THE BEHAVIOR OF THERMAL AND BREMSSTRAHLUNG RADIATION EMITTED BY MERGING BINARY NEUTRON STARS

by

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A senior capstone submitted to the faculty of

Brigham Young University

in partial fulfillment of the requirements for the degree of

Bachelor of Science

Department of Physics and Astronomy

Brigham Young University

April 2010

BRIGHAM YOUNG UNIVERSITY

DEPARTMENT APPROVAL

of a senior capstone submitted by

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This capstone has been reviewed by the research advisor, research coordinator, and department chair and has been found to be satisfactory.

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ABSTRACT

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We model the electromagnetic emissions of a binary neutron star merger. We use the ideal gas equation of state and rely on thermal and bremsstrahlung radiation as the sources of emission. We calculate the intensity of this radiation through radiative transfer to produce numerical and graphical data. As the merger progresses we see high intensity areas increase in the center of the stars and fluctuations in the outer areas, including the formation and disappearance of luminous appendages. Right before the collapse of the merger into a black hole, we see four distinct high intensity arms develop a halo around the center of the stars. This halo may be caused by gravitational forces and angular momentum effects. We also see a sharp drop in hard gamma emissions at the later stages of the merger which could be connected to a gamma ray burst.

ACKNOWLEDGMENTS

I would foremost like to thank Dr. David Neilsen for allowing me to work on this project and helping me every step of the way. I would also like to thank Dr. Matt Anderson of Louisiana State University for sharing with me his code, time and help. I would like to show appreciation to the several graduate students in the theory lab for answering my endless questions and being willing to review my work. I also would like to thank the Department of Physics and Astronomy at Brigham Young University for their financial support and all the resources they provided for me that made this project possible.

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Chapter 1

Introduction

1.1 Pulsars and Gamma Ray Bursts

Neutron stars have been objects of astronomical curiosity for nearly a century. The existance of neutron stars was first suggested in the 1930's by Baade and Zwicky who proposed that neutron stars were products of some supernovae [1]. However, the existence of these stars was not granted serious consideration by the scientific community until the 1960's, with the discovery pulsating stars emitting intense radio waves and X-rays. Following the explanation of these pulsating stars, or pulsars, as "rotating magnetized neutron stars", neutron stars have been accepted as the source of many energetic and interesting phenomena in the universe [1]. Gamma ray bursts (GRBs) are particularly energetic events which are thought to be the result of the merging of two compact objects, such as binary neutron stars or a neutron star and a black hole. In this paper we study the electromagnetic emissions of two merging neutron stars using a simple radiative transfer equation. This is an initial effort to explore the characteristics of a merger, and possibly qualify a binary neutron star merger as a source for a GRB.

1.2 Neutron Stars

Nuetron stars are formed when the core of a star, of a certain size, collapses in a supernovae explosion. As neutron stars are composed mostly of neutrons, neutron degeneracy pressure stabalizes the star against gravitational collapse. With solar masses of about 1.4 – 3 $M_{\odot}$ and a small radii around R $\approx$ 10 – 15 km, neutron stars themselves are the most compact form of matter known [1]. A neutron star's composition may be its greatest contribution to expanding our knowledge of the physical world, as little is yet known of the star's internal structure. An equation of state is an equation relating major state variables such as pressure and density. The equation of state (EOS) for a neutron star has not yet been found, and may give physicists significant insight not only into the properties of dense (asymmetric) matter, but also a better understanding of nuclear and particle physics. As neutron stars consist not only of neutrons but also protons and electrons under high pressure, the basic interactions of fermions may be studied in a new environment [1]. While limited research has been done in laboratories with dense compilations of nucleons, most information on a neutron star's components can only be gathered through astronomical observation and theoretical prediction.

1.3 Context

In this project we calaculate the electromagnetic emissions from merging binary neutron stars by calculating the paths of the light rays and intensities of photons along the paths. The mass of each neutron star is modeled as an ideal fluid using the ideal gas law as their EOS. We calculate geodesics in the spacetime of the neutron stars by integrating backwards from a “camera” located at spatial infinity. We then solve a simple radiation transfer equation for thermal and bremstrahlung emissions from the stars. Using these methods, we calculate graphical intensity distributions for the emissions from the merger at various times and electromagnetic frequencies. Further explanations of our methods are found in chapter 2, and our results are recorded in chapter 3.

