)|^2. \quad (8)$$

The square root of the equation above will provide a root-mean squared (RMS) amplitude of a gravitational wave for a specific wave number. To complete the power spectrum, we show that the amplitude of gravitational waves can be expressed as

$$h(n,\eta) = [\frac{4l_{pl}}{\sqrt{\pi}}n]|h(\eta)|. \quad (9)$$

Using the relation $n_H = 4\pi$, which corresponds to the current Hubble radius [19, 20],

$$h(n,\eta) = 16\sqrt{\pi}l_{pl}\frac{n}{n_H}|h(\eta)|. \quad (10)$$

Grischuk shows that this can be expressed in a convenient form as

$$h(n) = 16\sqrt{\pi}l_{pl}\frac{b}{l_0}(\frac{n}{n_H})^{2+\beta}. \quad (11)$$

The variable β is the power-law ination parameter with -2 corresponding to the de Sitter universe and b is a constant defined in terms of β as

$$b = \frac{2^{|2+\beta|}}{|1+\beta|^{|1+\beta|}} \quad (12)$$

l_0 is a constant that denotes an arbitrary Hubble radius during inflation, it is on the order of $10^6 l_{pl}$ according to Grischuk.

$$a(\eta) = l_0|\eta|^{1+\beta} - \infty \leqslant \eta\ ; \ -2 \leqslant \beta \leqslant -1 \quad (13)$$

Since Grishchuk's solution effectively varies by wavenumber, n_H, to some power between 0 and -1, we can see that Boyle and Grishchuk's solutions may be equivalent for β = -1.5. By setting n_H to reflect a Hubble parameter earlier than the current epoch, we can calculate the spectrum of gravitational waves at any time in the history of the universe post inflation.

III. Overview of the Software

As described in the article, Numerical Relativity as a Tool for Studying the Early Universe [17], the code used here was specifically developed to study relativistic plasma physics in the early universe. This code is based on the Cactus Framework (www.cactuscode.org). Cactus was originally developed to perform numerical relativistic simulations of colliding black holes but it's modular design has since allowed it to be used for a variety of Physics, Engineering and Computer Science applications. It is currently being maintained by the Center for Computation and Technology at Louisiana Sate University. Cactus codes are composed of a esh (which provides the framework) and the thorns (which provide the physics). The code used within this work, SpecCosmo, is a collection of cactus thorns written in a combination of F90, C and C++.

The code uses the relativistic MHD evolution equations proposed by Duez [14]. It is also designed to utilize a variety of different differencing schemes including 2nd order Finite Differencing, 4th order Finite

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Differencing and Spectral Methods. This work uses Fourier Spectral Methods and periodic boundary conditions exclusively. These involve treating the functions as generic periodic functions and calculating the derivatives using FFTs and inverse FFTs. The code is capable of solving Einstein's Equations directly (through a modified BSSN formulation) as well as the relativistic MHD equations. The code was thoroughly tested [17] and found to accurately model known GRMHD dynamics. These tests included MHD waves induced by gravitational waves test, the consistency of cosmological expansion test and shock tests.

The initial data used was derived from work done by several projects involving primordial magnetic fields, phase transitions and early universe cosmology in general [16, 28, 34, 36, 37]. This study models a high energy epoch of the universe after inflation and the Electroweak phase transition when the universe was about 3 minutes old. The author chose this as the starting point for our study because it was the beginning of the Primordial Nucleosythesis in the early universe.

IV. Evolution Equations

The MHD equations used here are based on Duez's evolution equations [14].

$$\partial_t \rho_* + \partial_j(\rho_* v^j) = 0, \tag{14}$$

$$\partial_t \tilde{\tau} + \partial_i(\alpha^2\sqrt{\gamma}\, T^{0i} - \rho_* v^i) = s, \tag{15}$$

$$\partial_t \tilde{S}_i + \partial_j(\alpha\sqrt{\gamma}\, T^j_i) = \frac{1}{2}\alpha\sqrt{\gamma}\, T^{\alpha\beta} g_{\alpha\beta,i}, \tag{16}$$

$$\partial_t \tilde{B}^i + \partial_j(v^j\tilde{B}^i - v^i\tilde{B}^j) = 0. \tag{17}$$

Here ρ_* is conserved density, v^j is velocity, $\tilde{\tau}$ is the energy variable, $\tilde{S}_i$ is the momentum variable, s is the source term, α is the lapse term, γ is the determinate of the three metric and T^{ij} is the stress-energy tensor. The tilde denotes that the term was calculated with respect to the conformal metric. The first equation comes from conservation of baryon number, the second derives from conservation of energy, the third is conservation of momentum and the fourth is the magnetic induction equation. For this simulation we use Geodesic Slicing, α= 1.0, β_i = 0.0.

The code utilizes a first order version of the BSSN equations to simulate the background space-time. For fixed gauge conditions, the modified BSSN equations as defined by Brown [6] are:

$$\begin{aligned}
\overline{\partial}_0 K &= \alpha\left(\tilde{A}^{ij}\tilde{A}_{ij} + \frac{1}{3}K^2\right) + 4\pi\alpha(\rho + S)\ . && (18)\\
\overline{\partial}_0 \phi &= -\frac{\alpha}{6}K\ , && (19)\\
\overline{\partial}_0 \phi_i &= -\frac{1}{6}\alpha\overline{D}_i K - \kappa^\phi \mathcal{C}_i\ , && (20)\\
\overline{\partial}_0 \tilde{\gamma}_{ij} &= -2\alpha\tilde{A}_{ij}\ , && (21)\\
\overline{\partial}_0 \tilde{A}_{ij} &= e^{-4\phi}\left[\alpha(\tilde{R}_{ij} - 8\pi S_{ij}) - 2\alpha\overline{D}_{(i}\phi_{j)} + 4\alpha\phi_i\phi_j + \Delta\tilde{\Gamma}^k{}_{ij}(2\alpha\phi_k)\right]^{TF} \\
&\quad + \alpha K\tilde{A}_{ij} - 2\alpha\tilde{A}_{ik}\tilde{A}^k_j\ , && (22)\\
\overline{\partial}_0 \tilde{\gamma}_{kij} &= -2\alpha\overline{D}_k\tilde{A}_{ij} - \kappa^\gamma\mathcal{D}_{kij}\ , && (23)\\
\overline{\partial}_0 \tilde{\Lambda}^i &= -\frac{4}{3}\alpha\tilde{D}^i K + 2\alpha\left(\Delta\tilde{\Gamma}^i{}_{k\ell}\tilde{A}^{k\ell} + 6\tilde{A}^{ij}\phi_j - 8\pi\tilde{\gamma}^{ij}S_j\right)\ . && (24)
\end{aligned}$$

The bar denotes a derivative taken with respect to the fiducial metric and the tilde again denotes a derivative taken with respect to the conformal metric. Also, $\mathcal{C}_i$ and $\mathcal{D}_{kij}$ are constraint equations and κ^ϕ and κ^γ are proportionality constants. ρ, S, S_j and S_{ij} are source terms as found in the standard version of the BSSN equations. Brown et al also defined:

$$\begin{aligned}
\mathcal{C}_i &= \phi_i - \overline{D}_i\phi = 0,\\
\mathcal{D}_{kij} &= \tilde{\gamma}_{kij} - \overline{D}_k\tilde{\gamma}_{ij} = 0,\\
\Delta\tilde{\Gamma}^i{}_{k\ell} &= \frac{1}{2}\tilde{\gamma}^{ij}\left(\tilde{\gamma}_{k\ell j} + \tilde{\gamma}_{\ell kj} - \tilde{\gamma}_{jk\ell}\right)\ ,\\
\tilde{R}_{ij} &= -\frac{1}{2}\tilde{\gamma}^{k\ell}\overline{D}_k\tilde{\gamma}_{\ell ij} + \tilde{\gamma}_{k(i}\overline{D}_{j)}\tilde{\Lambda}^k + \tilde{\gamma}^{\ell m}\Delta\tilde{\Gamma}^k_{\ell m}\Delta\tilde{\Gamma}_{(ij)k}
\end{aligned}$$

$$+\tilde{\gamma}^{k\ell}[2\Delta\tilde{\Gamma}^m{}_{k(i}\Delta\tilde{\Gamma}_{j)m\ell}+\Delta\tilde{\Gamma}^m{}_{ik}\Delta\tilde{\Gamma}_{mj\ell}] \ ,$$

V. Experimental Set-Up and Assumptions

In order to determine the upper limit of primordial magnetic fields that existed at a particular stage in the evolution of our universe, we inject a broad spectrum of gravitational waves into a homogenous relativistic plasma field with a constant magnetic field and study the results. This is similar to what Duez did in the second of two papers [15]. The basic idea of the Duez paper was to calculate the effect that standing gravitational plane waves would have on a homogenous plasma field with a constant magnetic field. The result was to excite magnetosonic and Alfen waves in the plasma based on the polarization of the gravitational waves and other parameters such as the density, temperature and magnetic field of the plasma. This was done as a test of their GRMHD code but we use it here to probe what magnetic fields may have been physically allowable in the early universe. We choose to perform this study 180s after the big bang although such a study could have been performed anytime after electro-weak symmetry breaking. For the results to be relevant, we must assume that magnetogenesis and any dynamo effects had already created and strengthened a primordial magnetic fields

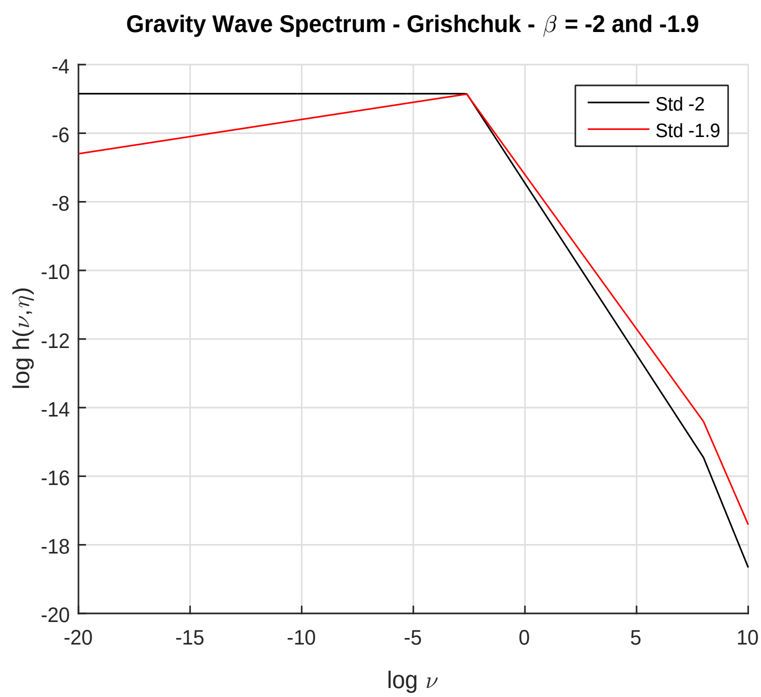

Figure 1: Primordial Gravitational Wave spectrum as calculated by Grishchuk's method for t = 180 s.

that would gradually be weakened by the expansion of the universe. The temperature, density, Hubble parameter, scale factor and mass contribution of the universe at this stage are all well known [28]. We utilized an initial temperature of 1.0×10^9 K. The scale factor and Hubble Parameter are $a = 2.81\times10^{-9}$ and $H = 2.46\times10^{-3}s^{-1}$ respectively. The mass/energy density at the time was $1.08\times10^4\frac{kg}{m^3}$. Our study assumes that 80% of the mass density of the universe was composed of "dark matter". This was chosen to be consistent with our current dark matter to baryonic matter ratio. This "dark matter" was simulated using a pressureless, non-magnetic fluid with no internal energy, in addition to the magnetofluid used to simulation regular matter. This was done to keep us from over estimating the effects of magnetic fields on the matter field. The amplitude of the gravitational waves at this epoch was determined using Grishchuk's solution described in a previous section.

