# Origin of Structure in the Early Universe from Gravitational Radiation

by David Garrison

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ABSTRACT—Cosmology has become an exciting topic in recent years due to many new discoveries and theories. However, no one has successfully simulated the creation of structure in the universe from a smooth inflationary stage using a fully-relativistic-non-linear-dynamical code. Cosmic structure formation is usually simulated using linear codes in which structures evolve from scalar quantum fluctuations. This work will focus on the interaction between the primordial plasma and gravitational wave fields as a cause of cosmic structure formation. We will examine whether or not gravitational waves lead to plasma turbulence and will predict the spectrum of the resulting relic waves.

Standard cosmological theory holds that fields of homogenous high-energy plasma and gravitational radiation populated the early universe. However, relatively little work has been done which examines the impact of the interaction between these fields on the evolution of the universe. For example, work by Kodama and Sasaki[1] examined how scalar, vector and tensor perturbations directly resulted in density fluctuations but neglected the dynamical effects caused by these perturbations. Adding dynamical effects such as turbulence will significantly reduce or eliminate the role of cold dark matter in early universe structure formation. We are, therefore, working to examine the effects of primordial gravitational waves on structure formation in the early universe through dynamic interactions with the plasma field.

We are currently examining the effects of both isotropic and birefringent gravitational waves on the plasma field. An extensive literature search reveals that a study such as this has never been attempted. Our hypothesis is that General Relativistic Magneto-hydrodynamic (GRMHD) turbulence contributed significantly to structure formation in the early universe. The goal of this work is to identify and evolve the initial conditions for the standard model that led to the development of the observed mass concentration in clusters and super-clusters of galaxies. The initial conditions are selected so that alignment with observed values of the spectrum and isotropy of the cosmic background radiation are preserved as the solution evolves forward in time.

This project is a computational study of GRMHD turbulence. For this work we use Cactus, an open-source framework for computational physics. This tool will prove useful in the development of a cosmic simulation program capable of recreating many of the conditions found in the early universe shortly after the inflationary period. This code will solve Einstein's equations given these initial conditions and evolve a set of coupled General Relativistic and Magneto-Hydrodynamic equations. This GRMHD code can be used to solve a variety of astrophysics problems, but, for this project, we will focus on the problem of cosmic structure formation. Consequently, we expect to simulate the formation of certain structures from an initially homogenous plasma field and a field of gravitational radiation. These structures include: magnetic fields, density and temperature variations, and secondary gravitational waves. The spectrum and polarization of the resulting gravitational waves should be observable by future gravitational wave observatories such as LISA and advanced LIGO.

**Methodology**

As with any other numerical project, our first step is to develop initial data for the code. The initial data used will be based on initial conditions that involve the state of both the plasma field and the spacetime. The initial time chosen for this study is three minutes after inflation in order to avoid significant quantum effects. We utilize the framework developed by Duez[2,3] in order to classify the variables needed for the initial data and for evolution equations. Initial conditions for the plasma field include mass density, magnetic field, velocity, pressure, and energy density for the magneto-fluid. Initial conditions for the spacetime include the scale factor, Hubble parameter, tensor perturbations, gauge conditions and the Stress-Energy Tensor calculated from the initial plasma conditions. The goal is to model the homogenous plasma described by the standard model of cosmology on top of a perturbed Freidman-Robertson-Walker (FRW) spacetime.

Various assumptions must be made in order to calculate these initial conditions; therefore our choice of initial conditions is not unique. These initial conditions will be continuously refined and improved throughout this experiment. Dark Matter or Scalar Fields may be added as the project develops.

Our plan is to use a General Relativistic Magneto-Hydrodynamic computer code (GRMHD) to simulate the early universe during the classical plasma-filled regime. This code must be developed and tested as part of the project. The Cactus framework will be utilized for this work. Cactus 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. It originated in the academic research community, where it has been 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 individuals or groups. The advantage of this modular approach to software development in an educational environment is that it significantly reduces the learning curve for students working on the project and leads to greater research productivity in a shorter amount of time. Each student will be able to concentrate on developing his or her section of the project while treating the rest of the code like a collection of objects.

**BEOWULF—PI David Garrison stands at the secondary Beowulf cluster built by Lee Morin, an astronaut currently working on his master's degree in physics. Morin built the unit in his garage and at the Advanced Space Propulsion Laboratory, Netural Bouyancy Laboratory.**

I have been working with the students involved in this project to develop a code called Cosmo. Cosmo is an arrangement for Cactus and contains the MHD thorns, the basic unit of the Cactus framework. This code is capable of modeling the Magneto-Hydrodynamic (MHD) equations in a curved space-time and interacting with other Cactus thorns resulting in a fully dynamical GRMHD code. In particular, Cosmo interacts with the BSSN_MOL thorn developed by the Albert Einstein Institute in Germany. BSSN_MOL then models Einstein's equations in order to evolve the spacetime. Because the early universe is considered to be homogenous and isotropic, it is assumed that the simulation domain is a homogenous slice of the early universe, and periodic boundary conditions are applied to the simulation domain. Also, both linear and logarithmic scales are used for calculating data in the simulation domain, making it possible to compare results at multiple length scales. This program can therefore effectively model the dynamic plasma-filled Friedman-Robertson-Walker (FRW) universe.

