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A Gamma-Ray Burst Fireball Model via the Compression and Heating of Binary Neutron Stars

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Abstract. A model is proposed for gamma-ray bursts based upon general relativistic hydrodynamic studies of the compression, heating, and collapse of close binary neutron stars as they approach their last stable orbit. Relativistic compression and heating before collapse may produce a neutrino burst of $\sim 10^{53}$ ergs lasting several seconds. The associated thermal neutrino emission produces an e^+e^- pair plasma by $\nu\bar{\nu}$ annihilation. We present a hydrodynamic simulation of the formation and evolution of the pair plasma associated with the neutrino burst. We find that this pair plasma leads to the production of $\sim 10^{51} - 10^{52}$ ergs in γ-rays with spectral and temporal properties consistant with observed gamma-ray bursts.

1. Introduction

The origin of gamma-ray bursts (GRBs) has been one of the major outstanding astrophysical problems since their discovery three decades ago [1]. GRBs are observed from Earth orbit daily and are distributed isotropically across the sky [2], yet attempts to find an optical counterpart have not met with success until recently. In the past two years the field has radically advanced due to high angular resolution burst detections from the BeppoSax X-ray satellite as well as observations from ASCA, RXTE and ROSAT. For the first time arcminute gamma-ray burst locations have been determined quickly enough to allow follow-up searches for optical or radio counterparts. These searches have revealed that at least some γ-ray bursts involve weak X-ray, optical, or radio transients, and are of cosmological origin [5]. The Mg I absorption and [O II] emission lines along the line of sight from the GRB970508 optical transient, for example, indicate a redshift $Z \geq 0.835$ [6]. The implied distance means that this burst must have released of order $\gtrsim 10^{51}$ ergs in γ-rays on a time scale $\sim$ seconds. This requirement has been rendered even more demanding by other events such as GRB971214 [7] which appears to be centered on a galaxy at redshift 3.42. This implies that the energy of a 4π burst would have to be as much as 3×10^{53} ergs, comparable to the visible light output of $\sim 10^9$ galaxies.

Based upon the accumulated evidence one can probably conclude that the following four features which characterize the source environment: 1) The ratio of burst energy to the beam solid angle $4\pi E/\Omega$ is $\sim 10^{53}$ erg, e.g. with 1% beaming the burst energy is $\sim 10^{51}$ erg; 2) The multiple peak temporal structure of most bursts probably requires either multiple colliding shocks [8] or a single shock impinging upon a clumpy interstellar medium; 3) The observed afterglows imply some surrounding material on a scale of light hours; and 4) the presence of OII emission lines suggests that the bursts occur in a young metal-enriched stellar population.

Possible sources consistent with these conditions probably involve some kind of catastrophic collapse/accretion in an environment somewhat depleted in baryons. Some proposed sites include accretion onto supermassive black holes, AGN's, relativistic stellar collisions, hypernovae, and binary neutron star coalescence. Each of these possibilities, however, remains speculative until realistic models can be constructed for their evolution. In this paper we construct a model for relativistically driven GRBs from compressing/collapsing neutron-stars in a binary system. We show that the characteristic features of GRBs can be accounted for in the context of this model.

2. Compression in Close Neutron Star Binaries

It has been speculated for some time that inspiraling neutron stars could provide a power source for cosmological gamma-ray bursts. The rate of neutron star mergers (when integrated over the number of galaxies out to high redshift) could account for the observed GRB event rate. Previous Newtonian and post Newtonian studies [9] of the direct merger of two neutron stars have found that the neutrino emission time scales are so short that it would be difficult to drive a gamma-ray burst from this source. However, our numerical studies of the strong field relativistic hydrodynamics of close neutron star binaries in three spatial dimensions [10, 11, 12, 13] have shown that neutron stars in a close binary can experience relativistic compression and heating over a period of seconds. This effect can cause each of the stars to collapse to individual black holes prior to merger. During the compression phase released gravitational binding energy can be converted to internal energy. Subsequently, as much as 10^{53} ergs in thermally produced neutrinos can be emitted before the stars collapse [12]. This effect may provide a new mechanism to power cosmological gamma-ray bursts and their X-ray and optical counterparts. Here we report on efforts to quantify this release of neutrino energy around the binary and numerically explore its consequences for the development of a e^+e^- plasma and associated GRB.

