GAMMA-RAY BURSTS FROM DELAYED COLLAPSE OF NEUTRON STARS TO QUARK MATTER STARS

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ABSTRACT

We propose a model to explain how a gamma-ray burst can take place days or years after a supernova explosion. Our model is based on the conversion of a pure hadronic star (neutron star) into a star made at least in part of deconfined quark matter. The conversion process can be delayed if the surface tension at the interface between hadronic and deconfined quark matter phases is taken into account. The nucleation time (i.e., the time to form a critical-size drop of quark matter) can be extremely long if the mass of the star is small. Via mass accretion the nucleation time can be dramatically reduced and the star is finally converted into the stable configuration. A huge amount of energy, on the order of $10^{52} - 10^{53}$ ergs, is released during the conversion process and can produce a powerful gamma-ray burst. The delay between the supernova explosion generating the metastable neutron star and the new collapse can explain the delay inferred in GRB 990705 and in GRB 011211.

Subject headings: dense matter — equation of state — gamma rays: bursts — stars: neutron

1. INTRODUCTION

The discovery of a transient (13 s) absorption feature in the prompt emission of the ~40 s gamma-ray burst (GRB) of 1999 July 5 (GRB 990705) (Amati et al. 2000) and the evidence of emission features in the afterglow of several GRBs (Piro et al. 1999; Yoshida et al. 1999; Piro et al. 2000; Antonelli et al. 2000; Reeves et al. 2002) have stimulated the interpretation of these characteristics in the context of the fireball model of GRBs. Amati et al. (2000) attribute the transient absorption feature of GRB 990705 (energy released $\sim 10^{53}$ ergs, assuming isotropy) to a redshifted K edge of iron contained in an environment not far from the GRB site ($\sim 0.1$ pc) and crossed by the GRB emission. They estimate an iron abundance typical of a supernova (SN) environment ($A_{Fe} \sim 75$) and a time delay of about 10 years between the SN explosion and the GRB event. Lazzati et al. (2001) give a different interpretation of the absorption feature, in terms of a redshifted resonance scattering feature of H-like iron (transition 1$s$–2$p$, $E_{rest} = 6.927$ keV) in an inhomogeneous high-velocity outflow, but invoke a iron-rich environment as well, due to a preceding SN explosion, even if a shorter time delay ($\sim 1$ yr) between SN and GRB is inferred. An SN explosion preceding the GRB event is also inferred for explaining the properties of the emission features in the X-ray afterglow spectrum of GRB 000214 (Antonelli et al. 2000) and GRB 991216 (Piro et al. 2000). In the latter case, the possibility cannot be excluded that the SN explosion occurred days or weeks before the GRB (Rees & Mészáros 2000). Reeves et al. (2002), to explain the multiple emission features observed in the afterglow spectrum of GRB 011211 (time duration of $\sim 270$ s, isotropic gamma-ray energy of $5 \times 10^{52}$ ergs), invoke an SN explosion preceding the GRB event by $\sim 4$ days (in the isotropic limit, a minimum of 10 hr). Even if other interpretations for the afterglow emission lines are possible without invoking a previous SN explosion (e.g., Rees & Mészáros 2000; Mészáros & Rees 2001), this explosion seems to be the most likely way to explain the transient absorption line observed from GRB 990705 (Böttcher, Fryer, & Dermer 2002). In conclusion, the previous observations suggest that, at least for a certain number of GRBs, an SN explosion happened before the GRB, with a time interval between the two events ranging from a few hours to a few years. In this context, an attractive scenario is that described by the supranova model (Vietri & Stella 1998) for GRBs. In this model, the GRB is the result of the collapse to a black hole (BH) of a supramassive fast rotating neutron star (NS), as it loses angular momentum. According to this model the NS is produced in the SN explosion preceding the GRB event. The initial baryonic mass $M_B$ of the NS is assumed to be above the maximum baryonic mass for nonrotating configurations. However, as also noticed by Böttcher et al. (2002), on the basis of realistic calculations of collapsing NS (Fryer & Woosley 1998), in these collapses too much baryonic material is ejected and thus the energy output is expected to be too small to produce GRBs. Even if the introduction of magnetic fields or beaming could overcome this limitation, in any case, the GRB duration from an NS collapse should be very short ($\ll 1$ s), much shorter than that observed from GRB 990705.

In this paper, we propose an alternative model to explain the existence of GRBs associated with previous SN explosions. In this model, unlike the supranova model, the NS collapse to BH is replaced with the conversion from a metastable, purely hadronic star (neutron star) into a more compact star in which deconfined quark matter (QM) is present. This possibility has already been discussed in the literature (Cheng & Dai 1996; Bombaci & Datta 2000; Wang et al. 2000; Ouyed, Dey, & Dey 2002). The new and crucial idea we introduce here is the metastability of the purely hadronic star due to the existence of a nonvanishing surface tension at the interface separating hadronic matter from quark...
matter. The mean lifetime of the metastable NS can then be connected to the delay between the supernova explosion and the GRB. As we shall see, in our model we can easily obtain a burst lasting tens of seconds, in agreement with the observations. The order of magnitude of the energy released is also appropriate.