Chapter 2

Methods

2.1 Introduction

The study of two merging neutron stars draws on diverse fields of physics. Our gravitational forces are modeled with general relativity. The equations of fluid mechanics are used for the structure and motion of the stars. The nuclear matter of the interior of the stars is described by thermal and nuclear physics. These calculations are based on recent studies and estimates of the structure and EOS for neutron stars, as well as their mechanical and radiative behavior [2]. Together these equations form a complex, coupled, nonlinear set of partial differential equations that cannot be solved analytically. We therefore calculate numerical solutions using a computer simulation. We first establish state variables on a cartesian grid using the ideal gas law as our EOS, and then calculate new data for the position and state of the stars in time. We calculate the electromagnetic radiation as a post-processing step. We find the geodesics, or paths of the emissions, using 3-dimensional slices of spacetime. We then solve the radiative transfer equation on this spacetime, using the temperature and density of the fluid to approximate the emission and absorbtion of the traveling photons. We use thermal and brehmstrahlung radiation as our emission sources. Using these methods we produce graphical intensity distributions for the emissions from the merger at various times and electromagnetic frequencies. These distributions can be viewed at different inclination angles at a large distance from the merger.

2.2 Initial Calculations

The neutron star simulations are done on a Cartesian grid, using adaptive mesh refinement. Each state variable such as pressure and density is calculated at every point on the grid. As the simulation evolves in time, a new set of values for every point is calculated at each step. We initially place our stars about 50 km apart on the grid. This ensures that the stars are far enough apart that we will not miss any significant emission activity leading to the merger.

2.3 Fluid Approximation

The basic structure of the stars is modeled by a set of relativistic fluid equations. We use a simplified EOS to model each star. Initial data for the stars is calculated using the polytropic EOS.

$$P = K\rho^{\Gamma}. \tag{2.1}$$

In this equation P is pressure, K is a function of entropy (assumed to be constant), ρ is density, and Γ is the adiabatic exponent which defines how stiff the fluid material of the stars is. Here we assume Γ=2 to model stiff nonlinear matter. The initial data is generated by the LORENE (Langage Objet pour la RElativité NumériquE) code, which solves the initial value problem for initial data for neutron star systems.

During the evolution of the merger we use the ideal gas equation,

$$P = (\Gamma - 1)\rho\epsilon, \tag{2.2}$$

where Γ is the adiabatic exponent, and ϵ is the internal energy. This EOS is chosen to simplify the simulation, and its validity will be discussed in chapter 3 of this paper.

2.4 Radiation Behavior

After compiling the geometric data we calculate the system's radiation properties. The high mass and density of both of the neutron stars create curvature in the spacetime near the stars. Any calculations of electromagnetic radiation emitted by either star must take this curvature into account. A single ray of light in curved spacetime follows a path called a null geodesic. In this case the norm of the tangent vector of the geodesic is zero, in other words for any two neighboring points on the curve the infintismal interval between them is zero. In order to find the null geodesics for the emissions of our two stars, we must use the spacetime metric $g_{\alpha\beta}$ which defines the geometry of the spacetime around the stars. The geodesic equations we use are a first order system involving the metric, which give the geodesics in terms of an affine parameter λ. The affine parameter is a value representative of the path a photon takes in traveling along its geodesic at a constant velocity. This parameter takes into account both space and the proper time of the photon, or time relative to the traveling photon.

The intensity of the radiation along the geodesics, as a function of frequency, is found by solving the radiation transfer equation [3]

$$\frac{dI_\nu}{d\lambda} = -p^\alpha u_\alpha \left[\eta_0 - \chi_0 I_\nu\right]. \tag{2.3}$$

Here I_ν is the intensity for a given frequency, χ_0 and η_0 are the emissivity coefficient and the absorbtion coefficient respectively, and p^α and u_α are the four-momentum and four-velocity of the photon. We use the first order solution to solve this equation as given by Fuerst and Wu [3].

$$\begin{aligned} I_\nu(\lambda) &= I_\nu(\lambda_0)\exp\left(\int_{\lambda_0}^{\lambda}\chi_0(\lambda',\nu_0)u_\alpha p^\alpha d\lambda'\right) \\ &\quad -\int_{\lambda_0}^{\lambda}\exp\left(\int_{\lambda'}^{\lambda}\chi_0(\lambda'',\nu_0)u_\alpha p^\alpha d\lambda''\right)\eta_0(\lambda',\nu_0)u_\alpha p^\alpha d\lambda' \end{aligned} \tag{2.4}$$

We use fourth order Runge-Kutta to integrate backwards in time along the geodesics in terms of the affine parameter, to solve this equation for the intensity of each frequency.