We ran 6 simulations with different values of a fixed magnetic fields along the z-axis, $0\ G$, $10^2\ G$, $10^4\ G$, $10^5\ G$, $10^6\ G$ and $10^8\ G$. Each run used random tensor perturbations with amplitudes up to 10^{-19}. We utilized a three dimensional computational grid with 64^3 internal grid points corresponding to 4^3 meters with a courant factor of 0.1. The domain size of 4^3 meters was chosen to allow for multiple light crossing times during the course of the simulation. Geodesic slicing conditions and periodic boundary conditions were used for all simulation runs. We also used a 3rd order Iterative Crank Nicolson time scheme for time integration. A spectral differencing method was used and the simulations ran for over 1,000 iterations. There were no shocks or discontinuities in the system so we did not utilize our HRSC routines.

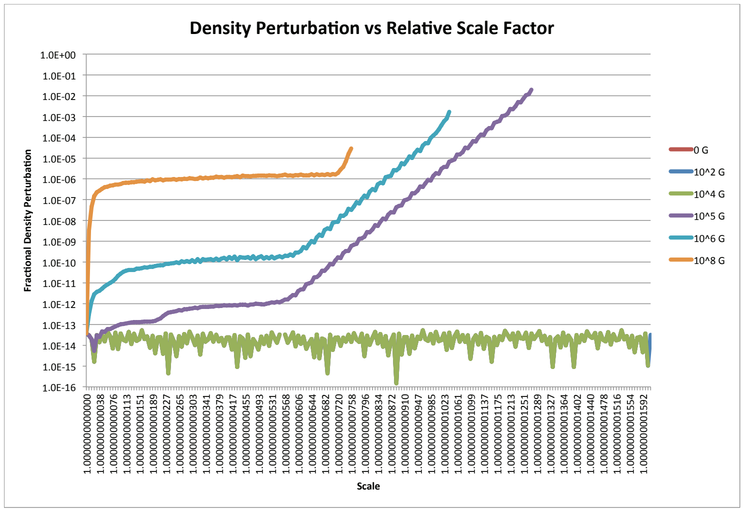

Figure 2: Density perturbations as the result of different initial magnetic fields

VI. Results

As one can see from Figure 2, the density perturbations appear larger as the intensity of the initial magnetic field increases. There appears to be no difference between the 0 G magnetic field and the 10^4 G magnetic field. However, the 10^5 G magnetic field seems to have a much larger effect on the plasma field with density perturbations on the order of a part in 10^{12} result. When the magnetic fields are near or above 10^5 G the perturbations continue to grow until the system becomes unstable. This is clearly an unphysical result. It should be noted that a primordial magnetic field of 10^8 would correspond to a current cosmological magnetic field of 10^{-9} G which is the established upper limit.

VII. Discussion

The goal of this project was to develop a technique for testing the upper limit of cosmological magnetic fields throughout different epochs of universal evolution. We did this using the beginning of Primordial Nucleosythesis as an example. We observed that the relative amplitude of density perturbations varied according to the strength of the initial magnetic fields. Our observed instabilities for magnetic fields greater than 10^4 G imply that such strong magnetic fields should not have been physically possible during the Primordial Nucleosynthesis epoch. We saw that the maximum possible magnetic field as determined by observation, is not physically viable. From this we conclude that the amplification of the seed magnetic fields either did not finish until much later or current cosmological magnetic fields should have amplitudes below 10^{-13} G. Future work will involve applying this technique to later epochs over a wider range of initial magnetic fields in order to more accurately determine upper limits for magnetic field intensities.

VIII. Conflicts of Interests

The author declares that there are no conflict of interests regarding the publication of this article.

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References Références Referencias

1. T. W. Baumgarte and S. L. Shapiro, Phys. Rev. D 59, 024007 (1999).
2. E. Battaner and H. Lesch, (2000) [arXiv:hep-ph/0408289]
3. L. A. Boyle and P. J. Steinhardt, Phys. Rev. D 77, 063504 (2008) doi:10.1103/PhysRevD.77.063504 [astro-ph/0512014].
4. L. A. Boyle, UMI-32-23849.
5. A. Brandenburg, K. Enqvist and P. Olesen, Phys. Rev. D 54, 1291 (1996)
6. J. D. Brown et al., Phys. Rev. D 85, 084004 (2012) doi:10.1103/PhysRevD.85.084004 [arXiv:1202.1038 [gr-qc]].
7. C. Caprini and R. Durrer, Phys. Rev. D 74, 063521 (2006) [arXiv:astro-ph/0603476]
8. C. Caprini, R. Durrer and G. Servant, JCAP 0912, 024 (2009) [arXiv:astro-ph/0909.0622]
9. S. M. Carroll, San Francisco, USA: Addison-Wesley (2004) 513 p
10. J. Cho, Astro. Phys. J. 621, 324-327 (2005)
11. J. Cho, J. of Korean Phys. Soc. 49, 4 (2006)
12. A. D. Dolgov, (2001) [arXiv:hep-ph/0110293
13. A. D. Dolgov, D. Grasso and A. Nicolis, Phys. Rev. D 66, 103505 (2002) [arXiv:astro-ph/0206461

14. M. D. Duez, Y. T. Liu, S. T. Shapiro and B. C. Stephens, Phys. Rev. D 72, 024028 (2005)
15. M. D. Duez, Y. T. Liu, S. T. Shapiro and B. C. Stephens, Phys. Rev. D 72, 024029 (2005)
16. R. Durrer and A. Neronov, Astron. Astrophys. Rev. 21, 62 (2013) [arXiv:1303.7121 [astro-ph.CO]].
17. D. Garrison, J. Grav. 2014, 407197 (2014) [arXiv:1207.7097 [gr-qc]].
18. D. Grasso and H. R. Rubinstein, Phys. Rept. bf 348 163-266 (2001) [arXiv:astro-ph/0009061]
19. L. P. Grishchuk, V. M. Lipunov, K. A. Postnov, M. E. Prokhorov and B. S. Sathyaprakash, Phys. Usp. 44, 1 (2001); Usp. Fiz. Nauk 171, 3 (2001); [arXiv:astro-ph/0008481]
20. L. P. Grishchuk, Phys. Rev. D 74, 083008 (2006), [arXiv:gr-qc/0605100]
21. J. N. Islam, Cambridge, UK: Univ. Pr. (1992) 190 p.
22. G. Gogoberidze, T. Kahniashvili and A. Kosowsky, Phys. Rev. D 76, 083002 (2007) [arXiv:astro-ph/0705.1733]
23. L. M. H. Hall, I. G. Moss, A. Berera, Phys.Rev. D69 (2004) 083525
24. K. M. Hu_enberger, H. K. Eriksen, F. K. Hansen, A. J. Banday, and K. M. Gorski, ApJ, 688 (2008) 1.
25. D. Hobill, A Burb and A Coley, Deterministic Chaos in General Relativity (New York, Plenum Press, 1994)
26. F. Hoyle 1951 IAU Symposium on the Motion of Gaseous Masses of Cosmical Dimensions: Problems of Cosmical Aerodynamics (Central Air Documents Office), p. 195
27. T. Inoue, K. Asano and K. Ioka, Astrophys. J. 734, 77 (2011) [arXiv:astro-ph.HE/1011.6350]
28. J. N. Islam, An Introduction to Mathematical Cosmology (Cambridge, Cambridge University Press, (1992)
29. S. Iso, Strong Coupling Gauge Theories in the LHC Perspective (SCGT12): pp. 238-246. arXiv:1304.0293 [hep-ph]
30. T. Kahniashvili, (2005) [arXiv:astro-ph/0508459]
31. T. Kahniashvili, G. Gogoberidze and B. Ratra, Phys. Rev. Lett. 95 151301 (2005) [arXiv:astro-ph/0505628]
32. T. Kahniashvili and B. Ratra, Phys. Rev. D 75 023002 (2007) [arXiv:astro-ph/0611247]
33. T. Kahniashvili, New Astron. Rev. 50, 1015 (2006) [astro-ph/0605440].
34. T. Kahniashvili, A. Kosowsky, G. Gogoberidze and Y. Maravin, Phys. Rev. D 78, 043003 (2008) [arXiv:astro-ph/0806.0293]
35. T. Kahniashvili, L. Campanelli, G. Gogoberidze, Y. Maravin and B. Ratra, Phys. Rev. D 78, 123006 (2008) [Erratum-ibid. D 79, 109901 (2009)] [arXiv:astro-ph/0809.1899]
36. T. Kahniashvili, L. Kisslinger and T. Stevens, Phys. Rev. D 81, 023004 (2010) [arXiv:astro-ph/0905.0643].
37. L. S. Kisslinger, Mod. Phys. Lett. A19, 1179-1186 (2004) [arXiv:hep-ph/0402001]
38. H. Kodama and M. Sasaki, Prog. Theor. Phys. Suppl. 78, 1 (1984)
39. H. Kurki-Suonio, Cosmological perturbation theory, part 2. Lecture notes for a course of cosmological perturbation theory given at the University of Helsinki 2010, (2010)
40. A. Melatos and C. Peralta, Astrophys. J. 709, 77 (2010) [arXiv:astro-ph.HE/0911.1609]
41. C. J. Moore, R.H. Cole and C. P. L. Berry, http: =www:ast:cam:ac:uk= _ cjm96=noise curve:pdf
42. S. Mukherjee, S. Das, M. Joy and T. Souradeep, JCAP 01 (2015) 043 arXiv:1410.8835 [astro-ph.CO]
43. A. Nicolis, Class. Quant. Grav. 21, L27 (2004) [arXiv:gr-qc/0303084]

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Extracting gravitational waves induced by plasma turbulence in the early Universe through an averaging process

David Garrison and Christopher Ramirez

Physics Department, University of Houston Clear Lake, Houston, TX 77058 United States of America

E-mail: garrison@uhcl.edu

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Abstract

This work is a follow-up to the paper, 'Numerical relativity as a tool for studying the early Universe'. In this article, we determine if cosmological gravitational waves can be accurately extracted from a dynamical spacetime using an averaging process as opposed to conventional methods of gravitational wave extraction using a complex Weyl scalar. We calculate the normalized energy density, strain and degree of polarization of gravitational waves produced by a simulated turbulent plasma similar to what was believed to have existed shortly after the electroweak scale. This calculation is completed using two numerical codes, one which utilizes full general relativity calculations based on modified BSSN equations while the other utilizes a linearized approximation of general relativity. Our results show that the spectrum of gravitational waves calculated from the nonlinear code using an averaging process is nearly indistinguishable from those calculated from the linear code. This result validates the use of the averaging process for gravitational wave extraction of cosmological systems.

Keywords: cosmology, numerical relativity, gravitational waves, relativistic MHD

(Some figures may appear in colour only in the online journal)

1. Introduction

Recent work by the Bicep 2 Collaboration [1], has resulted in increased interest in the existence of primordial gravitational waves. Although these results were later disproven [2, 3], speculation about the characteristics of primordial gravitational waves is still very much alive [11, 16–22]. Our ultimate goal is to determine the characteristics of these waves, given different cosmological theories, and if possible, find ways to observe them. However, before we can do that we must first determine how to efficiently extract gravitational waves produced by turbulence in the relativistic plasma which dominated the Universe shortly after the electroweak phase transition. Can these waves be accurately calculated using linearilized approximations of gravity? Does the chaotic nature of the general relativity's nonlinearities significantly affect the solution [14]? Can an averaging process be used to quickly extract gravitational waves from a dynamic spacetime [9]?

Primordial plasma turbulence is believed to have occurred as a result of stirring caused by bubble wall collisions and other chaotic events during inflation and the electroweak phase transition. The characteristic velocity of the turbulent eddies was calculated to be as high as 0.65 [19, 21]. The magnetic fields around this time may have been as high as 10^{20} G. This number was determined by extrapolating the accepted upper limit on cosmic magnetic fields, 10^{-9} G to a much smaller scale factor and assuming that the $B \propto a^2$ relationship holds [8].

The author's previous work [10] showed how the framework of numerical relativity could be used to study the cosmology of the early Universe. In this article, we expand on the techniques presented. We utilize two general relativistic magnetohydrodynamic (GRMHD) codes in order to simulate a turbulent plasma similar to that of the Universe when it was less than a second old. One of these codes utilizes full general relativity modeled using a modified version of the BSSN equations in order to simulate the dynamical spacetime background while the other relies on a linearized approximation of gravity. We characterize the gravitational waves produced and then compare the results produced by both codes.