In previous work [12] we computed properties of equal-mass neutron star binaries as a function of mass and EOS. From these studies we deduced that compression, heating and collapse can occur at times from a few seconds to a few hours before binary merger. Our calculation of the rates of released binding energy and neutron star cooling suggests that interior temperatures as hot as 70 MeV are possible. This leads to several seconds of high neutrino luminosity, $L_\nu \sim 10^{53}$ ergs sec^{-1}. This much neutrino luminosity would partially convert to an e^+e^- pair plasma above the stars as is also observed above the nascent neutron star in supernova simulations [16]. This plasma is a viable candidate source for cosmological gamma-ray bursts.

The source of energy for our gamma-ray model arises from the compression that neutron stars undergo as they spiral in. The primary cause for the inspiral is gravity wave emission, however at late times the inspiral rate is increased by neutrino emission. The compression phenomenon was first noted in 1995 [10]. The relation of the compression and subsequent heating was discussed in [12]. In the later paper it was pointed out that thermal energies up to 10^{53} ergs would be developed in neutron star binaries in times of the order of one second. Many papers have been published claiming the compression is nonexistent. In [14] we presented a rebuttal to the critics. Subsequent to the publication of [14], E. Flanagan found an error in our formula for the momentum constraint, see [15]. We have corrected the momentum constraint equation and redone a sequence of calculations for a binary neutron star system with various angular momenta. We still observe a compression effect able to release 10^{52} - 10^{53} ergs of gravitational binding energy.

In [12] we estimated the heating due to compression. It should be noted that the above calculations have been made with the stars at zero temperature. The estimated thermal energy is $\sim 10^{52}$ to $\sim 10^{53}$ ergs. The time scale to merger of the binary system can be estimated from $J/\dot{J}$ to be ~ 1 second. Large vortices are observed to form within the stars with a characteristic circulation time scale of ~ 0.001 sec. This circulatory motion is most important since it does two things: 1) This motion could induce reconnection of magnetic field lines and thereby amplify any existing magnetic field. We have calculated e-folding time of the interior magnetic field to be ~ 1 ms; and 2) since the velocities are nearly sonic it should help dissipate the compressional motion into thermal energy by shocks.

The fluid kinetic energy in a frame rotating with the average rotation of the orbit is $\approx 3 \times 10^{52}$ erg. This swirling motion will bring matter up from the inside to the outside on a time scale of milliseconds. Thus, we estimate that the rate of thermal emission (mostly in neutrino luminosity) is equal to the rate of generation of compressional energy. With a thermal energy in the range $\sim 10^{52}$ to $\sim 10^{53}$ ergs, the neutrino luminosity is estimated using $L = E\frac{\dot{J}}{J}$ to be in the range $\sim 10^{52}$ to $\sim 10^{53}$ ergs/second.

3. Neutrino Annihilation and Pair Creation

In the previous section we have outlined a mechanism by which neutrino luminosities of 10^{52} to 10^{53} may arise from binary neutron stars approaching their final orbits. Neutrinos emerging from the stars will deposit energy outside the stars predominantly by $\nu\bar{\nu}$ annihilation to form electron pairs. A secondary mechanism for energy deposition is the scattering of neutrinos from the e^+e^- pairs. Strong gravitational fields near the stars will bend the neutrino trajectories. This greatly enhances the annihilation rate [17]. In Figure 1 taken from [17] the enhancement factor, $\mathcal{F}$, of the rate of annihilation by gravitational bending is shown versus the radius to mass ratio (in units $G = c = 1$). For a typical neutron-star equation of state the radius to mass ratio is between $r/m \sim 3$ and 4 just before stellar collapse. Thus, the enhancement factor ranges from $\sim$8 to 28. Defining the efficiency of energy deposition as the ratio of energy deposition to neutrino luminosity, then from Eq. 24 of Ref. [17] we obtain,