2. QUARK MATTER NUCLEATION IN COMPACT STARS

Recently various possibilities have been discussed in the literature to get compact stars in which matter is, partially or totally, in a state of deconfined quarks (see e.g., Glendenning 2000; Heiselberg & Hjorth-Jensen 2000; Drago & Lavagno 2001). Concerning the stellar quark content, it is possible to have three different classes of compact stars: (a) purely hadronic stars (HS), in which no fraction of QM is present; (b) hybrid stars (HyS), in which only at the center of the star QM is present either as a mixed phase of deconfined quarks and hadrons or as a pure phase; and (c) quark stars (QS), in which the surface of the star is made of matter having a large density, on the order of nuclear matter saturation density or larger, and the bulk of the star is made of deconfined QM. The sizeable amount of observational data collected by the new generations of X-ray satellites has provided a growing body of evidence for the existence of very compact stars, which could be HyS or QS (Bombaci 1997; Cheng et al. 1998; Li et al. 1999a, 1999b; Xu 2002; Drake et al. 2002).

In our scenario, we consider a purely HS whose central density (pressure) is increasing due to spin-down or due to mass accretion (e.g., from fallback of ejected material in the SN explosion). As the central density approaches the deconfinement critical density, a virtual drop of quark matter can be formed in the central region of the star. The fluctuations of a spherical droplet of quark matter having a radius \( R \) are regulated by a potential energy of the form (Lifshitz & Kagan 1972)

\[
U(R) = \frac{4}{3} \pi n_q (\mu_q - \mu_h) + 4 \pi \sigma R^2 + 8 \pi \gamma R,
\]

where \( n_q \) is the quark baryon density, \( \mu_q \) and \( \mu_h \) are the hadronic and quark chemical potentials at a fixed pressure \( P \), and \( \sigma \) is the surface tension for the surface separating quarks from hadrons. The term containing \( \gamma \) is the so-called curvature energy. The value of the surface tension \( \sigma \) is poorly known, and typical values used in the literature range from 10 to 50 MeV fm\(^{-2} \) (Heiselberg, Pethick, & Staubo 1993; Iida & Sato 1998). Following the work of Iida & Sato (1998), we have assumed that the term with \( \sigma \) takes into account in an effective way also the curvature energy. The term with \( \gamma \) is discussed, e.g., by Masden (1993), while other more complicated terms, connected with the Coulomb energy, are discussed in the literature (Heiselberg et al. 1993; Iida & Sato 1998). We have neglected them in our analysis, since they do not dramatically modify both the nucleation time and the energy associated with the transition into the stable quark matter configuration.

If the temperature is low enough, the process of formation of a bubble with a critical radius proceeds through quantum tunnelling, the probability of which can be computed using a semiclassical approximation. The procedure is rather straightforward. First one computes, using the semiclassical (WKB) approximation, the ground state energy \( E_0 \) and the oscillation frequency \( \nu_0 \) of the virtual QM drop in the potential well \( U(R) \). Then it is possible to calculate in a relativistic frame the probability of tunneling as (Iida & Sato 1998):

\[
p_0 = \exp \left[ -\frac{A(E_0)}{\hbar} \right],
\]

where

\[
A(E) = 2 \int_{R_c}^{R} dR \sqrt{(2M(R) + E - U(R))(U(R) - E)}.
\]

Here \( R_c \) are the classical turning points and

\[
M(R) = 4\pi \rho_h \left(1 - \frac{n_q}{n_h}\right)^2 R^3,
\]

where \( \rho_h \) is the hadronic energy density (here and in the following we adopt the so-called ”natural units,” in which \( \hbar = c = 1 \)) and \( n_h \) and \( n_q \) are the baryonic densities at a same and given pressure in the hadronic and quark phase, respectively. The nucleation time is then equal to

\[
\tau = (\nu_0 p_0 N_c)^{-1},
\]

where \( N_c \) is the number of centers of droplet formation in the star, and it is on the order of \( 10^{48} \) (Iida & Sato 1998).