Both the nonlinear and linear GRMHD codes have advantages. By not solving Einstein's equations, the linear code is much faster and requires less memory to run. This is because the linear code does not have to solve nearly as many evolution equations. Solving Einstein's equations using a first order BSSN formalism adds about 35 additional evolution equations to the computer's workload. However, utilizing a nonlinear GRMHD code can have advantages as well. For example, the nonlinear code allows for nonlinear and dynamic spacetime solutions to evolve from initial conditions. Also, the nonlinear code allows for the injection of gravitational waves into the initial data which would then effect the dynamics of the plasma field and evolution of the system [7]. Because of this, it is important that we develop both codes and determine their accuracy and limitations.

2. Overview of the software

Our code uses SI units for input and output and geometerized units, $c = \hbar = G = 1$, are used for all calculations within the code. Throughout this article, we will refer to time and distance in units of meters.

As described in the preceding paper [10], the codes used here were specifically developed to study early Universe cosmology. These codes are based on the cactus framework (www.cactuscode.org). Cactus was originally developed to perform numerical relativistic simulations of colliding black holes but its modular design has since allowed it to be used for a variety of physics, engineering and computer science applications. It is currently being maintained by the Center for Computation and Technology at Louisiana Sate University. Cactus codes are composed of a flesh (which provides the framework) and the thorns (which provide the physics). The codes used within this work, FixedCosmo and SpecCosmo, are a collection of cactus thorns. They are written in a combination of F90, C and C++.

Both codes utilize the relativistic MHD evolution equations proposed by Duez [6]. Both codes are also designed to utilize a variety of different differencing schemes including second order finite differencing, fourth order finite differencing and spectral methods. The key difference between the codes is that while one is capable of solving Einstein's equations directly (through a modified BSSN formulation) as well as the relativistic MHD equations, the other solves the relativistic MHD equations but simulates an expanding spacetime and estimates the gravitational wave background without solving directly Einstein's equations. This allows us to perform a test to determine under what conditions it is important to spend computational resources to solve Einstein's equations directly and if the gravitational waves are being correctly extracted from the nonlinear code. The codes were thoroughly tested [10] and found to accurately model known GRMHD dynamics. These tests included MHD waves induced by gravitational waves test, the consistency of cosmological expansion test and shock tests.

The initial data used was derived from work done by several projects involving primordial magnetic fields, phase transitions and early Universe cosmology in general [8, 15, 19, 21, 22]. This study models an extremely high energy epoch of the Universe shortly after the electroweak phase transition when the Universe was about 10^{-6} s old. The authors chose this as the starting point for our study because it was the beginning of the Hadronic Epoch of the early Universe. It should be noted however, that the purpose of this paper is to test numerical techniques and not to exactly model the early Universe.

3. Evolution equations

The MHD equations used to evolve both numerical codes were based on Duez's evolution equations [6].

$$\partial_t \rho_* + \partial_j(\rho_* v^j) = 0, \tag{1}$$

$$\partial_t \tilde{\tau} + \partial_i(\alpha^2 \sqrt{\gamma}\, T^{0i} - \rho_* v^i) = s, \tag{2}$$

$$\partial_t \tilde{S}_i + \partial_j(\alpha \sqrt{\gamma}\, T_i^j) = \frac{1}{2}\alpha\sqrt{\gamma}\, T^{\alpha\beta} g_{\alpha\beta,i}, \tag{3}$$

$$\partial_t \tilde{B}^i + \partial_j(v^j \tilde{B}^i - v^i \tilde{B}^j) = 0. \tag{4}$$

The first equation comes from conservation of baryon number, the second derives from conservation of energy, the third is conservation of momentum and the fourth is the magnetic induction equation. For this simulation we use Geodesic Slicing, $\alpha = 1.0$, $\beta_i = 0.0$ for both codes. Here ρ_* is conserved density, v^j is velocity, $\tilde{\tau}$ is the energy variable, $\tilde{S}_i$ is the momentum variable, s is the source term, α is the lapse term, γ is the determinant of the three metric and T^{ij} is the stress-energy tensor. The tilde denotes that the term was calculated with respect to the conformal metric. These variables are defined in terms of the stress tensor, primitive variables and gauge quantities below.

$$\rho_* = \alpha\sqrt{\gamma}\rho u^0, \tag{5}$$

$$\tilde{\tau} = \alpha^2\sqrt{\gamma} T^{00} - \rho_* \tag{6}$$

$$\tilde{S}_i = \alpha\sqrt{\gamma} T_i^0, \tag{7}$$

$$s = \alpha\sqrt{\gamma}(T^{00}\beta^i\beta^j + 2T^{0i}\beta^j + T^{ij})K_{ij} - (T^{00}\beta^i + T^{0i})\partial_i\alpha \tag{8}$$

The nonlinear code utilizes a first order version of the BSSN equations to simulate the background space-time. For fixed gauge conditions, the modified BSSN equations as defined by Brown [5] are:

$$\overline{\partial}_0 K = \alpha\left(\tilde{A}^{ij}\tilde{A}_{ij} + \frac{1}{3}K^2\right) + 4\pi\alpha(\rho + S). \tag{9}$$

$$\overline{\partial}_0 \phi = -\frac{\alpha}{6}K, \tag{10}$$

$$\overline{\partial}_0 \phi_i = -\frac{1}{6}\alpha\overline{D}_i K - \kappa^\phi \mathcal{C}_i, \tag{11}$$

$$\overline{\partial}_0 \tilde{\gamma}_{ij} = -2\alpha\tilde{A}_{ij}, \tag{12}$$

$$\begin{aligned}\overline{\partial}_0 \tilde{A}_{ij} = \mathrm{e}^{-4\phi}&\left[\alpha(\tilde{R}_{ij} - 8\pi S_{ij}) - 2\alpha\overline{D}_{(i}\phi_{j)} + 4\alpha\phi_i\phi_j + \Delta\tilde{\Gamma}^k{}_{ij}(2\alpha\phi_k)\right]^{TF}\\ &+ \alpha K\tilde{A}_{ij} - 2\alpha\tilde{A}_{ik}\tilde{A}^k_j,\end{aligned} \tag{13}$$

$$\overline{\partial}_0 \tilde{\gamma}_{kij} = -2\alpha\overline{D}_k\tilde{A}_{ij} - \kappa^\gamma\mathcal{D}_{kij}, \tag{14}$$

$$\overline{\partial}_0 \tilde{\Lambda}^i = -\frac{4}{3}\alpha\tilde{D}^i K + 2\alpha\left(\Delta\tilde{\Gamma}^i{}_{k\ell}\tilde{A}^{k\ell} + 6\tilde{A}^{ij}\phi_j - 8\pi\tilde{\gamma}^{ij}S_j\right). \tag{15}$$

The bar denotes a derivative taken with respect to the fiducial metric (defined here to have a determinant of one) and the tilde again denotes a derivative taken with respect to the conformal metric. Also, $\mathcal{C}_i$ and $\mathcal{D}_{kij}$ are constraint equations and κ^ϕ and κ^γ are proportionality constants. ρ, S, S_j and S_{ij} are source terms as found in the standard version of the BSSN equations. Brown *et al* also defined:

$$\mathcal{C}_i = \phi_i - \overline{D}_i\phi = 0, \tag{16}$$

$$\mathcal{D}_{kij} = \tilde{\gamma}_{kij} - \overline{D}_k\tilde{\gamma}_{ij} = 0, \tag{17}$$

$$\begin{aligned}\Delta\tilde{\Gamma}^i{}_{k\ell} &= \frac{1}{2}\tilde{\gamma}^{ij}\left(\tilde{\gamma}_{k\ell j} + \tilde{\gamma}_{\ell kj} - \tilde{\gamma}_{jk\ell}\right),\\ \tilde{R}_{ij} &= -\frac{1}{2}\tilde{\gamma}^{k\ell}\overline{D}_k\tilde{\gamma}_{\ell ij} + \tilde{\gamma}_{k(i}\overline{D}_{j)}\tilde{\Lambda}^k + \tilde{\gamma}^{\ell m}\Delta\tilde{\Gamma}^k_{\ell m}\Delta\tilde{\Gamma}_{(ij)k}\end{aligned} \tag{18}$$

$$+ \tilde{\gamma}^{k\ell}[2\Delta\tilde{\Gamma}^m{}_{k(i}\Delta\tilde{\Gamma}_{j)m\ell} + \Delta\tilde{\Gamma}^m{}_{ik}\Delta\tilde{\Gamma}_{mj\ell}], \tag{19}$$

These equations allow gravitational waves to appear organically from the turbulent plasma field. For the linear code, we approximate the effect of an expanding spacetime and determine the gravitational wave spectrum without utilizing full general relativity. We do this by solving the Friedmann equations and the linearized gravitational wave equations [15].

$$\partial_0 a = aH \tag{20}$$

$$\partial_0 H = -H^2 - \frac{4}{3}\pi(\rho + 3p) \tag{21}$$

$$\partial_0 \tilde{h}_{ij} = q_{ij} \tag{22}$$

$$\partial_0 q_{ij} = \nabla^2 \tilde{h}_{ij}/a^2 - 2(2H^2 + \partial_0 H)(\delta_{ij}\tilde{h}^{ij} - \tilde{h}_{ij}) + 16\pi T_{ij}. \tag{23}$$

Where $\tilde{h}_{ij}$ are gravitational perturbations calculated by the linearized code and q_{ij} are their time derivatives.

4. Extraction methods

The purpose of this paper is to determine if an averaging method is effective in extracting gravitational waves from a cosmological spacetime. In this section, we will describe both averaging and Newman–Penrose, particularly as they apply to cosmological spacetimes. As described by Ellis [9], the averaging method assumes that the spacetime can be written in terms of perturbations as shown below:

$$\bar{g}_{ij} \equiv \langle g_{ij} \rangle \tag{24}$$

$$\bar{g}_{ab}\bar{g}^{bc} = \delta^a_c \tag{25}$$

$$g_{ab} = \bar{g}_{ab} + \delta g_{ab} \tag{26}$$

$$g^{ab} = \bar{g}^{ab} + h^{ab} \tag{27}$$

$$g_{ab}g^{bc} = \delta^a_c. \tag{28}$$

Unlike linearized gravity, $\bar{g}^{ij} \neq \langle g^{ij} \rangle$ and $h^{ab} \neq \delta g^{ab} \equiv g^{ae}g^{bf}(\delta g_{ef})$. This leads to the following equations for the Christoffel symbols and curvature tensors.

$$\Gamma^a_{bc} = \bar{\Gamma}^a_{bc} + \delta\Gamma^a_{bc} \tag{29}$$

$$R_{ab} = \bar{R}_{ab} + \delta R_{ab} \tag{30}$$

$$G_{ab} = \bar{G}_{ab} + \delta G_{ab} \tag{31}$$

For a cosmological spacetime, the bar terms are analogous to the unperturbed FRW spacetime while the delta terms correspond to the gravitational waves. This assumes that the average of the perturbations is effectively zero. Because of this, we can assume that $\delta g_{ij} = a^2 h_{ij}$, therefore

$$g_{ij} = \bar{g}_{ij} + a^2 h_{ij}. \tag{32}$$

Once these perturbations are calculated from the spacetime using the averaging method, we still need to derive the gravitational wave spectrum, taking into account that the resulting gravitational perturbations are not necessarily transverse-traceless. This will be discussed in the next section. An obvious limitation of the averaging method is that it is not practical when the background spacetime contains singularities. The Newman–Penrose formalism lacks such limitations but is much more complicated to utilize for a cosmological spacetime.

