A Model for Short Gamma-Ray Bursts: Heated Neutron Stars in Close Binary Systems

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Abstract. In this paper we present a model for the short (< second) population of gamma-ray bursts (GRBs). In this model heated neutron stars in a close binary system near their last stable orbit emit neutrinos at large luminosities (∼10^{53} ergs/sec). A fraction of these neutrinos will annihilate to form an \( e^+e^- \) pair plasma wind which will, in turn, expand and recombine to photons which make the gamma-ray burst. We study neutrino annihilation and show that a substantial fraction (∼1/2) of energy deposited comes from inter-star neutrinos, where each member of the neutrino pair originates from each neutron star. Thus, in addition to the annihilation of neutrinos blowing off of a single star, we have a new source of baryon free energy that is deposited between the stars. To model the \( e^+e^- \) pair plasma wind between stars, we do three-dimensional relativistic numerical hydrodynamic calculations.

Preliminary results are also presented of new, fully general relativistic calculations of gravitationally attracting stars falling from infinity with no angular momentum. These simulations exhibit a compression effect.

INTRODUCTION

In Salmonson et al. [1] a model was presented for the production of a GRB in a close neutron star binary system, near its last stable orbit. In that model the stars undergo compression due to non-linear general relativistic effects. Vortices and shocks within the stars will convert this compressional energy into thermal energy which will be radiated from the stars in neutrinos. These neutrinos emerging from the neutron stars will partially recombine via \( \nu\bar{\nu} \rightarrow e^+e^- \), an effect that is substantially augmented (up to 30 times) by bending of neutrino paths by strong gravitational fields [2]. Thus an \( e^+e^- \) pair plasma fireball emerges from the neutron stars and expands relativistically. A key parameter studied in Salmonson et al. [1] was the entropy per baryon, \( s \), of the plasma, representing the amount of baryons entrained in the \( e^+e^- \) fireball. Ita was found through 1D relativistic hydrodynamic simulations that if \( s \sim 10^8 \), then prompt gamma-ray emission would result from the eventual recombination of \( e^+e^- \rightarrow \gamma\gamma \). If the entropy is as low as \( s \sim 10^6 \), effectively all of the energy would be transferred as kinetic energy to the baryons, thus resulting in gamma-ray emission from an external shock as the relativistic baryons sweep into the interstellar medium. Each scenario was studied in detail in Salmonson et al. [1].

In the current work we employ three enhancements. The first is from recent refined simulations of the compression by Wilson & Mathews which show timescales ~ 1 second, thus this model is best suited to describe the short class of GRBs (< second). Second, we use new calculations by Salmonson and Wilson [3] of the \( \nu\bar{\nu} \rightarrow e^+e^- \) between the neutrons stars where each neutrino of the annihilation pair originates from each star. This effect is found to be of about the same importance as that of the previously considered annihilation from individual netron stars [2]. Thus we have a new source of baryon-free \( e^+e^- \) plasma between the neutron stars. Third, we implement fully relativistic 3D hydrodynamics to model the plasma expansion in the complex, rotating inter-star environment.

THE MODEL

In this model we estimate that 10% of the binding energy of a neutron star (∼10^{53} ergs) is converted to thermal energy via compression, vortices and shocks. This 10^{52} ergs of energy is released as a monotonically increasing luminosity of neutrinos over a timescale of order ~ 1/10 second as found by calculations of J. R. Wilson & G. J. Mathews. This neutrino luminosity ∼ 10^{53} ergs sec^{-1} annihilates into an \( e^+e^- \) pair plasma. Annihilation of high neutrino luminosities in the strong gravitational field of the neutron stars can have high efficiencies; near unity [1]. About half of the pair plasma energy is deposited uniformly around the neutron stars due to single star neutrino annihilation [2] (Figure 1) and the
other half is deposited between the stars due to interstar neutrino annihilation [3].

This plasma deposition morphology then becomes input for the 3D relativistic hydrodynamic code, which calculates the expansion of the plasma (Figure 2). These simulations show a plasma of very high entropy expanding out along the plane of symmetry between the neutron stars. In the regions around the stars lower entropy plasma is formed because a baryon wind is blown from the stars.

Thus this model predicts a variety of bursts. Viewed along the axis of rotation, a prompt quasi-thermal burst of duration $\sim 1/10$ second will result from the annihilation of fireball pairs. Because of the dearth of baryons left over to sweep into the interstellar medium, we do not predict the existence of an afterglow. This agrees with preliminary searches of the data archives for short-burst afterglows, which appear to be missing [4].

Viewed far from the axis of rotation a very different burst results. The lower entropy means that there will not be a prompt burst from pair annihilation in the fireball. However, there will be a baryon wind sweeping into the interstellar medium. Thus we expect a burst that decays into an afterglow as a power-law. This behavior will be made chaotic and complex by the rapid rotation of the binary system.

THE COMPRESSION EFFECT IN STRONGLY GRAVITATING SYSTEMS

In Wilson et al. [5] it was reported that neutron star binaries near their last stable orbit undergo a compression due to non-linear general relativistic (GR) effects. This effect could be strong enough to crush the stars to black holes and perhaps release binding energy as thermal neutrinos in the process. Since that report, this effect has remained controversial.

Wilson recently has done a similar calculation of two stars gravitationally falling together without angular momentum. The calculations were done both in full GR and using the “conformal flat approximation” (CFA), often cited by critics to be the spurious source of the compression effect. Preliminary results, schematically shown in Figure 3, demonstrate a compression effect for both calculations. Thus, not only is the CFA not the source of the compression, but perhaps the compression effect, here demonstrated in a non-rotating system, is more general than previously thought.

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FIGURE 1. A contour plot of interstar neutrino annihilation energy deposition rates on a slice through a neutron star binary system [3], with stellar radii 10 km and separation 30 km. Lighter colors correspond to higher levels of energy deposition where black includes zero.

FIGURE 2. Three dimensional relativistic simulation of two 10 km radius neutron star separated by 30 km emitting $10^{53}$ ergs/sec of energy in $\mu^+\mu^-$ pair plasma and about 1 % equivalent mass in baryons. The contour map, with right star cutaway, is of baryon density. The vector field is the 3-velocity of expanding plasma. This problem settles down to a static flow after about one orbit with period $\sim 1/300 \text{ second}$.

FIGURE 3. A schematic diagram of the increase in central density as a function of the spatial 4-velocity of two close neutron stars observed in three different calculations. The point marked with an 'X' shows the magnitude of the compression calculated by Mathews and Wilson [6] in neutron star binary calculations at their last stable orbit. The curves show two calculations for two neutron stars falling toward each other from infinity, with no angular momentum. One curve is done in full general relativity (GR), made possible by the axisymmetry of this problem, and the other with the conformal flat approximation (CFA) used in the neutron star binary calculations [6]. One can see that all the CFA does a good job of reproducing the solution of the exact, full GR calculations. Also, we see that compression is observed for both rotating and linear systems.