2.5 Radiation Sources

Our model uses two main sources of radiation: thermal and bremsstrahlung. The thermal radiation in our program is calculated from blackbody emission. The second source, bremsstrahlung radiation, is the radiation emitted by colliding ions within the stars.

2.5.1 Thermal Radiation

Thermal radiation acts as our initial source of radiation. Basic thermal emissions are calculated by treating each star and the combined mass during the later stages of the merger as a blackbody. We of course rely on the Stefan-Bolztman law,

$$j* = \sigma T^4, \tag{2.5}$$

where $j*$ is the emissive power, σ is the Stefan-Boltzmann constant and T is Temperature. We then use Plank's law,

$$I_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{\exp\left(\frac{h\nu}{kT}\right)-1} \tag{2.6}$$

to predict the intensity of thermal emissions. Here I_ν is the intensity for a specific frequency ν, and T, h, k, and c are the temperature of the fluid, Plancks constant, Boltzmann's constant, and the speed of light respectively.

2.5.2 Bremsstrahlung Radiation

Neutron stars, contrary to their name contain more than just neutrons. Many parts of the star contain high concentrations of protons and electrons. During the later stages of the merger, tidal forces produce instabilities in the stellar envelopes, which results in a greater amount of thermal activity. This thermal activity and other effects of structural instability increase the amount and speed of nuclear reactions within each star including neutron decay and pair production. Thus ion density and therefore bremsstrahlung emissions increases as the merger becomes more violent. In calculating the bremsstrahlung radiation we must first account for these ion densities and interactions within the star. We initially model the particle interaction on a Maxwellian plasma, a commonly used approximation in astrophysics of a plasma in thermal equilibrium where the distribution of particle velocity can be represented by an isotropic Maxwellian [4]:

$$f(r,v) = n\left(\frac{m}{2\pi kT}\right)^{\frac{3}{2}} \exp\left(\frac{-m(v-\langle v\rangle)^2}{2kT}\right) \tag{2.7}$$

Here r is position, v is velocity, m is mass, k is Boltzman's constant, T is temperature, and $\frac{m(v-\langle v\rangle)^2}{2}$ is associated with the kinetic temperature.

The ion densities in the star can then be found as,

$$n_e = \frac{\rho}{\mu_e m_p}\,, \qquad n_i = \frac{\rho}{\mu_i m_p}\,, \tag{2.8}$$

where

$$\mu_e = \frac{2}{1+X}\,, \qquad \mu_i = \frac{4}{1+3X}\,. \tag{2.9}$$

and n_e, n_i are the electron and ion number densities respectively, ρ is the rest density of the fluid, m_p is the mass of a proton, and X is the relative abundance of hydrogen in the universe. We now calculate the emissivity as

$$\eta_0 = 6.8 \times 10^{-38} Z^2 n_e n_i T^{-1/2} \times \bar{g}_{\text{ff}}(\nu, T) e^{\frac{h\nu}{kT}} \, \frac{\text{erg}}{\text{s cm}^3 \text{ Hz}}\,, \tag{2.10}$$

where h, k, and T are is Planck's constant, Boltzmann's constant, and the temperature of the plasma respectively [5]. Here $\bar{g}_{\text{ff}}$ is the temperature averaged Gaunt factor, a value that acts as a correction factor to include quantum-machanical effects in the plasma [2].

Our last necessary value, absorption, is found using a modified version of Kramer's Opacity law, similar to the one used to find the opacity in a normal star [6].

$$\chi_0 = 5 \times 10^{24} \rho^2 T^{-7/2} \left(\frac{1 - e^{-x}}{x^3} \right) \text{ cm}^{-1}. \tag{2.11}$$

Here again ρ is density, T is temperature, and $x = \frac{h\nu}{kT}$.