3. RESULTS

The typical mass-radius relations for the three types of stars we are discussing can be found, e.g., in Figure 3 of Drago & Lavagno (2001), where a relativistic nonlinear Walecka-type model (Glendenning & Moszkowski 1991) has been used to describe the hadronic phase. It appears that stars containing QM (either HyS or QS) are more compact than purely HS. In particular QSs can have much smaller radii than HSs when they have a small mass. In our scenario a metastable HS having a mass of, e.g., 1.3 M\(_\odot\) and a radius of \( \sim 13 \) km can collapse into an HyS having a radius of \( \sim 10.5 \) km or into a QS with radius \( \sim 9 \) km (with respect to the results of Fig. 3 of Drago & Lavagno 2001, here we use an equation of state [EOS] that includes hyperonic degrees of freedom). The nature of the stable configuration reached after the stellar conversion (i.e., an HyS or a QS) will depend on the parameters of the quark phase EOS.

The time needed to form a critical droplet of deconfined quark matter can be calculated for different values of the stellar central pressure \( P_c \) (which enters in the expression of the energy barrier in eq. [1]) and it can be plotted as a function of the gravitational mass \( M_{\text{HS}} \) of the HS corresponding to that given value of central pressure. The results of our calculations for a specific EOS of hadronic matter (the GM3 model with hyperons of Glendenning & Moszkowski 1991) are reported in Figure 1, where each curve refers to a different value of the bag constant \( B \). If we assume, for example, \( B^{1/4} = 170 \) MeV (which corresponds to \( B = 109 \) MeV fm\(^{-3}\) and the initial mass of the HS to be \( M_{\text{HS}} = 1.32 M_\odot \), we find that the ”lifetime” for this star is about \( 10^{12} \) yr. As the star accretes a small amount of matter, the consequent increase of the central pressure leads to a huge reduction of the nucleation time, and, as a result, to a dramatic reduction of the HS lifetime. For our HS with initial mass of 1.32 M\(_\odot\), the accretion of about 0.01 M\(_\odot\) reduces the star lifetime to a few years. We would like to stress that in our model the
delay between the SN explosion and the GRB is regulated by the mass accretion rate, rather than by the mass and the spinning of the metastable star itself. Since the mass accretion rate is generally larger during the first days after the SN explosion, a delay of a few days will be rather typical in our scenario. However, longer delays are also possible if the material ejected during the SN explosion has a small fallback.

In the model we are presenting, the GRB is due to the cooling of the newly formed HyS or QS via neutrino-antineutrino emission (and maybe also via emission of axion-like particles; see below). The subsequent neutrino-antineutrino annihilation generates the GRB. In our scenario the duration of the prompt emission of the GRB is therefore regulated by two mechanisms: (1) the time needed for the conversion of the HS into a HyS or QS, once a critical-size droplet is formed, and (2) the cooling time of the newly formed HyS or QS. Concerning the time needed for the conversion into QM of at least a fraction of the star, the seminal work by Olinto (1987) has been reconsidered by Horvath & Benvenuto (1988). The conclusion of this latter work is that the stellar conversion is a very fast process, having a duration much shorter than 1 s. On the other hand, the neutrino trapping time, which provides the cooling time of a compact object, is on the order of a few tens of seconds (Prakash et al. 1997), and it gives the typical duration of the GRB in our model. In Table 1 we give the measured duration and the estimated electromagnetic energy (assuming isotropic emission) of the GRBs associated with Fe emission or absorption lines. All bursts last at least 10 s. According to our model, the first few tens of seconds correspond to a prompt $\gamma$-ray emission, while the subsequent emission should be interpreted as the beginning of the afterglow. Actually it has been found that at least the second half of the prompt emission of long bursts is likely due to afterglow (Frontera et al. 2000). We would like to remark, however, that we are not suggesting that all the GRBs should be explained by our model. In particular, long and energetic bursts could be originated, e.g., by collapsars (MacFadyen & Woosley 1999). On the other hand, the variety of GRB durations could be explained within the QS formation scenario itself, making use of the “unstable photon decay” mechanism proposed by Ouyed & Sannino (2002).

Next we consider the total energy $\Delta E$ released in the transition from a metastable HS (with hyperonic degrees of freedom) to HyS or QS (which final state is reached in this transition depends on the details of the QM EOS and in particular on the value of the bag constant). The energy released is calculated as the difference between the gravitational mass of the metastable HS and that of the final stable HyS (or QS) having the same baryonic mass (Bombaci & Datta 2000). In Table 2 we report the energy released for various values of the bag constant $B$ and of the surface tension $\sigma$. Notice that the transition will take place when the nucleation time has been reduced to a value on the order of years, due, e.g., to mass accretion on the HS (recall the exponential dependence of the nucleation time on the mass of the HS, as shown in Fig. 1). Therefore the total energy released in the collapse will be always of the same order of magnitude, once the parameters of the model have been fixed. As shown in Table 2, the released energy is in the range $(3-5) \times 10^{52}$ ergs for all the sensible choices of the EOS parameters. The “critical mass” $M_{\text{cr}}$ of a metastable HS with a lifetime $\tau = 1$ yr is in the range $(0.9-1.4) M_\odot$. When the mass of the HS reaches a value near $M_{\text{cr}}$, the conversion process takes place. It is worth mentioning that the energy released in the conversion can be larger if a diquark condensate forms inside the QS (see, e.g., Hong, Hsu, & Sannino 2001).