The Newman–Penrose formalism works by contracting the Weyl tensor (C_{abcd}) with a complex null tetrad in order to form five complex scalars, Ψ_0 ... Ψ_4. The Weyl tensor is by definition the traceless part of the Riemann tensor and the tetrad is formed by a combination of real ingoing and outgoing vectors as well as a complex vector and its complex conjugate. In order to extract gravitational waves using the Newman–Penrose formalism, we would first need to calculate the 10 traceless components of the Riemann tensor and then determine the ingoing and outgoing vectors with relationship to the source. Once these quantities are known, gravitational waves can then derived from the Ψ_0 and Ψ_4 Weyl scalars, defined as

$$\Psi_0 = -C_{abcd} l^a m^b l^c m^d \tag{33}$$

$$\Psi_4 = -C_{abcd} k^a \bar{m}^b k^c \bar{m}^d. \tag{34}$$

Here l^a and k^a are the outgoing and ingoing null vectors respectively, m^b is the complex vector constructed by two spatial vectors that are orthogonal to the null vectors and $\bar{m}^b$ is the complex conjugate of m^b . Once calculated, Ψ_4 can be used to calculate gravitational wave luminosity and energy/angular momentum loss due to an outgoing gravitational wave. The Ψ_0 Weyl scalar can be used to do the same for ingoing gravitational waves. This brings up a major problem with using Weyl scalars to extract gravitational waves from a cosmological spacetime. How does one define ingoing and outgoing gravitational waves when the source is everywhere? Even if it was possible to define an appropriate complex null tetrad, wouldn't the computation needed to derive Ψ_0 and Ψ_4 Weyl scalars far exceed what is needed to extract gravitational waves using an averaging scheme? Because of these questions, we believe that it was necessary to determine if averaging could be used for extracting gravitational waves from cosmological systems.

5. Calculation of the gravitational wave spectrum and polarization

The gravitational wave spectrum is output as characteristic strain, energy density and degree of polarization by the numerical code [24]. For the full GR code, we utilize an averaging process to calculate the gravitational waves produced by the simulation [9]. Here gravitation perturbations can be found by subtracting the mean value of the metric, $\bar{g}_{ij}$ from its value at any point and correcting for the scale factor.

$$h_{ij} = (g_{ij} - \bar{g}_{ij})/a^2 \tag{35}$$

Unfortunately these perturbations are not necessarily in the transverse-traceless gauge so the energy density must be calculated as

$$t_{00} = \frac{1}{32\pi G}\langle(\partial_0 h_{ij})(\partial_0 h^{ij}) - \frac{1}{2}(\partial_0 h)(\partial_0 h) - (\partial_\rho h^{\rho\sigma})(\partial_0 h_{0\sigma}) - (\partial_\rho h^{\rho\sigma})(\partial_0 h_{0\sigma})\rangle. \tag{36}$$

The brackets denote the average over several wavelengths. By utilizing geodesic slicing conditions the last two terms are identically zero. The time derivatives of the perturbations can be rewritten in terms of the extrinsic curvature (K), lapse (α), hubble parameter ($H = \frac{\dot{a}}{a}$), and scale factor (a).

$$\partial_0 h_{ij}\partial_0 h^{ij} - \frac{1}{2}\partial_0 h \partial_0 h = 2[(2\alpha^2 K_{ij}K^{ij} + 4\alpha HK + 6H^2) - (\alpha K + 3H)^2]/a^4 \tag{37}$$

The mass density is then normalized by dividing by the critical density

$$\rho_c = \frac{3H^2}{8\pi G}. \tag{38}$$

This results in a normalized energy density,

$$\Omega_N = -\langle(2\alpha^2 K_{ij}K^{ij} + 4\alpha HK + 6H^2 - (\alpha K + 3H)^2)/(6a^4H^2)\rangle. \tag{39}$$

The normalized energy density for the linearized code is then simply calculated as

$$\Omega_L = \frac{1}{12H^2a^4}\langle q_{ij}q^{ij} - \frac{1}{2}(q_i^i)^2\rangle. \tag{40}$$

For both codes, the magnitude of the characteristic strain is calculated using the quadratic mean of the plus and cross polarizations of the gravitational waves perceived to be traveling along the x, y and z axes. The plus polarizations are calculated by finding the difference between the diagonal transverse perturbation terms while the cross terms relate directly to the perturbations in the off-diagonal transverse terms.

$$h_x^+ = \frac{1}{2}(h_{yy} - h_{zz}) \tag{41}$$

$$h_y^+ = \frac{1}{2}(h_{zz} - h_{xx}) \tag{42}$$

$$h_z^+ = \frac{1}{2}(h_{xx} - h_{yy}) \tag{43}$$

$$h_x^\times = h_{yz} \tag{44}$$

$$h_y^\times = h_{xz} \tag{45}$$

$$h_z^\times = h_{xy} \tag{46}$$

$$h_i(k,t) = \sqrt{|h_i^+(\vec{k},t)|^2 + |h_i^\times(\vec{k},t)|^2} \tag{47}$$

$$h(k,t) = \sqrt{h_x(k,t)^2 + h_y(k,t)^2 + h_z(k,t)^2} \tag{48}$$

According to Kahniashvili [18], the degree of polarization can be defined as,

$$P(k,t) = \frac{\langle h^{R*}(\vec{k},t)h^R(\vec{k'},t) - h^{L*}(\vec{k},t)h^L(\vec{k'},t)\rangle}{\langle h^{R*}(\vec{k},t)h^R(\vec{k'},t) + h^{L*}(\vec{k},t)h^L(\vec{k'},t)\rangle} \tag{49}$$

Where the right and left polarizations for waves traveling along the x, y or z axis are defined as,

$$h_i^R = h_i^+ + \mathrm{i}h_i^\times \tag{50}$$

$$h_i^L = h_i^+ - \mathrm{i}h_i^\times \tag{51}$$

By expanding the left and right polarizations into plus and cross polarizations, the polarization degree can be rewritten as,

$$P_i(k_i,t) = \frac{2\langle \mathrm{Im}[h_i^+(k_i,t)]\mathrm{Re}[h_i^\times(k_i,t)] - \mathrm{Re}[h_i^+(k_i,t)]\mathrm{Im}[h_i^\times(k_i,t)]\rangle}{\langle |h_i^+(k_i,t)|^2 + |h_i^\times(k_i,t)|^2\rangle} \tag{52}$$

6. Experimental set-up

Our simulation begins shortly after the electroweak energy scale, at the beginning of the hadronic epoch. The numerical values for the initial conditions where calculated using the available literature [15] and are the exact same for both codes. These calculations give us

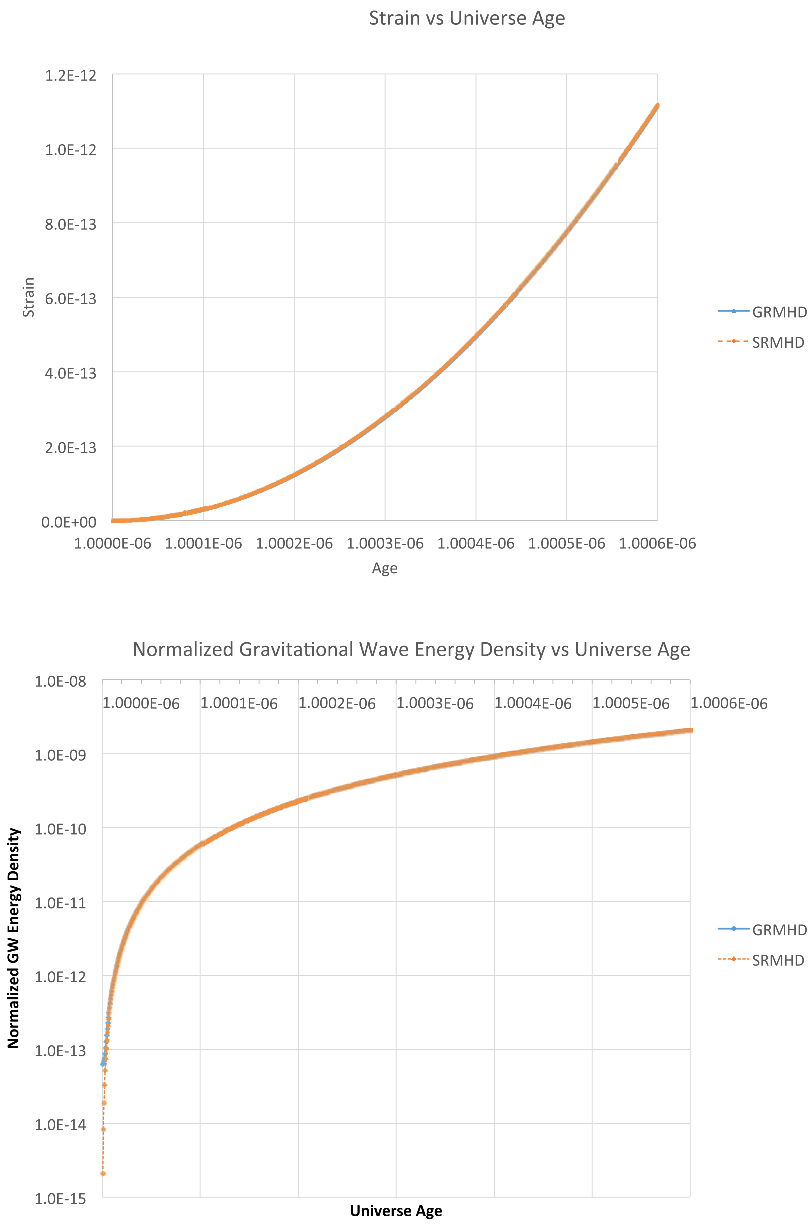

Figure 1. Strain of gravitational waves produced by the linear and nonlinear codes. Normalized energy density of gravitational waves produced by the linear and nonlinear codes.

an initial temperature of 1.30×10^{13} K at time 1.0×10^{-6} s. The scale factor and Hubble parameter are $a = 2.096 \times 10^{-13}$ and $H = 7.99 \times 10^{6}$ s^{-1} respectively. The critical mass/energy density at the time was 1.14×10^{23} kg m^{-3}. The characteristic velocity of the turbulent eddies for all runs was set to 0.25 [19, 21]. The magnetic field at the time could have been as large as 10^{17} G so we set the amplitude of the magnetic fields to 10^{14} G for our simulations.

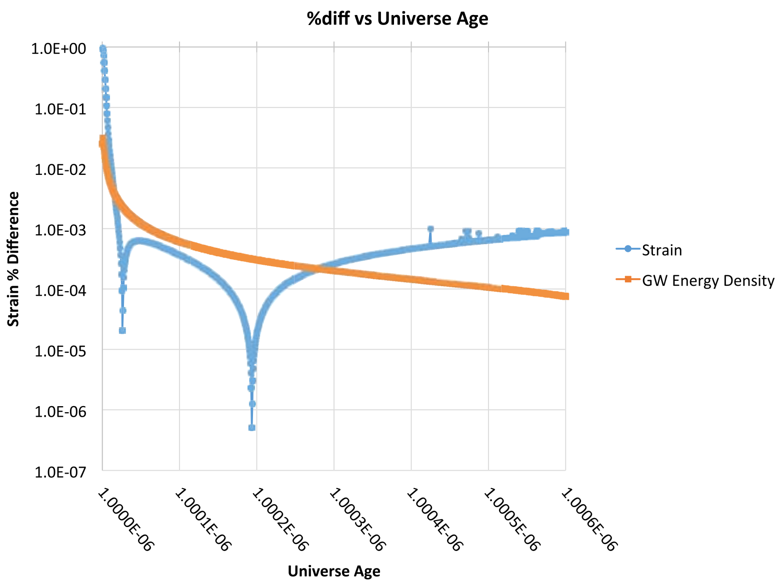

Figure 2. The relative error was calculated by dividing the difference in strain (energy density) by the strain (energy density) of the nonlinear code.

Table 1. Degree of polarization at the final time.