$$\frac{\dot{Q}}{L} \approx 0.03\mathcal{F}(R/M)L_{53}^{5/4} \quad . \tag{1}$$

Thus, the efficiency of annihilation ranges from 0.1 to $0.67 \times L_{53}$. For the upper range of luminosity the efficiency is quite large. To better analyze the annihilation process we have adapted the Mayle-Wilson [16] supernova model to this problem. We emphasize that the Mayle-Wilson model is fully general relativistic. To investigate this problem, a hot neutron star of the appropriate R/M was constructed and the internal temperature adjusted to achieve the correct neutrino luminosities. The Curant condition requires that the time steps be quite small ($\sim 10^{-9}$ second). Hence, the calculations could only be evolved for a short time. The entropy per baryon of the e^+e^- pair plasma

$$s/k = \frac{4m_b c^2 (ae^3)^{1/4}}{3k\rho} \tag{2}$$

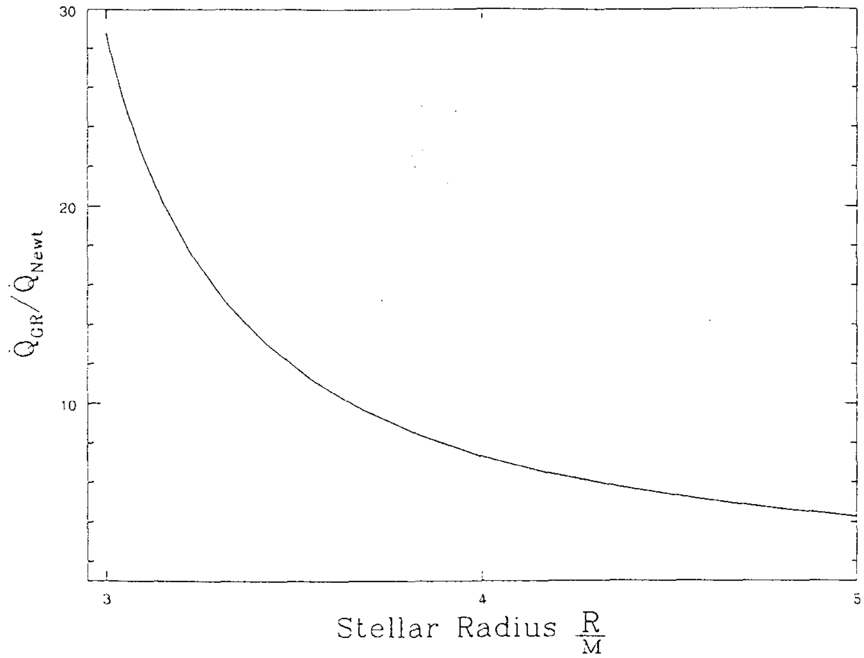

Figure 1. General relativistic augmentation $\mathcal{F} \equiv \dot{Q}_{GR}/\dot{Q}_{Newt}$ as a function of neutron star neutrinosphere radius down to $R = 3M$, where general relativistic energy deposition is $\dot{Q}_{GR}$, and newtonian energy deposition is $\dot{Q}_{Newt}$.

where d is the baryon density and e is the energy density, is the critical quantity for gamma-ray production. The entropy per baryon was found to be as high as $\geq 10^6$ for the high luminosities.

The efficiency of neutrino annihilation determines the total energy of the pair plasma and the entropy. This provides the initial conditions for the subsequent fireball expansion.

Pair Plasma Expansion

Having determined the initial conditions of the hot e^+e^- pair plasma near the surface of a neutron star, we wish to follow its evolution and characterize the observable gamma-ray emission. To study this we have developed a spherically symmetric, general relativistic hydrodynamic computer code to track the flow of baryons, e^+e^- pairs, and photons. For the present discussion we consider the plasma deposited at the surface of a $1.45 M_\odot$ neutron star with a radius of 10 km.