Chapter 3

Results and Discussion

3.1 Introduction

The intensity data given here are displayed graphically for specific electromagnetic frequencies between 1×10^{12} and 5×10^{24} Hz. The intensity in each image is normalized using the maximum intensity, represented as the upermost red of the color map provided for each image. The images occur at different times within the merger and may be viewed at different angles from the normal, zero degrees being directly above the center of the two stars initial orbits. The axis scale of the images is in units of the total mass of the stars.

These results are preliminary as our program is still a prototype and some methods, such as the equation of state, are still too simple to be fully realistic. With this in mind, we can not be completely sure of the quantitative details of the results, especially minor differences in the intensity distribution between frequencies. However, while most of the methods used in this simulation are very complex and realistic, we can assume that the general qualitative trends seen are true. We of course plan to further test and evaluate these results through additional runs and models.

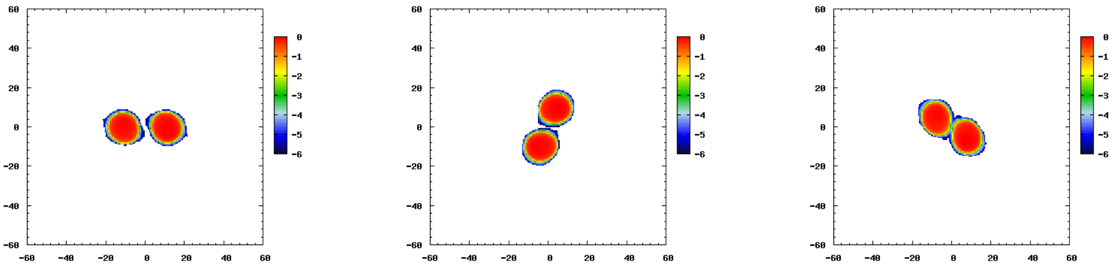

Figure 3.1 These images are of the merger at 1040μs, 1120μs, and 1200μs from the beginning of the simulation, respectively. The frequency of the emissions shown is 1×10^{12} Hz. Each image displayed here has a view directly above the center of the system.

3.2 Results

In our simulation it appears that the neutron stars stay relatively cold with nearly identical emission intensity distributions, except for increased intensity in mass extended from each star along the gravitational pull between the stars, until a significant portion of the stars begin to merge as shown in Fig. 3.1.

In the next stages of the merger we see the emmissive intensity increase and spread. We can also see the formation of various appendages curving around the new central mass, as shown in Fig. 3.2. As time progresses we see greater intensity fluctuations in the area surrounding the core, and the development of appendages and inner arm-like structures with more intense emissions, as seen in Fig.3.3.