	X–Direction	Y–Direction	Z–Direction
Nonlinear (mean)	0.0	$-1.561\,25 \times 10^{-17}$	0.0
Linear (mean)	0.0	0.0	0.0
Nonlinear (standard deviation)	0.592 164 099	0.518 579 627	0.569 916 566
Linear (standard deviation)	0.592 333 947	0.515 687 302	0.572 444 906

We ran three sets of simulations using the nonlinear and linear codes with the exact same initial conditions. The first simulation utilized a grid 1000 m cubed with 64^3 grid points and a timestep of 10^{-6} m. These dimensions were chosen so that any resulting gravitational waves would correspond to the frequency range of pulsar timing observations once universal expansion is taken into account. The other two used higher or lower resolutions in order to establish convergence in our results. Geodesic slicing conditions, periodic boundary conditions and Fourier spectral differencing were used for all simulation runs. There were no shocks or discontinuities in the system so we did not utilize our high resolution shock capturing (HRSC) routines. We also used a third order iterative Crank Nicolson time scheme for time integration. All runs started with no initial gravitational waves but the density, temperature, velocity and magnetic fields were all perturbed to model that of an early Universe space-time [4, 8, 12, 13, 23, 25]. The initial density and temperature were perturbed by random phase cosine functions with an amplitude proportional to their wavenumber, k, effectively a Fourier series. The initial magnetic field consisted of random phase cosine waves with an amplitude proportional to their wavenumber squared, k^2. The initial velocity field consisted of random phase cosine waves with an amplitude proportional to their wavenumber cubed, k^3. Each run utilized 64 processing cores on the Maxwell computing cluster at the University of Houston's Center for Advanced Computing and Data Systems. Over 10 000 iterations were produced for each data run.

7. Results

It should be noted that these results have not been extrapolated for present day observations and only represent a relatively short period in the early Universe. This is because of limits in our available computing resources to perform such a long simulation. The strain and normalized energy density outputs for all runs appeared to be independent of k, so we chose to focus on the mean value of these quantities. As one can see from figure 1, the difference between the average strain as calculated by the nonlinear and linear codes is negligible. We see that the same is true for the energy density as shown in figure 2. Based on the data, we can assume that strain and energy density calculations derived from the linear code is accurate to within a part in a thousand of those derived from the nonlinear code using the averaging technique.

As shown in table 1, The degree of polarization for the gravitational waves appears to be the same for both the linear and nonlinear calculations. These results appear to agree with work done by Kahniashvili [16, 18]. This calculation was performed from a sample of five different times between 1.0005×10^{-6} s and 1.0006×10^{-6} s. As expected, since the initial data was isotropic, there does not appear to be any bias in the degrees of polarizations for the X, Y and Z directions or between left and right polarized gravitational waves generated by the turbulent system. Further, the statistics of the polarizations for both the nonlinear and linear simulations appear to be the same to two significant figures.

8. Discussion

In this article, we tested the averaging process to extract gravitational waves from nonlinear cosmological simulations. We did this by using cosmological linear and nonlinear codes to solve the exact same problem and comparing the results. We looked at three characteristics of the resulting gravitational waves, strain, normalized energy density and degree of polarization. We found that the results agreed for all three measures. The tiny differences that did occur may be partially explained by small nonlinear effects. We believe that these results prove that the averaging process outlined in section 4 of this paper is an accurate method of extracting gravitational waves for cosmological systems that lack spacetime singularities. We have demonstrated that this holds true for gravitational waves with strains up to 10^{-12} and normalized energy densities as high as 10^{-8}. Further work is needed to test the limits of the averaging process. Also, as a result of this work, we can conclude that the linear and nonlinear codes produce the same gravitational waves to within a part in 10^3.

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ORCID

Christopher Ramirez https://orcid.org/0000-0003-1101-4312

References

[1] Ade P A R *et al* and BICEP2 Collaboration 2014 *Phys. Rev. Lett.* **112** 241101
[2] Ade P A R *et al*, The BICEP2/Keck and Planck Collaborations 2015 *Phys. Rev. Lett.* **114** 101301
[3] Ade P A R *et al* and The Planck Collaboration 2015 *Astron. Astrophys.* **594** A20
[4] Ade P A R *et al* and The Planck Collaboration 2014 *Astron. Astrophys.* **571** A22
[5] Brown J D *et al* 2012 *Phys. Rev.* D **85** 084004
[6] Duez M D, Liu Y T, Shapiro S T and Stephens B C 2005 *Phys. Rev.* D **72** 024028
[7] Duez M D, Liu Y T, Shapiro S T and Stephens B C 2005 *Phys. Rev.* D **72** 024029
[8] Durrer R and Neronov A 2013 *Astron. Astrophys. Rev.* **21** 62
[9] Ellis G F R 2011 *Class. Quantum Grav.* **28** 164001
[10] Garrison D 2014 *J. Grav.* **2014** 407197
[11] Gogoberidze G, Kahniashvili T and Kosowsky A 2007 *Phys. Rev.* D **76** 083002
[12] Hall L M H, Moss I G and Berera A 2004 *Phys. Rev.* D **69** 083525
[13] Huffenberger K M, Eriksen H K, Hansen F K, Banday A J and Gorski K M 2008 *Astrophys. J.* **688** 1
[14] Hobill D, Burb A and Coley A 1994 *Deterministic Chaos in General Relativity* (New York: Plenum)
[15] Islam J N 1992 *An Introduction to Mathematical Cosmology* (Cambridge: Cambridge University Press)
[16] Kahniashvili T, Gogoberidze G and Ratra B 2005 *Phys. Rev. Lett.* **95** 151301
[17] Kahniashvili T and Ratra B 2007 *Phys. Rev.* D **75** 023002
[18] Kahniashvili T 2006 *New Astron. Rev.* **50** 1015
[19] Kahniashvili T, Kosowsky A, Gogoberidze G and Maravin Y 2008 *Phys. Rev.* D **78** 043003
[20] Kahniashvili T, Campanelli L, Gogoberidze G, Maravin Y and Ratra B 2008 *Phys. Rev.* D **78** 123006
Kahniashvili T, Campanelli L, Gogoberidze G, Maravin Y and Ratra B 2009 *Phys. Rev.* D **79** 109901
[21] Kahniashvili T, Kisslinger L and Stevens T 2010 *Phys. Rev.* D **81** 023004
[22] Kisslinger L S 2004 *Mod. Phys. Lett.* A **19** 1179–86
[23] Kurki-Suonio H 2010 *Cosmological Perturbation Theory* (Part 2 Lecture notes for a course of cosmological perturbation theory given at the University of Helsinki)
[24] Moore C J, Cole R H and Berry C P L http://ast.cam.ac.uk/ cjm96/noise_curve.pdf
[25] Mukherjee S, Das S, Joy M and Souradeep T 2015 *J. Cosmol. Astropart. Phys.* JCAP01(2015)043

Relativistic Magnetohydrodynamic Turbulence in the Early Universe

David Garrison

Department of Physics, University of Houston Clear Lake, 2700 Bay Area Blvd, Box 39, Houston, Texas, USA
(E-mail: garrison@uhcl.edu)

Abstract. The dynamics of all physical systems can be understood in terms of their invariant quantities. In this letter, we look at the invariant quantities of Relativistic and Non Relativistic fluids of charged particles in order to understand the spontaneous generation of magnetic seed fields which may have been responsible for magnetogenesis in the early universe. We show how the invariants of Relativistic Magnetohydrodynamic systems naturally lead to the development of seed magnetic fields while the invariants of non-relativistic magnetohydrodynamic systems will suppress such a development.
Keywords: Relativistic MHD, Turbulence, Cosmology.

A significant volume of work has been performed in order to understand the invariants of Non Relativistic Magnetohydrodynamic (MHD) systems in both the compressible and incompressible regimes [1,5,7–13]. In such systems there could be as many as 3 invariants; energy (E), and the psuedoscalars Cross Helicity (H_C) and Magnetic Helicity (H_M).

Table 1. Invariants for Ideal Non Relativistic MHD.

Case	Mean Field	Angular Velocity	Invariants
I	0	0	E, H_C, H_M
II	$B_0 \neq 0$	0	E, H_C
III	0	$\Omega_0 \neq 0$	E, H_M
IV	$B_0 \neq 0$	$\Omega_0 = \sigma B_0$	E, H_P
V	$B_0 \neq 0$	$\Omega_0 \neq 0$ ($B_0 \times \Omega_0 \neq 0$)	E

The Cross Helicity and Magnetic Helicity can be expressed as:

$$H_C = \frac{1}{2} \int \mathbf{V} \cdot \mathbf{B} \; \mathbf{d^3x} \tag{1}$$
$$H_M = \frac{1}{2} \int \mathbf{A} \cdot \mathbf{B} \; \mathbf{d^3x}. \tag{2}$$

For the magnetofluid, $\mathbf{V}$ is the velocity of the fluid element, $\mathbf{B}$ is the magnetic field and $\mathbf{A}$ is the vector potential. A conservation law is satisfied when the

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time derivative of one of the terms above is zero. According to work by Yoshida et al [4,14], in addition to 4-momentum, relativistic systems are expected to conserve a quantity called Relativistic Helicity. It is defined below using the canonical 4-momentum density, $\mathcal{P}^\mu$ and vorticity, $\mathbf{\Omega} = \nabla \times \mathcal{P}$, of the system.

$$\kappa = (\mathcal{P} \cdot \mathbf{\Omega}, \mathcal{P}_\mathbf{0}\mathbf{\Omega} + \mathcal{P} \times (\nabla \mathcal{P}_\mathbf{0} + \partial_\mathbf{0} \mathcal{P})) \tag{3}$$

Here the canonical 4-momentum density $\mathcal{P} = (\mathcal{P}_0, \mathcal{P})$ is a combination of mechanical and electromagnetic momentum densities, $\mathcal{P}_\mu = P_\mu + eA_\mu$. The conservation of Relativistic Helicity is then effectively, $\int \partial_\mu \kappa^\mu \mathbf{d^3x} = \mathbf{0}$. If we ignore the electromagnetic momentum and physical vorticity, we recover a relativistic version of Cross Helicity Density, $\kappa_\mathbf{C}$. If we set the particle's kinetic momentum to zero, we recover a relativistic version of Magnetic Helicity Density, $\kappa_\mathbf{M}$.

$$\kappa_\mathbf{C} = (\mathbf{P} \cdot \mathbf{B}, \mathbf{P_0 B} - \mathbf{P} \times \mathbf{E}) \tag{4}$$

$$\kappa_\mathbf{M} = (\mathbf{A} \cdot \mathbf{B}, \mathbf{A_0 B} - \mathbf{A} \times \mathbf{E}) \tag{5}$$

Here the magnetic field is related to the vector potential by the equation, $\mathbf{B} = \nabla \times \mathbf{A}$. The electric field is defined using the MHD conditions, $\mathbf{E} = \mathbf{B} \times \mathbf{V}$. One can see that in the non relativistic limit, the Cross Helicity and Magnetic Helicity should equate to those shown in Equation 1 and 2 assuming that mass density is constant. Previous work by the author [3] has shown that only Relativistic Helicity and Energy are conserved in Relativistic MHD systems, see Figures 1-3. It can be shown that the four divergences of the Relativistic, Cross and Magnetic Helicities for Relativistic MHD reduce to:

$$\partial_\mu \kappa^\mu = 2\Omega \cdot (\nabla \mathcal{P}_0 + \partial_0 \mathcal{P}) = \mathbf{0} \tag{6}$$

$$\partial_\mu {\kappa_\mathbf{C}}^\mu = -(\nabla \cdot V)(\mathbf{P} \cdot \mathbf{B}) \neq \mathbf{0} \tag{7}$$

$$\partial_\mu {\kappa_\mathbf{M}}^\mu = -2(\nabla \cdot V)(\mathbf{A} \cdot \mathbf{B}) \neq \mathbf{0} \tag{8}$$

Because $\partial_0 \mathcal{P} = -\nabla \mathcal{P}_\mathbf{0} = \mathbf{F}$, the four divergence of the Relativistic Helicity is identically zero. However, the four divergences of the cross helicity and magnetic helicity are not identically zero because the divergence of velocity is not necessarily null and the Lorentz Transformations result in components of the magnetic field and vector potentials parallel to the velocity vector. Note that since the magnetic field and velocity perturbations are initially random, there will be components of magnetic field that lie along the velocity vector, relativistic effects will amplify these components.