The fluid is modeled by evolving the following spherically symmetric general relativistic hydrodynamic equations:

$$\frac{\partial D}{\partial t} = -\frac{\alpha}{r^2}\frac{\partial}{\partial r}\left(\frac{r^2}{\alpha} D V^r\right) \tag{3}$$

$$\frac{\partial E}{\partial t} = -\frac{\alpha}{r^2}\frac{\partial}{\partial r}\left(\frac{r^2}{\alpha} E V^r\right) - P\left[\frac{\partial W}{\partial t} + \frac{\alpha}{r^2}\frac{\partial}{\partial r}\left(\frac{r^2}{\alpha} W V^r\right)\right] \tag{4}$$

$$\frac{\partial S_r}{\partial t} = -\frac{\alpha}{r^2}\frac{\partial}{\partial r}(\frac{r^2}{\alpha}S_r V^r) - \alpha\frac{\partial P}{\partial r} - \alpha\frac{M}{r^2}\left(\frac{D+\Gamma E}{W}\right)\left[\left(\frac{W}{\alpha}\right)^2 + \frac{(U^r)^2}{\alpha^4}\right] \quad (5)$$

where $D = \rho W$ and $E = \epsilon\rho W$ are the Lorentz contracted coordinate densities of baryonic and thermal energy (e^+e^- and photons) respectively. The quantity S_r is the radial coordinate momentum density. U_r is the radial component of the covariant 4-velocity. $W \equiv \alpha U^t$ is the generalized Lorentz factor, V^r is the radial coordinate three velocity, and Γ is an equation of state index. These are defined by

$$\alpha \equiv \sqrt{1-\frac{2M}{r}} \quad ; \quad U_r \equiv \frac{S_r}{D+\Gamma E} \quad ; \quad W \equiv \sqrt{1+U^i U_i}$$
$$V^r \equiv \frac{U^r}{W} \quad ; \quad \Gamma \equiv 1 + \frac{PW}{E} \quad (6)$$

To evolve the e^+e^- pair plasma, we define a pair equation. The observed pair annihilation rate must be corrected for relativistic effects; specifically time dilation slows the apparent pair annihilation process for a fast moving fluid. Thus, we construct a continuity equation analogous to Equation (3) and add a term to account for annihilation and pair-production reactions:

$$\frac{\partial N_{pairs}}{\partial t} = -\frac{\alpha}{r^2}\frac{\partial}{\partial r}(\frac{r^2}{\alpha}N_{pairs}V^r) + \overline{\sigma v}((N^0_{pairs}(T))^2 - N^2_{pairs})/W^2 \quad (7)$$

where N_{pairs} is the coordinate pair number density, and $\overline{\sigma v}$ is the maxwellian averaged mean pair annihilation rate per particle. Although $\overline{\sigma v}$ depends on T, it varies little in the temperature range of interest and thus can be taken as constant. $N^0_{pairs}(T) = n^0_{pairs}(T)W$, where $n^0_{pairs}(T)$ is the local proper equilibrium e^+e^- pair density at temperature T given by the appropriate Fermi integral with a chemical potential of zero.

The total proper energy equation, including photons and e^+e^- pairs, is

$$e_{tot} = aT^4 + e_{pairs} \quad (8)$$

where coordinate energy in Equation (4) is related to proper energy by $E = e_{tot}W$ and e_{pairs} is the appropriate zero chemical potential Fermi integral normalized to give the proper e^+e^- pair density $n_{pair} = N_{pairs}/W$ as determined by Equation (7).

We model the energy deposition at the surface of a $1.45M_\odot$ NS by injecting baryon and pair-photon energy densities into the innermost zone above the $r = 10$ km neutron-star surface. The rate of deposition is determined by the rate of input of thermal energy estimated from the binary gravitational wave luminosity [12]:

$$\dot{E}_{th}(t) = \frac{(32/5)(Mf)^{5/3}fE^0_{th}}{[1-(64/5)(Mf)^{5/3}ft]^{3/2}} \quad (9)$$

where $t < 0$ and $t = 0$ is the end of energy deposition when the neutron star is assumed to have collapsed into a black hole or passed inside the last stable orbit. In the results presented here we have injected a total energy of $E^0_{th} = 10^{51}$, 10^{52}, 10^{53} ergs, covering a range of possible available energy estimated in the NSB calculations discussed above.

The entropy per baryon (Equation 2) of the wind is crucial to the behavior of the burst. An entropy that is too high will create a burst which is much hotter than those observed, while an entropy that is too low will extinguish the burst with baryons. We find that entropies of the order 10^7 to 10^8 are ideal for producing an isotropic burst. In the calculations shown we cover a range of possible entropies per baryon from 10^6 to 10^8.