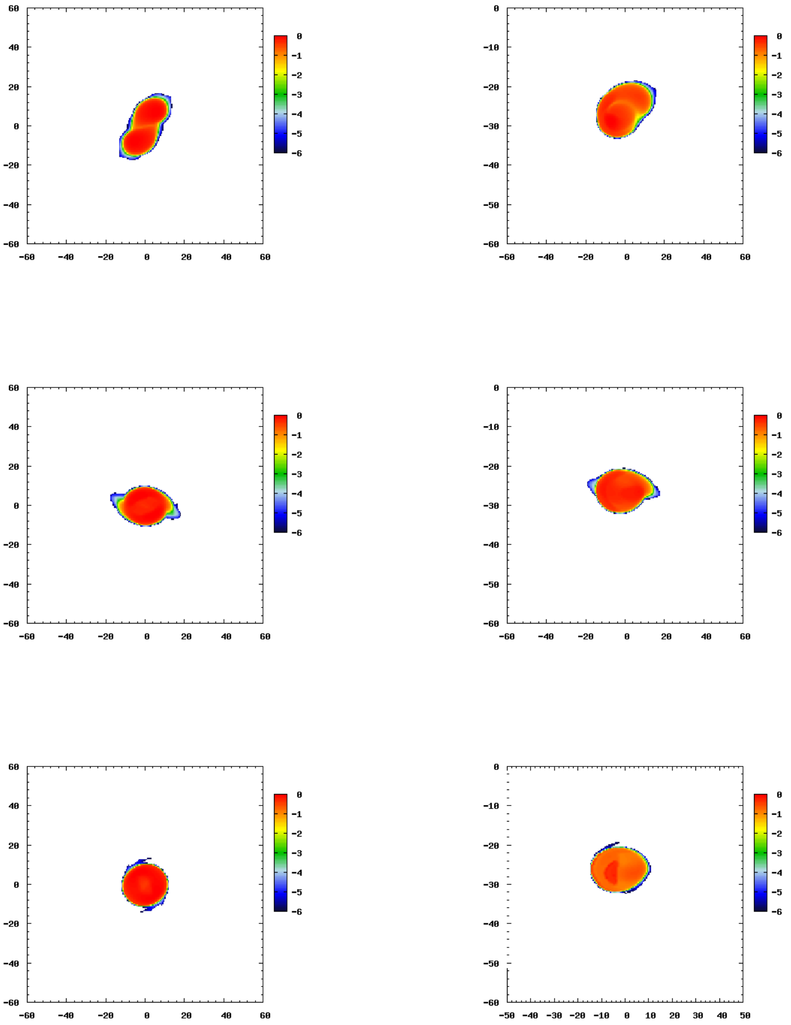

Figure 3.2 These images are of the merger at $1280\mu s$, $1360\mu s$, and $1440\mu s$ from the beginning of the simulation, respectively from top to bottom. Each row contains a view directly above the center of the merger, followed by a view 60 degrees from the normal to the center of the merger. The frequency of the emissions shown is 1×10^{12} Hz.