There are many challenges to evolving the numerical code. First, there are the standard difficulties of dealing with a nonlinear finite-differenced relativity code. We utilize periodic boundary conditions in order to eliminate boundary errors. However, we may also need to develop more advanced gauge conditions to create a truly stable code. Second, additional challenges are created by the GRMHD code's utilization of a nonlinear "primitive variable" solver to recover elements of the Stress-Energy Tensor from the MHD evolution variables, as well as a technique called "divergence cleaning" to maintain physical values for the B-field. Optimizing and improving these solvers are essential to developing a stable code. In addition, preliminary results show that a large computational grid is required to accurately produce gravitational wave-induced MHD waves. Incorporating techniques such as adaptive mesh refinement (AMR) into the evolution code have proven effective in other numerical relativity projects and may also be useful for this project. The use of AMR will allow us to effectively create a large computational grid with minimal computational resources.

Much of the data analysis work will involve the addition of new analysis routines to the code as well as the use of third-party software. Visualization of Cactus-generated data will be done using a variety of open-source software such as OpenDX, xgraph, ygraph and gnuplot. OpenDX will require the writing of implementation scripts. These scripts will tell the visualization program how to convert the Cactus-generated data files into the proper analysis format. These may include Fast Fourier Transforms (FFT) or Hilbert-Huang Transforms (HHT) for spectral analysis of the data. This part of the project will require significant data visualization resources.

The real test of how structure was created in the early universe will occur after the results of the code can be shown to reasonably match those of the analytic results. At this stage, we will be refining the initial conditions so that they more accurately represent the early universe's homogenous MHD field on a perturbed FRW background spacetime.

As these numerical experiments are being performed, the students and I will be analyzing the output. We will look for variations in the density, temperature and magnetic field of the output data. If such variations are seen, a spectral analysis and phase space portrait of the data will be used to determine the relative size and distribution of these structures. Gravitational waves in the simulation domain will be extracted in order to determine the spectrum and relative amplitude of secondary gravitational waves created as a result of the development of the structures. Numerical experiments will then be repeated for different scales and initial conditions.

We have outlined the process of evolving the GRMHD conditions for the early universe using an established framework. A numerical simulation of the initial conditions is designed to model the early life of the universe after the creation of subatomic particles, when a relativistic plasma field could describe the universe. It is expected that these conditions will result in fluctuations of the density of the plasma, growing seed magnetic fields and a modified spectrum of primordial gravity waves that we predict will one day be seen by observatories such as LISA. We may also witness the development of inhomogenities in the background temperature of the plasma field in agreement with that observed in the cosmic microwave background by WMAP.

**Equipment and Special Technology**

We currently have a computational laboratory with 30 2-GHz Pentium-4 based Linux machines and a small 16-node Beowulf cluster. In addition, we recently acquired a Beowulf cluster consisting of 48 dual processor nodes powered by 1.4 GHz PIII's. The Beowulf has a 1.0 TB raid storage unit. This machine is linked to an educational grid of similar machines bringing the total computational availability to more than 600 processors. Once the code has been tested and science data runs begin, we can utilize faster supercomputers. We use a variety of software including OpenDX, xgraph, ygraph and gnuplot to visualize the output data.

**Results**

We expect the continued development of the Cosmo arrangement to be a long-term project with constant improvements as new data are generated. We began multiprocessor runs and testing of the code in the summer of 2006. The analysis of the data began soon after and the code is continuously being tested and improved. During the spring of 2007, FRW spacetimes should replace the analytically known solutions used to test the numerical code. We should begin seeing the results of this work by summer 2007. At that time, significant effort will be required to analyze and visualize the data.

**Discussion**

To date, much of our work on this project has consisted of code development, computer hardware development, and software testing. We are currently pursuing external grants to finish this work and begin science runs. The focus of this project is to create a numerical simulation of initial conditions, which are designed to model the early life of the universe after the creation of subatomic particles, when a relativistic plasma field can describe the universe. It is expected that these conditions will result in fluctuations of the density of the plasma, growing seed magnetic fields, and a modified spectrum of primordial gravity waves that may one day be seen by observatories such as LISA.

We may also witness the development of inhomogenities in the background temperature of the plasma field in agreement with that observed in the cosmic microwave background by WMAP.

**References**

[1]H. Kodama and M. Sasaki, "Cosmological Perturbation Theory," *Prog. Theor. Phys. Suppl.* 78 (1985): 1-166.

[2]M. D. Duez, Y. T. Liu, S. T. Shapiro, and B. C. Stephens, "Relativistic Magnetohydrodynamics in Dynamical Spacetimes: Numerical Methods and Tests," *Phys. Rev.* D72 (2005): 024028.

[3]M. D. Duez, Y. T. Liu, S. T. Shapiro, and B. C. Stephens, "Excitation of MHD Codes with Gravitational Waves: A Testbed for Numerical Codes," *Phys. Rev.* D72 (2005): 024029.

**Publications**

Garrison, D., C. Ballard, R. de la Torre, and J. Hamilton. "Initial Conditions for Numerical Cosmic Evolution Using GRMHD Equations," *Classical and Quantum Gravity* (2006). (*Submitted for publication.*)

**Presentations**

Garrison, D. "Cosmic Structure Formation via Gravitational Radiation," University of Oregon Invited Talk, May 11, 2006.

Garrison, D. "Initial Conditions for Cosmic Evolution Using GRMHD Equations," 2006 American Physical Society April Meeting, April 22, 2006.

Garrison, D. "Cosmic Structure Formation From Gravitational Radiation," 2006 National Society of Black Physicists Meeting, Feb. 17, 2006.

Garrison, D. "Cosmic Structure Formation From Gravitational Radiation," Physics Department Seminars, UH-Clear Lake, 2006.

**Proposals**

Garrison, D. "Origin of Structure in the Early Universe from Gravitational Radiation," National Science Foundation, June 1, 2007–May 31, 2010. $291,861. (*Submitted.*)

Garrison, D. "Cosmic Structure Formation from Gravitational Radiation," The Research Corporation, June 1, 2007–Aug. 31, 2008. $53,684. (*Submitted.*)