The hydrodynamic equations are evolved, allowing the plasma to expand. Once the system becomes transparent to Thompson scattering, ($\int N_{pair}(r)\sigma_T dr \sim 1$ where σ_T is the Thompson cross-section) we assume the photons are free-streaming, the calculation is stopped and the photon gas is analyzed to determine the photon signal.

4. Analysis of the Spectrum and Lightcurve

We find that the photons and e^+e^- pairs appear to decouple at virtually the same time throughout the entire photon-e^+e^- pair plasma (when the cloud has reached a radius $\sim 10^{12}$ cm), thus we take decoupling to be instantaneous and to occur when the plasma becomes optically thin to Thompson scattering. Furthermore, we find that virtually none of the energy deposited in the e^+e^- pair plasma remains in the pairs ($\sim .001\%$), thus the conversion of e^+e^- pair energy to photons and baryons is very efficient. We then look at two observables, the time integrated number spectrum $N(\epsilon)$ and the total energy received as a function of observer time $\varepsilon(t)$.

4.1. The Spectrum

As mentioned above, we assume that the e^+e^- pairs and photons are equilibrated to the same T when they decouple. Thus, the photons in the fluid frame (denoted with a prime: ') make up a Planck distribution of the form

$$u'_{\epsilon'}(T') \approx \frac{\epsilon'^3}{exp(\epsilon'/T') - 1} \quad , \tag{10}$$

but u_ϵ/ϵ^3 is a relativistic invariant [18]. This implies $\frac{\epsilon}{T}$ is also a relativistic invariant. So a Planck distribution in an emitter's rest-frame with temperature T' will appear Planckian to a moving observer, but with boosted temperature $T = T'/(\gamma(1 - v\cos\theta))$ where $v\cos\theta$ is the component of fluid velocity (c=1) directed toward the observer. Thus,

$$u_\epsilon(\theta, v, T') \approx \frac{\epsilon^3}{exp(\gamma(1 - v\cos\theta)\frac{\epsilon}{T'}) - 1} \tag{11}$$

gives the observed spectrum of a blackbody with rest-frame temperature T' moving at velocity v and angle θ with respect to the observer.

In the present case we wish to calculate the spectrum from a spherical, relativistically expanding shell as seen by a distant observer. Since we know v, T' and the radius R of the shell, we integrate over volume (i.e., shell, angle) with respect to the observer. We thus get the observed number spectrum $N_\epsilon = \int \frac{u_\epsilon \, dVolume}{\epsilon}$, per photon energy ϵ, per steradian, of a relativistically expanding spherical shell with radius R, thickness dR in cm, velocity v, Lorentz factor γ and fluid-frame temperature T' to be (in photons/eV/4π)

$$N_\epsilon(v, T', R) = (5.23\times 10^{11})4\pi R^2 dR \frac{\epsilon T'}{v\gamma} log\left[\frac{1 - exp[-\gamma\epsilon(1+v)/T']}{1 - exp[-\gamma\epsilon(1-v)/T']}\right] \tag{12}$$

which has a maximum at $\epsilon_{max} \cong 1.39\gamma T'$ eV for $\gamma \gg 1$. We may then sum this spectrum over all shells (the zones in our computer code) of our fireball to get the total spectrum. Since we *a priori* assume that the photons are thermal, our spectrum has a high frequency exponential tail, but the resultant total spectrum is not thermal up through $\epsilon = 5$ MeV.

4.2. *The Light Curve*

To construct the observed light curve $\varepsilon(t)$ we again decompose the spherical plasma into concentric shells and consider two effects: First, is the relative arrival time of the first light from each shell: light from outer shells will be observed before light from inner shells; Second, is the shape of the light curve from a single shell.

Emission from moving stuff is beamed along the direction of travel within an angle $\theta \sim 1/\gamma$. The surface of simultaneity of a relativistically expanding spherical shell as seen by an observer is an ellipsoid [19]. The observer time of intersection of an expanding ellipse with a fixed shell of radius R as a function of θ (i.e. the time at which emission from this intersection circle is received) is:

$$t = \frac{R}{v}(1 - v\cos\theta) \cong \frac{R}{2\gamma^2 c} \tag{13}$$

for $\theta \ll 1, \gamma \gg 1$. We find that, integrating our boosted Planck distribution of photons (Equation 11) over frequency, a relativistically expanding shell of radius R will have a time profile (in ergs/seconds/4π)

$$\varepsilon(\tau, v, T', R) = \frac{a}{2}\left(\frac{T'}{\gamma\tau}\right)^4 R^2 \frac{dR}{v} \sim 1/\tau^4 \tag{14}$$

for $\tau > 1$ and where $\tau \equiv \frac{vt}{R}$. Thus, the larger the radius R of the expanding shell at the moment of emission, the broader the $1/\tau^4$ tail on the light curve. The final light curve is then constructed by summing the signal from all shells.