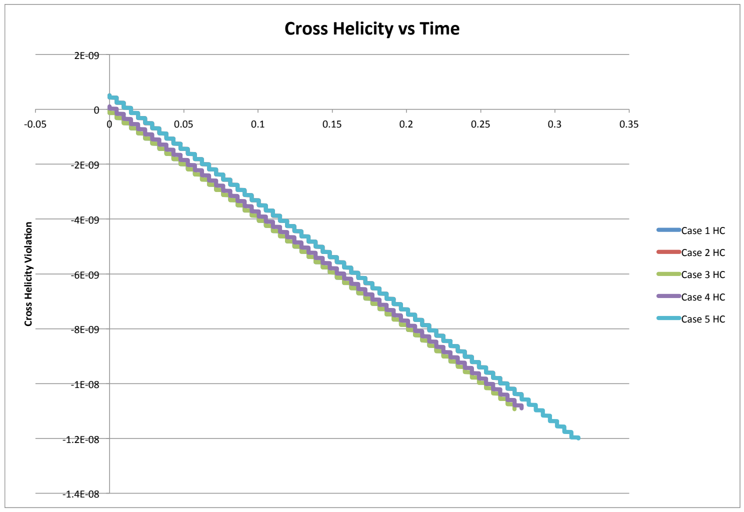
$$\mathbf{B}' = \gamma(\mathbf{B} - \frac{\mathbf{V}(\mathbf{B} \cdot \mathbf{V}) - \mathbf{B}\mathbf{V^2}}{\mathbf{c^2}}) - (\gamma - \mathbf{1})(\mathbf{B} \cdot \hat{\mathbf{V}})\hat{\mathbf{V}} \tag{9}$$

$$\mathbf{A}' = \gamma \mathbf{A} - \frac{\gamma \mathbf{A_0}}{\mathbf{c^2}} \mathbf{V} - (\gamma - \mathbf{1})(\mathbf{A} \cdot \hat{\mathbf{V}})\hat{\mathbf{V}} \tag{10}$$

For the non relativistic versions of Cross and Magnetic Helicity, we evaluate their time derivatives below assuming conservation.

$$\partial_t H_C = \frac{1}{2} \int (\frac{\partial \mathbf{V}}{\partial t} \cdot \mathbf{B} + \mathbf{V} \cdot \frac{\partial \mathbf{B}}{\partial \mathbf{t}}) \ \mathbf{d^3x} = \mathbf{0} \rightarrow \frac{\partial \mathbf{B}}{\partial \mathbf{t}} = -\frac{\hat{\mathbf{V}}}{|\mathbf{V}|}(\mathbf{B} \cdot \frac{\partial \mathbf{V}}{\partial \mathbf{t}}) \tag{11}$$

$$\partial_t H_M = \frac{1}{2} \int (\frac{\partial \mathbf{A}}{\partial t} \cdot \mathbf{B} + \mathbf{A} \cdot \frac{\partial \mathbf{B}}{\partial \mathbf{t}}) \ \mathbf{d^3x} = \mathbf{0} \rightarrow \frac{\partial \mathbf{B}}{\partial \mathbf{t}} = \frac{\hat{\mathbf{A}}}{|\mathbf{A}|}(\mathbf{B} \cdot \nabla \mathbf{A_0}) \tag{12}$$



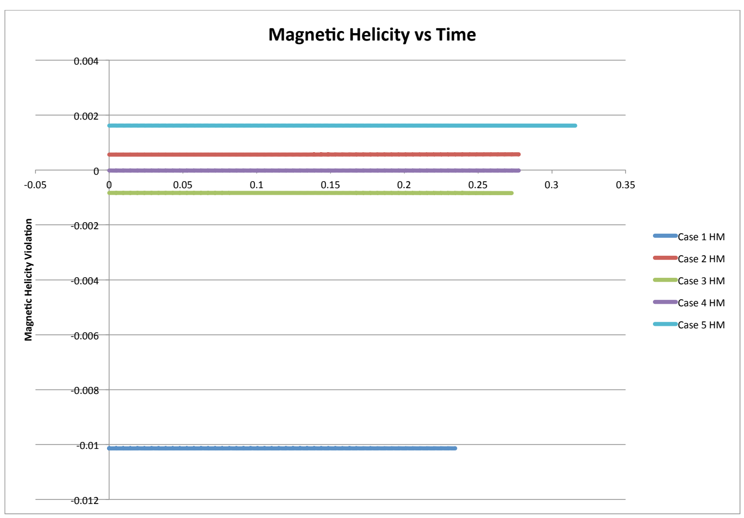


Fig. 1. *The four-divergences of Cross Helicity and Magnetic Helicity Densities do not approach zero. This appears true regardless of whether or not there is a mean magnetic field and/or mean angular velocity. This is evidence that these are not conserved quantities in Relativistic MHD Turbulence. Case 1 - no mean magnetic field or angular momentum, Case 2 - nonzero mean magnetic field, Case 3 - nonzero angular momentum, Case 4 - mean magnetic field and angular momentum aligned, Case 5 - mean magnetic field and angular momentum perpendicular.*

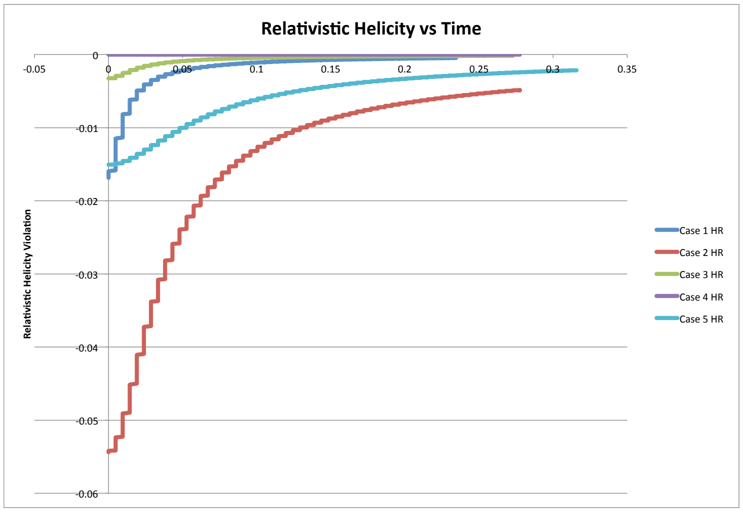


Fig. 2. *The four-divergence of Relativistic Helicity Density approaches zero regardless of whether or not there is a mean magnetic field and/or mean angular velocity. This is evidence that this is a conserved quantity in Relativistic MHD Turbulence. Case 1 - no mean magnetic field or angular momentum, Case 2 - nonzero mean magnetic field, Case 3 - nonzero angular momentum, Case 4 - mean magnetic field and angular momentum aligned, Case 5 - mean magnetic field and angular momentum perpendicular.*

Equation 11 and 12 imply that $\frac{\partial \mathbf{B}}{\partial t}$ is constrained by the relationship between the magnetic field, acceleration and gradient of potential. The magnetic field is on average perpendicular to any acceleration of the fluid. The Lorentz Force and therefore acceleration should also be zero because of the MHD condition. In addition, Equation 12 implies that a changing magnetic field can only result from a magnetic field that is aligned with a potential gradient. This does not occur on average unless there is a mean magnetic field. This could explain why Magnetic Helicity is only conserved when a mean magnetic field does not exist in the system. Because of this the non relativistic MHD equations will tend to suppress any net change in the magnetic field of the system unless a mean magnetic field exists initially. If the initial magnetic field is zero, these equations clearly imply that the net field should remain zero. Relativistic MHD systems don't seem to suffer from the same problem. While the absence of an initial magnetic field will cause the Cross and Magnetic Helicities to be zero, there is no reason why they should remain as such since they are independent of $\frac{\partial \mathbf{B}}{\partial t}$.

In a turbulent MHD system, a magnetic field could be generated by the electric field that results from variations in the concentrations of electric charges in the plasma field. Biermann showed that this is related to small variations in the density and temperature of the fluid [2,6].

$$\mathbf{E} = \frac{\nabla \mathbf{p}}{\mathbf{nq}} = -\frac{\nabla(\mathbf{n}\frac{\mathbf{T}}{\gamma})}{\mathbf{nq}}. \tag{13}$$

Here n is the number density of charges q. Such density variations can be linked to temperature fluctuations, T, that are expected in a turbulent fluid. These electric fields may then lead to the development of magnetic seed fields. The seed fields can then be amplified by the dynamics of the MHD system. In the case of non relativistic MHD, the potential amplification may by limited by the constraints of Cross and Magnetic Helicity conservation described above, resulting in a zero mean magnetic field. For relativistic systems, these constraints are nonexistent, allowing the magnetic fields to grown unconstrained. Because of this, we see that Relativistic MHD systems have a more natural tendency to develop seed magnetic fields while Non Relativistic MHD systems tend to suppress the development of seed magnetic fields.

References

1. S. Banerjee, “Compressible turbulence in space and astrophysical plasmas: Analytical approach and in-situ data analysis for the solar wind” *Diss. Universit Paris Sud-Paris* **XI** , 2014.
2. L. Bermann, Nature **A5**, 65 (1950)
3. D. Garrison and P. Nguyen, ”Invariants in Relativistic MHD Turbulence” J. of Modern Phys. **7**, 281-289 (2016)
4. Y. Kawazura, Z. Yoshida, and Y. Fukumoto, “Relabeling symmetry in relativistic fluids and plasmas” **47 (46)**, 465501. doi:10.1088/1751-8113/47/46/465501 (2014)
5. E. Marsch, and A. Mangeney, “Ideal MHD equations in terms of compressive Elssser variables” *J. Geophys. Res.* **92(A7)**, 73637367 (1987), **doi:10.1029/JA092iA07p07363**
6. E. Miller, *Magnetogenesis through Relativistic Velocity Shear*, Ph.D. thesis, Dartmouth College (2016)
7. J. V. Shebalin and D. Montgomery, “Turbulent magnetohydrodynamic density fluctuations” J. of Plasma Phys. **39**, 339-367 (1988)
8. J. V. Shebalin, “The Statistical Mechanics of Ideal Homogeneous Turbulence” NASA TP-2002-210783 (2002)
9. J. V. Shebalin, “Theory and simulation of real and ideal magnetohydrodynamic turbulence” Discrete & Continuous Dynamical Systems B **5**, 153-175 (2005)
10. J. V. Shebalin, “Broken symmetries and magnetic dynamos” Physics of Plasmas **14**, 102301 (2007)
11. J. V. Shebalin, “Broken Ergodicity in Magnetohydrodynamic Turbulence” Geophys. Astrophys. Fluid Dyn., Online DOI:10.1080/03091929.2011.589385 (2011)
12. J. V. Shebalin, “Broken ergodicity, magnetic helicity and the MHD dynamo” Geophys. Astrophys. Fluid Dyn., Online DOI:10.1080/03091929.2012.689299 (2012)
13. N. Yokoi, “Cross Helicity and related dynamo” Geophys. Astrophys. Fluid Dyn., Online DOI:10.1080/03091929.2012.754022 (2013)

14. Z. Yoshida, Y. Kawazura and T. Yokoyama, "Relativistic helicity and link in Minkowski space-time" J. of Math. Phys. **55 (4)**, 043101. doi:10.1063/1.4872236 (2014)

9 LETTERS

RICE

Dr. David Alexander
Rice University

July 23, 2013

Dear Dean Czajkiewicz,

This letter is in support of the promotion of Dr. David Garrison, Department of Physics, UH Clear Lake, as an external reviewer of his promotion materials. I have known Dr. Garrison for about three years since my participation in a joint $10M proposal to the FAA on which Dr. Garrison was PI, and more recently via his engagement with the Rice Professional Science Masters program. I also recently had the pleasure of meeting with him and some of his staff at UHCL to discuss possible collaborations with the Dept. of Physics and Astronomy here at Rice.

I am currently a Professor of Physics and Astronomy at Rice University and Director of the Rice Space Institute. My primary area of research is solar astrophysics. I received a Presidential Early Career Award for Scientists and Engineers in 2004 and was appointed a Kavli Frontiers Fellow by the National Academy of Sciences in 2006. I recently served as Chair of the Solar Physics Division of the American Astronomical Society (2011 – 2013), Chair of the Solar Heliospheric and Interplanetary Environment (SHINE) Program sponsored by the NSF (2010 – 2013), and am currently Chair of the Mauna Loa Solar Observatory User's Committee and a Rice University Faculty Senator. In recent years I have also served on the NASA Advisory Council's Heliophysics sub-committee and on the Publications Committee of the American Geophysical Union.