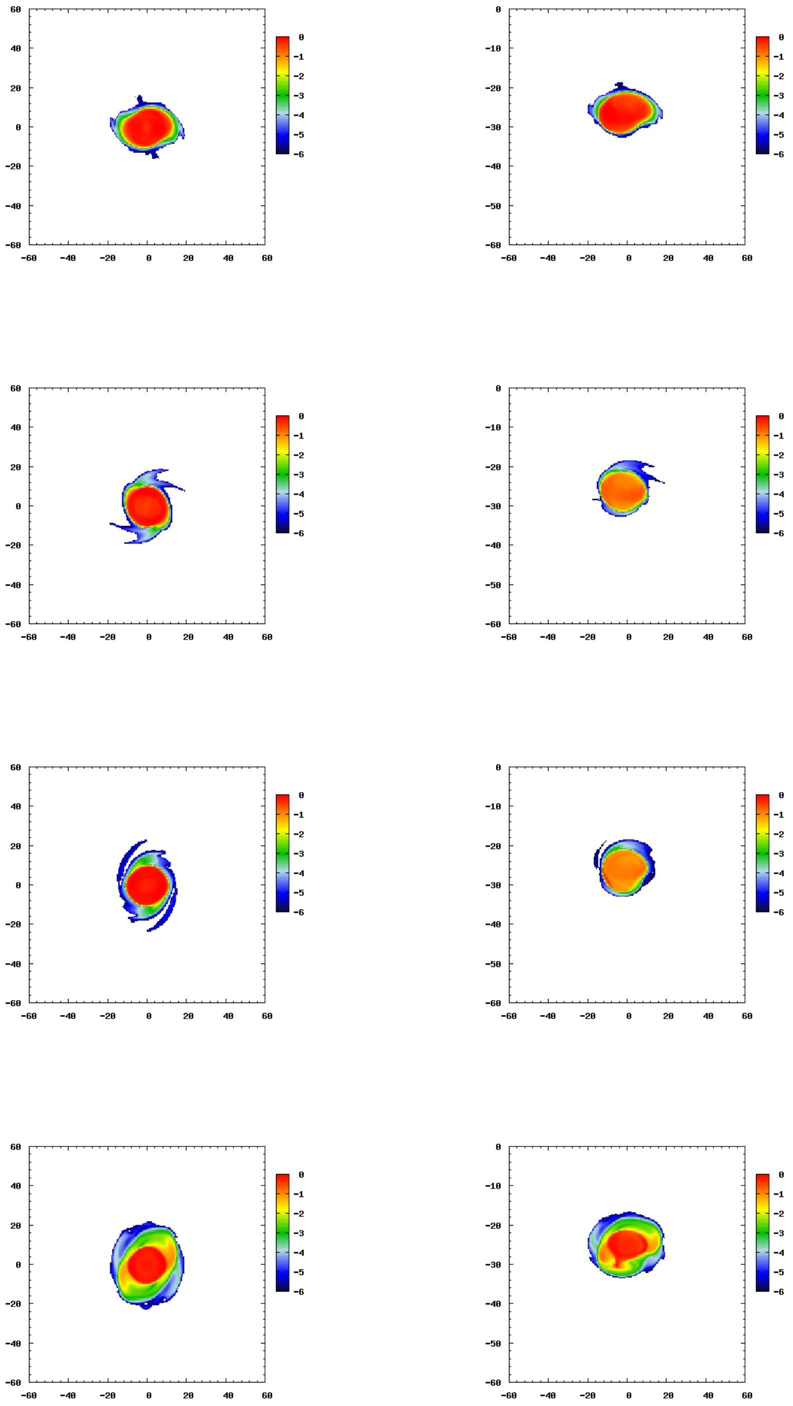

Figure 3.3 These images are of the merger at $1520\mu s$, $1600\mu s$, $1680\mu s$, and $1760\mu s$ from the beginning of the simulation, respectively from top to bottom. Each row contains a view directly above the center of the merger, followed by a view 60 degrees from the normal to the center of the merger. The frequency of the emissions shown is 1×10^{12} Hz.

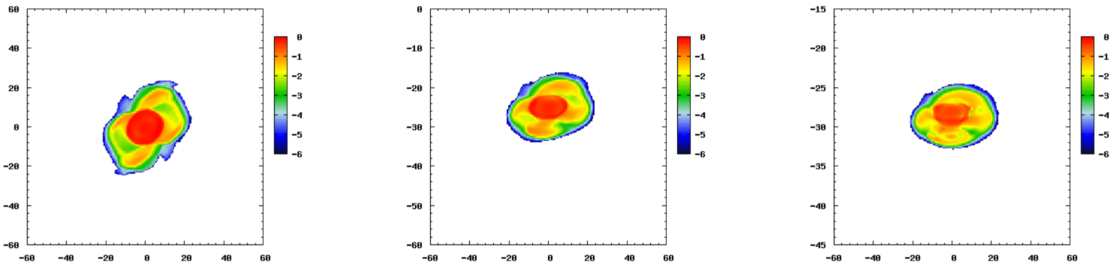

Figure 3.4 These images are given for the time 1840μs from the beginning of the simulation. From right to left the views shown are that of 0, 60 and 90 degrees from the normal of the center of the merger. The frequency of the emissions shown is 1×10^{12} Hz.

Four arm-like structures, each with very intense emissions appear right before the star collapses into a black hole. In Fig. 3.4 the most intense emissions appear to come from the core and the arms, which appear to be forming a disk like shape of strong emissions around the core of the new mass. This halo shape in Fig. 3.4 may be connected to gravitational forces leading to black hole formation.

The data given during the merging process shows little to no variance in intensity distribution between frequencies from 1×10^{12} and 5×10^{24} Hz, during the early and middle stages of the merger. However, as shown in Fig. 3.5, at about 1680μs from the beginning of our simulation, we begin to see less intense emissions in frequencies at 5×10^{24} Hz as compared to those below. These frequencies are in the high frequency gamma range, and may be related to a GRB. Further study will be needed to confirm such a correlation.