Variation in the ratio of star mass in the NSB effects the relative compression and heating rate of each star, thus allowing a variety of GRB durations. We parameterize the overall duration of the burst by t_{90}, the time interval over which 90% of the energy is received.

5. Results

We have run a variety models over a range of entropies per baryon and total energies. The results are summarized in Figures 2, 3 & 4. We see that more powerful bursts are derived from higher entropies per baryon and higher total energies. The duration of the burst is determined by the duration of emission because the timescale of emission from any single shell is very short; $t_{shell} \approx R/2\gamma^2 c \sim 0.01$ seconds (Equation 13) for $R \sim 10^{12}$ cm and $\gamma \sim 100$, compared to the timescale of compression and coalescence: $J/\dot{J} \sim$ seconds. Thus there is no particular correlation of burst duration with the etropy per baryon or total energy. We can see that entropies per baryon of a few $\times 10^7$ allow a burts with a spectral peak ~ 100 keV and efficiencies $E_\gamma/E_{tot} \sim 10\%$. This is not inconsistent with the entropies calculated for the e^+e^- plasma deposited above the neutron stars. Much further work needs to be done to better characterize the nature of the stellar compression and energy transport withing the stars. Also, more elaborate simulations must be done to resolve the flow in three dimensions and

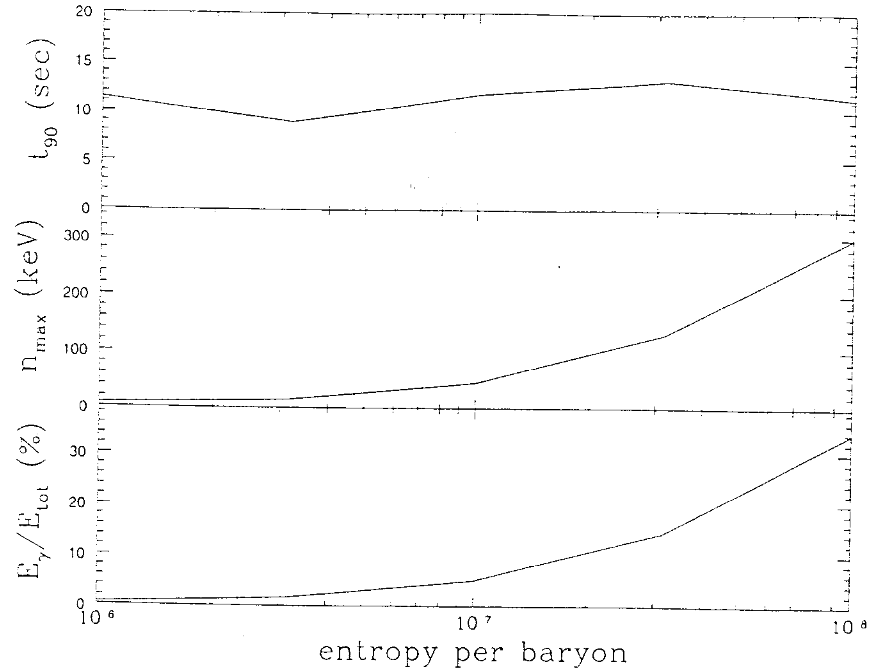

Figure 2. The duration, peak energy and gamma-ray efficiency are plotted for a total energy $E_{tot} = 10^{52}$ ergs over a range of entropies 10^6 to 10^8.