Dr. Garrison is very clearly a major asset of UHCL. His record of service is exemplary and the programs in Physics that he has developed over his tenure at UHCL have significantly raised the university's profile. Dr. Garrison has shown a level of dedication to the education of his students that, in my experience, is extremely rare. This is reflected, in part, in the number of students mentored, the many innovations he has implemented in his teaching, and the evaluations from the students themselves. Most impressive is the way he has taken a Physical Sciences program and built it into a strong undergraduate and then graduate Physics program. I would not be surprised to see a strong Physics PhD program complementing the Collaborative PhD program in the next few years.

In terms of research while at UHCL, his output is steady and of high quality but somewhat on the low side. However, this is not surprising given his relative lack of access, over the years, to students who were trained and ready for research activities and to his strong devotion to developing a high quality Physics program. Student research is starting to grow along with the growth of the new graduate programs that should increase his research productivity.

The application of numerical relativity techniques to real problems of astrophysical interest is extremely difficult: the mathematics and computation themselves are not trivial and the application to meaningful problems of relevance add a further degree of complexity. Dr. Garrison has utilized gravitational wave observations coupled to his detailed modeling to explore black hole physics and to characterize gravitational wave physics with some success, providing quantifiable observational constraints for future advanced gravitational wave observatories, such as LISA. This is important as it provides guidance to the gravity physics accessible to these observational programs.

The VASIMR engine utilizes an advanced form of propulsion to provide much higher specific impulses than conventional chemical propulsion. The VASIMR engine provides thrust by ionizing and heating neutral gas to very high temperature and utilizes a magnetic nozzle to guide the newly formed ions outwards providing the propulsion. Understanding the characteristics of the plume generated and thus the thrust capability requires detailed knowledge of the magnetohydrodynamic (MHD) system. Dr. Garrison worked with his NASA colleagues to modify his numerical relativity code to include magnetic fields and apply it to the MHD plume problem. Preliminary results indicated the evolution of the energy along the nozzle as the plume moves outwards. Currently, experiments are underway to observationally characterize the MHD system in the plume (Olsen, 2013).

In short, I believe that Dr. Garrison has accomplished much in his time at UHCL and is a valued faculty member deserving of promotion to Full Professor. His major achievement is the wholesale augmentation of the teaching of Physics at UHCL with a number of notable programs being developed and established in a relatively short time. This bodes well for the future success of these programs and the university as a whole. His collaboration with colleagues around the UHCL campus, with other major universities, and with NASA can only enhance his position as a faculty leader. In addition, he has maintained his research activity and put in place the means, via student research and mentorship, to increase the research output of the department.

I wholeheartedly recommend Dr. David Garrison for promotion to Full Professor at the University of Houston Clear Lake.

If you have questions or require further information please do not hesitate to contact me.

Sincerely,

Dr. David Alexander
Professor, Physics & Astronomy
Director, Rice Space Institute
Dept. Physics & Astronomy, MS-108
Rice University
6100 Main St.
Houston TX 77005
Tel.: 713.348.3633
Email: dalex@rice.edu

Center for Gravitational Wave Astronomy
A NASA University Research Center
The University of Texas at Brownsville

Mario Díaz, Ph.D
Director

October 15, 2013

Dr. Zbigniew J. Czajkiewicz
Dean, School of Science and Computer Engineering
University of Houston Clear Lake
2700 Bay Area Boulevard
Houston, TX 77058

Dear Dr. Czajkiewicz,

I was asked to review the application for promotion to Professor made by Dr. David Garrison.
I will do this with pleasure.
I will base my recommendation on the guidelines and policies outline in:
http://prtl.uhcl.edu/portal/page/portal/PRV/FORMS_POLICY_PROCEDURES/FACULTY_HANDBOOK/FACULTY5.3
In these rules it is stated that to be promoted to professor, candidates must have state, regional, or national reputations. This reputation may be achieved in any of the three areas of professorial responsibility.
It is very clear to me that Dr. Garrison has achieved state recognition due to his outstanding work in developing a physics program at UHCL.
Soon after UHCL hired him, Dr. Garrison began work on developing a Physics program. He succeeded in developing a degree plan that prepares students for work in Physics research, and the he also succeeded in developing a full fledged physics program at the BS and MS level including a collaborative doctoral program. The UHCL MS in physics program became famous state wide for having one of the highest graduation rates in the state of Texas. Dr. Garrison's efforts are truly exemplary and have made him one of the most respected young physicists in the state.
Additionally Prof. Garrison has presented in his portfolio clear evidence of excellence in both teaching and research.
Consequently I fully endorsed the promotion of Dr. David Garrison to Full Professor of Physics.
Sincerely,

Mario Diaz, Professor of Physics, Director CGWA

80 Fort Brown • Cavalry 105 • Brownsville, Texas 78520 • 956-882-6690 • Fax 956-882-6722 • mario@phys.utb.edu

THE UNIVERSITY OF
CHICAGO

Division of the Physical Sciences

Edward W. (Rocky) Kolb, Dean
Arthur Holly Compton Distinguished Service Professor
Department of Astronomy and Astrophysics

5747 South Ellis Avenue
Jones Laboratory, Room 122
Chicago, Illinois 60637-2745

Rocky.Kolb@uchicago.edu
T 773.702.7950

physical-sciences.uchicago.edu

Dr. Zbigniew J. Czajkiewicz
Dean, School of Science and Computer Engineering
University of Houston Clear Lake
2700 Bay Area Boulevard
Houston, TX 77058

Dear Dr. Zbigniew,

I am happy to provide a letter for the promotion case of Dr. David Garrison, a candidate for promotion to Professor of Physics at the University of Houston Clear Lake. David has my strong recommendation for promotion.

First, I would like to comment on his research career. David's field is numerical relativity. Although I am a theoretical cosmologist and not a numerical relativist, the fields are closely intertwined, and I am sufficiently knowledgeable to make two observations. First, the field is active and vital. Throughout the 80s and 90s it was somewhat stagnant, but recent advances has led to a revitalization of numerical relativity. The field has a lot of promise for the future, both near-term and long term. The second observation is that Dr. Garrison remains an active contributor to the field. He continues to publish and present his work at conferences. His work is valued in the community.

Now I would like to turn to the instructional aspect of his work. Although I have no first-hand experience of his teaching, I did form a very strong positive impression during a two-day visit to Clear Lake a couple of years ago as a Shapley Lecturer. In conversations about his research, David was very clear, organized, and enthusiastic. He demonstrated mastery of the scientific material, and an ability to communicate it clearly. I was very impressed. I am confident he is a great lecturer, and appreciated by the students.

Another impression during my visit is that Dr. Garrison is enthusiastic and committed to teaching. This was not just the lecture aspect of the profession of teaching, but he was committed to the students learning the material. David has a vision for the physics program at Clear Lake.

Physics often is perceived as an intimidating subject. Garrison is dedicated to de-intimidating the subject, while at the same time preserving the intellectual rigor.

Dr. David Garrison has a rare combination of mastery of physics, the ability to communicate it clearly, and enthusiasm and dedication to teaching. In this combination, he is rare.

I strongly and enthusiastically support his promotion to Professor.

Sincerely yours,

Edward Kolb

Dean of the Physical Sciences
Arthur Holly Compton Distinguished Service Professor

TEXAS SOUTHERN UNIVERSITY
3100 CLEBURNE AVENUE - HOUSTON, TEXAS, 77004

DEPARTMENT OF PHYSICS
OFFICE: (713) 313-7980
FAX: (713) 313-1833

October 10, 2015

From: C. J. Tymczak, Ph. D.
Professor
Department of Physics
Texas Southern University
3100 Cleburne Ave
Houston, Texas

To: Tenure and Promotion Committee
University of Houston, Clear Lake
Clear Lake, Texas

Dear Tenure and Promotion Committee,

It is my pleasure to write a letter of support for Dr. David Garrison promotion to full professor. I have known Dr. Garrison for several years. He is a superb scientist, scholar, mentor and leader. I recommend him very strongly without reservation

I have reviewed Dr. Garrison's application and he has met or exceeded all the requirements for promotion. As per the standard contained in the policy and procedure's faculty handbook of the University of Houston Clear Lake, section 5.3, there are three review criteria that most be evaluated, teaching, research and service.

Teaching: Dr. Garrison has taught enumerable number of courses from the undergraduate to the graduate level. This large breadth's of courses taught shows that Dr. Garrison has a superb command of the complexities of all the topics in physics. Reading the comments from the student evaluation, it is obvious that Dr. Garrison is an excellent and caring teaching who inspires his student to achieve. We need more teachers like this at our Universities! Dr. Garrison is also a natural mentor, has defined and organized new courses, updated the course curriculum, etc. I would rank Dr. Garrison in the top 5% of all teachers at Universities in this country and I give him a score of 9.5/10

Research: Dr. Garrison has published sixteen papers and has had twenty-one invited talks since he stared at UHCL. Given Dr. Garrison teaching load, this is a phenomenal achievement. Additionally Dr. Garrison has multiple small funded proposals and several large funded proposals, garnering a total of 800k in resources. However, one small problem is Dr. Garrison work has not garnered a lot of recognition. My instinct in this is more because of the esoteric-ness of his chosen field and not because of the importance of his work. Reading through some of his more relevant papers I found them to be both topical and relevant, and theoretically very sound. Therefore will give him an overall score of 8.5/10

Service: Dr. Garrison's service to the community, the profession and the University is outstanding. I am in awe of his energy and dedication to service. He has served on the faculty senate as a member and as the chair. He has organized multiple conferences. Improved and supported the Ph.D. programs. Served on enumerable University committees, and etc. In this I give him the highest of mark of the three evaluations criteria of 9.75/10. He is a true asset to the UHCL.

In conclusion, Dr. Garrison is obviously a phenomenal asset to UHCL and as an outside evaluator I recommend his promotion to full professor without reservation.

Sincerely,

C. J. T

Professor
C. J. Tymczak

GRINNELL COLLEGE

Department of Physics
Grinnell College
Grinnell, Iowa 50112-1690

641-269-3172
fax 641-269-4285
www.grinnell.edu

July 23, 2015

Dear Dr. Casserly:

This is a letter presenting my evaluation of the case for promotion of Prof. David Garrison to full professor of physics at the University of Houston, Clear Lake. I am professor of physics at Grinnell College, where I have taught for 23 years. I have served as chair of the physics department, chair of the science division, and member of executive council (the senior elected faculty body on campus), so I have some experience in academic leadership on the faculty side, as well as in the evaluation of faculty for promotion and tenure. I know Dr. Garrison primarily from talks he presented at meetings of the National Society of Black Physicists since 2003, discussions with him at those conferences, and from a seminar he presented at Grinnell College in 2004. My research area (experimental solid-state physics) differs significantly from Dr. Garrison's (computational and theoretical approaches to gravity), so I am not in a position to evaluate the quality of his scholarship; I presume you have other referees who can provide that perspective. I further presume you have good direct evidence of the quality of his teaching, as it is difficult for me to judge that from afar. Nevertheless, in looking over Dr. Garrison's dossier, I believe I see a strong case for promotion.

The most remarkable thing I believe Dr. Garrison has done at UHCL was to develop and lead a half dozen new graduate and undergraduate degree programs in physics and the physical sciences. I have seen faculty at Grinnell College try to initiate new undergraduate programs in fields such as biological chemistry; environmental studies; and Japanese. Some were successful; many were not. Successful efforts seemed to require either a team of committed tenure-line faculty to divide the work, or one ambitious, talented, and politically savvy senior faculty member who could assemble the necessary resources to bring the program together through sheer determination. Dr. Garrison is in this latter category, despite having begun development of these new programs as a new assistant professor. This sort of effort requires much course development work and administrative oversight, both of which have been done primarily by Dr. Garrison. It is impressive that the American Institute of Physics has recognized the UHCL master's program in physics as one of the most productive physics master's programs in the nation under Dr. Garrison's leadership.