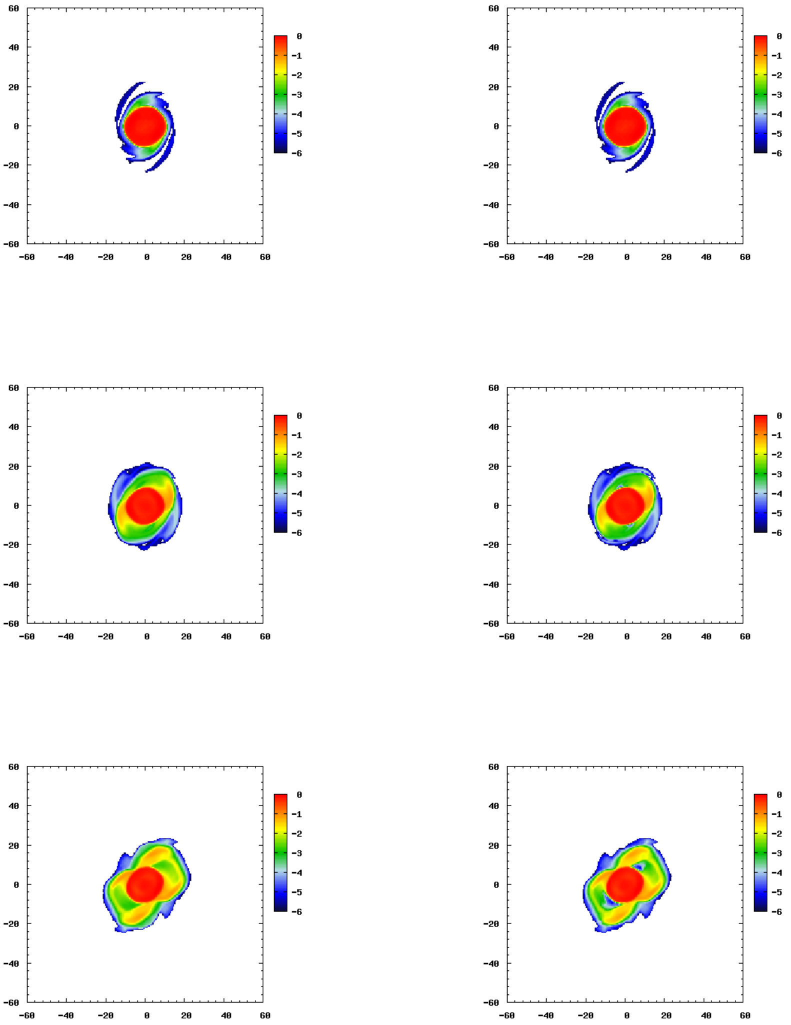

Figure 3.5 These images are of the merger at 1680μseconds, 1760μs, and 1840μs from the beginning of the simulation, respectively from top to bottom. Each image has a view directly above the center of the merger. The frequencies of these emissions are 1×10^{24} Hz for the left hand column and 5×10^{24} Hz for the right hand column.

3.3 Accuracy

The study of binary neutron star systems in full relativity is currently in its early stages. In building a model of such complex systems, we have chosen to start with a base of simple but predictable components. We then improve our program by replacing each simple component, in turn, with a new, more realistic set of equations. This method helps us ensure the accuracy of each part of our model, as we improve it. The current program was upgraded from its previous version by improving the calculations of the gravitational interaction of the stars. In a later prototype we plan on improving our equation of state. Our ideal approach would be to include all involved interactions within the stars: electromagnetic, nuclear, and gravitational. These calculations would then be applied to a better approximation of ion and particle densities to create separate equations of state for the inner core, outer core, inner crust and outer crust [1]. Each component of the star contains different types of particles at different concentrations and pressures, so each layer would need its own set of EOS calculations to support our radiation source calculations. Our program's approximate equation of state strongly affects the type of radiation we see emitted, as well as some intensity levels in our results. Although some error is propagated because of our use of the ideal gas equation, this estimate is close enough that the general trends found in the results are reasonable.

Chapter 4

Conclusion

4.1 Results

We study the electronmagnetic properties of the merger of two binary neutron stars. We use radiative transfer to calculate the intensity of emissions caused by thermal and brehmstahlung radiation from these stars. We find that the stars appear cold in intensity distribution until the two star masses form a central mass. As the merger progresses we see high intensity areas spread across the newly formed central mass, and the formation and fading of an assorment of appendages with intense emissions. Right before the collapse of the merger into a black hole we see four distinct arms have developed forming a halo around the center of mass of the merger. This halo may be caused by the transport of angular momentum and gravitational interactions between the high density of the core and the outer areas of the new central mass. We also see a sharp drop in high frequency gamma emissions at the later stages of the merger, which could be connected to a GRB. As this model is still a prototype, in order to completely validate our results more work should be done with this and improved prototypes.

4.2 Future Work

Future prototypes are planned to verify and elaborate on the results and conclusions given. A better EOS is planned for a future model. Calculations of inverse Compton scattering as additions to our radiation behavior methods will also be added. Our next specific planned improvement is to include synchrotron emission as another source of radiation from the stars. Synchrotron radiation is the radiation emitted by electrons when accelerated in a magnetic field. Neutron stars have intense magnetic fields of about 10^{12} Gauss [2], which cause extreme movement among electrons and other charged particles within the star. This results in sizable radiation emissions. These changes in future models should verify and elaborate upon our results, giving us a better model and insights into the luminous behaviour of merging binary neutron stars.

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