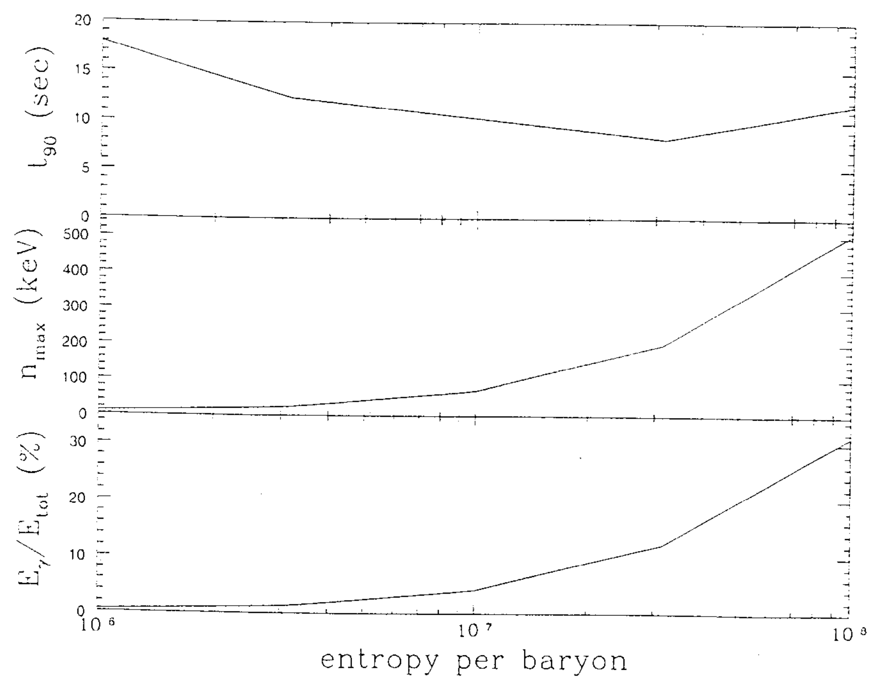

Figure 3. The duration, peak energy and gamma-ray efficiency are plotted for a total energy $E_{tot} = 10^{53}$ ergs over a range of entropies 10^6 to 10^8.

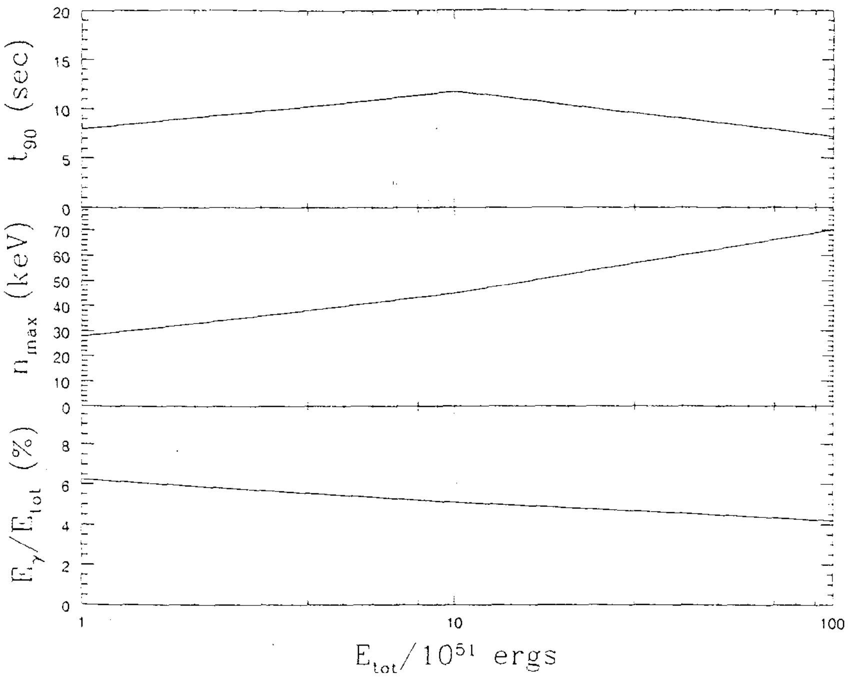

Figure 4. The duration, peak energy and gamma-ray efficiency are plotted for an entropy per baryon $s = 10^7$ over a range of energies 10^{51} to 10^{53} ergs.

the effects of magnetic fields. In conclusion, stellar compression of close neutron star binaries is a viable candidate for the creation of gamma-ray bursts.

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