Dr. Garrison's leadership in service is impressive, even beyond the development of the aforementioned new degree programs. He has served on the faculty senate as president, member of its executive committee, and chair of its research committee. He is director of graduate programs for his school, overseeing 13 programs, and appears to be chair for life of the physics department. He is a long-time active participant in the National Society of Black Physicists, a vital source of support for a seriously under-represented community of physicists (roughly 10 of 1600 Ph.D. degrees conferred in physics each year go to African American physicists). I can say, having participated in searches for presidents, academic deans, and associate deans at Grinnell that Dr. Garrison's portfolio of institutional service is comparable in strength to those of some of the top candidates we interviewed.

Dr. Garrison is an active scholar who continues to publish in the peer-reviewed literature and present at conferences despite his heavy service workload. He oversees many undergraduate and graduate research students; some of this research has led to publications with undergraduate co-authors. Despite being a theorist, Dr. Garrison has nevertheless submitted a great many proposals for internal and external funding, some to support his research, some to support development of new programs, some to support conference travel. His total funding level to date of $810k would be well above average for a science faculty member at Grinnell College.

In summary, I believe Dr. Garrison to be have a strong case for promotion to professor. The graduate and undergraduate programs he has founded at UHCL have become quite successful, the MS physics program in particular, having gained national recognition for its productivity. He is a proven leader amongst faculty in service to the institution. His research productivity and grant activity appear good by Grinnell standards and I would imagine are appropriate for a non-doctoral institution.

Sincerely:

Charles E. Cunningham

Professor of Physics

MORGAN STATE UNIVERSITY
GATEWAY TO OPPORTUNITY • STAIRWAY TO EXCELLENCE

Department of Physics

October 6, 2015

To: Dean Czajkiewicz, School of Science and Computer Engineering

From: Dr. Keith Jackson, Chair Department of Physics Morgan State University

Subject: Letter of recommendation for the promotion of Dr. David Garrison

Dean Czajkiewicz:

I appreciate the opportunity to recommend Dr. David Garrison for promotion to Full Professor of Physics at the University of Houston/Clearlake. I can say at the onset that I have never known a more distinguished theoretical physicist in the field of Gravitational Radiation. I would like to take some time and space here to enumerate some of the highlights of Dr. Garrisons career. I have known of the research and academic work of Dr. David Garrison for over fifteen years: from the early stages in his career as a graduate student at Pennsylvania State University. As a practicing Physicist (not in this field) I have known of his research contributions in gravitational wave simulation and modeling , more recently on what I would call gravitational cosmology.

Early in Dr. Garrison's career at M.I.T., he studied under Dr. Jorge Pullin performing fundamental work in the field of gravity wave simulation geared toward the experimental activity of the Laser Interferometer Gravitational-Wave Observatory (LIGO). LIGO is a large-scale physics experiment aiming to directly detect gravitational waves that started in 1992. As a graduate student the soon to be Dr. Garrison wrote his Ph.D. dissertation on the detection of gravitational radiation from "Binary Black Hole Codes in Strong field Regimes". After completion of his Ph.D. work at M.I.T he took a position as a Visiting Assistant Professor at the University of Houston Clearlake in the Department of Physics.

At the University of Houston/Clearlake his academic career developed, moving quickly through the position of visiting assistant professor to that of associate professor and physics department chair. He was recently appointed as director of Graduate Programs for the School of Science and Computer Engineering and has been instrumental in the development and enhancement of graduate programs within the school.

As I was reviewing Dr. Garrison's scientific works I was struck by the depth and breath of his scientific contributions, teaching and service to the greater University of Houston at Clearlake community. Even appearing on the history channel in the program the "Universe". Dr. Garrison has made fundamental contributions to our understanding of gravitational physics and cosmology. Dr. Garrison has clearly demonstrated long-term productivity as a teacher and member of the international community of gravitational physicists. These contributions are clearly at the level I would expect of a full professor. He has been able to communicate his research ideas assertively without causing negative reactions; to do this in the community of theoretical gravitational physicists is no small accomplishment.

The evidence for this, first of all, is in the production of refereed research publications, that when compared to institutions comparable to the University of Houston /Clearlake substantially exceeds in quantity and quality the minimum required for promotion to the level of tenured Full Professor. Given the relatively large teaching load and a developing research culture at the institution I am surprised Dr. Garrison was able to do as well as he has. More importantly, there is ample evidence that the research in which Dr. Garrison has engaged throughout his career has contributed to new physics. Overwhelming is the ability of Dr. Garrison to provide simple physically intuitive explanations for one of the most complex physical phenomenon imaginable. One example of this ability lies in his paper A Numerical Simulation of Chern-Simons Inflation: "One criticism of inflation is that specific theories can focus too much on formalism and lack a clear connection to physical processes that actually could have occurred." The mathematical formalism associated with theories of Cosmic Inflation are perhaps some of the most cutting edge work in theoretical physics ever performed, but Garrison's observations is that this is detached from physical mechanisms which associated from the mathematics. His comment is simple and has deep physical meaning.

Dr. Garrison has worked with some of the most distinguished members of the gravitational physics community. Dr. Garrison has a tremendous breath of knowledge. He is first of all a theoretical physicist of the highest rank however he has also made contributions in more applied areas such as the use of computers in Physics and Physics instruction. The number of different physics courses that Dr. Garrison has taught over the years amazes me. He has taught every course from Introductory Physics to General Relativity. He has served as a mentor to numerous undergraduate students some of which have graduated from the university and moved on to positions at Johnson Spaceflight Center and graduate work. Positions in physics are extremely competitive and it speaks well of Dr. Garrison that he has been able mentor undergraduate students and prepare them for graduate work or industry. Dr. Garrison has established a state of the Art Center for Computational Physics that benefits not only students of physics but other students of science as well.

To summarize, Dr. Garrison is a theoretical physicist of the highest caliber. Dr. Garrison is a demonstrated leader in his field. He has and continues to contribute new physical insights into some of the most profound mysteries of modern science gravitational radiation. He is an established author and has produced a significant scientific book. As an administrator he has provided significant leadership for the Physics Department and the School at the undergraduate and graduate level. Dr. Garrison has fulfilled the promise demonstrated in his early career and maintained his commitment to graduate and undergraduate education. On a personal note, Dr. Garrison is a man of the highest

1700 E. Cold Spring Lane • Calloway Hall G22 • Baltimore, Maryland 21251
Tel: 443-885-3226 • Fax: 443-885-8288

ethical and professional standards. The promotion of Dr. David Garrison to the rank of full professor would be, an enormous asset to the Department, School of Science and Computer Engineering and the University of Houston at Clearlake. I can recommend Dr. David Garrison for appointment as full Professor of Physics at the University of Houston at Clearlake, highly and without any reservation.

Best Regards
Dr. Keith Jackson
Professor and Chair
Morgan State University

1700 E. Cold Spring Lane • Calloway Hall G22 • Baltimore, Maryland 21251
Tel: 443-885-3226 • Fax: 443-885-8288

TRINITY
UNIVERSITY

DEPARTMENT OF PHYSICS AND ASTRONOMY

ONE TRINITY PLACE
SAN ANTONIO, TX 78212-7200
www.trinity.edu

kcheng1@trinity.edu
TEL: (210) 999-8469
FAX: (210) 999-7423

To: Dr. Zbigniew J. Czajkiewicz
Dean, School of Science and Computer Engineering
University of Houston Clear Lake
2700 Bay Area Boulevard
Houston, TX 77058

From: K. Kelvin Cheng, Williams Endowed Professor of Interdisciplinary Physics

Date: July 12, 2015

Ref: Application of Dr. David Garrison Promotion to Full Professor

Dear Dean Czajkiewicz,

I write to give my support to the application of Dr. David Garrison for his current application of promotion to Full Professor in the University of Houston Clear Lake (UHCL). I have read the promotion material you have sent to me. I will first describe my credentials and then I will comment on Dr. Garrison's teaching, research, service and collegiality.

My Credentials. I am the Williams Endowed Professor of Interdisciplinary Physics at Trinity University, San Antonio, Texas. As a tenured and endowed professor, I serve in the executive committees of Neuroscience degree program and the new Molecular Biology and Biochemistry degree program of Trinity University. My goal is to create and develop a vibrant interdisciplinary physics program that integrates physics with biological and computational sciences. I interact with faculty members from the Math, Biology, Chemistry and Engineering Departments in teaching, curriculum development and undergraduate research. I hold an adjunct professor position at Texas Tech University and maintain a fruitful collaboration with the Physics and Chemical Engineering Departments of Texas Tech in both computational and experimental molecular biophysics research. I have served as the Chair of Texas Section American Physical Society (TSAPS), a division of the National American Physical Society. I am aware of the challenges facing the Physics Departments in Texas and this country regarding recruitment and retention of Physics Majors.

Dr. Garrison's Teaching: Based on the student evaluations and peer-evaluations, Dr. Garrison is an effective and good quality professor. He can teach undergraduate and graduate physics courses. He engages students in learning. I see that he is a gifted teacher.

Dr. Garrison's Research: He had a slow start in picking up the pace of research at the beginning. However, considering the lack of resources, I admire his efforts in building the research program in a timely fashion and keeping a steady momentum to a point that his research is now functional. He is a theorist and is respected in the computational field. The published work is of good quality and has good impact in his research area. I am confident that he productivity will increase steadily.

Compared with institutions serving mainly undergraduate students, his research productivity is sufficient to justify the promotion to full professorship.

Dr. Garrison's Service: Dr. Garrison has made a huge contribution in building the physics department from scratch. His vision of creating a collaborative PhD program with UH is a smart move to promote the department to a new level. I trust that the department will continue to grow and thrive under his leadership. UHCL-Physics will become a model for other departments to follow in curriculum and degree program development.

Dr. Garrison's collegiality: Dr. Garrison is energetic and has vision of what and how the physics department should move forward. He is very approachable and friendly. Most importantly, he is a team player.

In summary, I believe that Dr. Garrison is an asset to UHCL. I also feel that he has met the requirements of promoting to full professor in all areas of teaching, research, service and collegiality. I therefore strongly support his application of promotion.

Sincerely,

KH Cheng.

K. Kelvin Cheng, PhD
Professor of Physics
Williams Endowed Chair of Interdisciplinary Physics

JOHNS HOPKINS
UNIVERSITY

The Henry A. Rowland Department of Physics and Astronomy

Bloomberg Center
3400 N. Charles Street
Baltimore MD 21218-2695
(410) 516-7347 / FAX (410) 516-7239

Dr. Zbigniew J. Czajkiewicz
Dean, School of Science and Computer Engineering University of Houston Clear Lake
2700 Bay Area Boulevard
Houston, TX 77058

Dear Dean Czajkiewicz,

I am writing in response to your request for an evaluation of Prof. David Garrison in connection with his candidacy for promotion to Professor.

I only met Prof. Garrison recently. I heard a very nice talk he gave at a conference back in June 2015 in which he reported results from work in progress on the numerical calculation of the cosmic gravitational-wave background from a first-order phase transition in the early Universe. Cosmologists have long speculated that such gravitational waves may exist. However, analytic calculations of the amplitude of the signal and the frequency spectrum are extremely difficult, and different groups have come to quite different conclusions. Garrison's work holds the potential to sort out the right answer and to possibly provide some intuition on the validity of arguments that the analytic calculations have been based upon.

Garrison has also been doing work on numerical simulations of models of inflation based upon birefringent gravitational waves. The idea is motivated by the desire to merge a theory of inflation with a theory for the origin of baryons. Again, relic gravitational waves are expected in these scenarios, but analytic calculations of both the inflationary model and the gravitational-wave productions are unreliable. Garrison's calculations hold the potential to show precisely how these inflationary models evolve and what their observational signatures may be.

I am impressed by Garrison's work in these areas, as it is quite a distance from the work he did in graduate school. Although that work was also numerical and dealt with gravitational-wave production, the physics of the astrophysical sources he was considering there is just enormously different from that in the early Universe. His ability to move in this new direction is indeed impressive.

I am also impressed that Garrison has been able to keep active in research while working so hard with teaching and with developing what appears to be a very strong physics curriculum at UHCL. I should also mention that the type of work Garrison has done, and the connections he has made with collaborators elsewhere, provides outstanding research opportunities for undergraduate students.

In brief, Garrison seems to have a broad set of achievements and contributions to education and research, and the promotion to full professor seems most certainly warranted.

Sincerely yours,

Marc Kamionkowski