To generate a strong GRB, an efficient mechanism to transfer the energy released in the collapse into an electron-photon plasma is needed. In an earlier work (Fryer

![Figure 1](https://example.com/figure1.png)

**Figure 1.**—Time needed to form a quark matter droplet as a function of the mass of the HS for five different values of $B^{1/4}$ (MeV). The hadronic phase has the GM3 parameters set with hyperons, the quark phase has $m_s = 150$ MeV, and a surface tension $\sigma = 50$ MeV/fm$^2$ is assumed.

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**Table 1**

| GRB      | Duration (s) | $E_{\text{iso}}/10^{51}$ ergs |
|----------|--------------|-------------------------------|
| 970508   | 20           | 7                             |
| 970828   | 160          | 270                           |
| 990705   | 42           | 210                           |
| 991216   | 20           | 500                           |
| 000214   | 10           | 9                             |
| 011211   | 270          | 50                            |

**Notes.**—Duration and energy released (assuming isotropy) of the GRB associated with the presence of emission or absorption Fe lines in the spectrum. The data have been extracted from Amati et al. 2002 and Bloom, Frail, & Sari 2001.

**Table 2**

| $B^{1/4}$ (MeV) | $\sigma$ (MeV fm$^{-2}$) | $M_{\text{cr}}/M_\odot$ | $\Delta E$ ($10^{51}$ ergs) |
|-----------------|--------------------------|--------------------------|----------------------------|
| 170             | 20                       | 1.25                     | 30.0                       |
| 170             | 30                       | 1.33                     | 33.5                       |
| 170             | 40                       | 1.39                     | 38.0                       |
| 165             | 30                       | 1.15                     | 38.6                       |
| 160             | 30                       | 0.91                     | 45.7                       |

**Notes.**—Critical mass $M_{\text{cr}}$ of the metastable hadronic star (in units of Solar mass $M_\odot$ = 1.989 $\times 10^{33}$ g) and energy released $\Delta E$ in the conversion to hybrid star assuming the hadronic star mean lifetime $\tau$ equal to 1 yr. Results are reported for various choices of the surface tension $\sigma$ and of the bag constant $B$. The strange quark mass is taken equal to 150 MeV. For the hadronic matter EOS the GM3 model with hyperons (Glendenning & Moszkowski 1991) has been used.
& Woosley 1998), it was this difficulty that hampered the possibility to connect GRBs and the hadronic-quark matter phase transition in compact stars. Only more recently it was noticed (Salmonson & Wilson 1999) that near the surface of a compact stellar object, due to general relativity effects, the efficiency of the neutrino-antineutrino annihilation into $e^+e^-$ pairs is strongly enhanced with respect to the Newtonian case. The efficiency of the conversion of neutrinos in $e^+e^-$ pairs could be as high as 10%. In the computation of the energy associated with the final GRB we must take into account the possibility of a moderate anisotropy of the electron motion, due to the presence of the magnetic field of the star, which will in turn generate a moderate anisotropy of the burst emission. Other anisotropies in the GRB emission could be generated by the rotation of the star, which could affect the efficiency of the neutrino-antineutrino annihilation due to general relativity effects. On the basis of these considerations, the energy deposited in the burst could be sufficient to explain the isotropic energy of the GRBs listed in Table 1. We must also recall that more efficient ways to generate photons and/or $e^+e^-$ pairs have been proposed in the literature, based on the decay of axion-like particles (Berezhiani & Drago 2000). This mechanism would have an extremely high efficiency and would transfer most of the energy produced in the collapse into GRB electromagnetic energy.

There are various specific signatures of the mechanism we are suggesting. First, two classes of stars having similar masses but rather different radii should exist: (a) pure (metastable) HS, with radii in the range 12–20 km, as is the case of the compact star 1E 1207.4-5209, assuming $M = 1.4 M_\odot$ (Sanwal et al. 2002), and (b) HyS or QS with radii in the range 6–8 km (Bombaci 1997; Li et al. 1999a, 1999b; Drake et al. 2002). Second, all the GRBs generated by the present mechanism should have approximately the same isotropic energy and a duration of at least 10 s.

4. CONCLUSIONS

We propose the following origin for at least some of the GRBs with a duration of tens of seconds. They can be associated with the transition from a metastable HS to a more compact HyS or a QS. The time delay between the supernova explosion originating the metastable HS and the GRB is regulated by the process of matter accretion on the HS. While most of the stellar objects obtained by an SN explosion will possibly have a mass larger than $M_\odot$ and will therefore directly stabilize as HyS or QS at the moment of the SN explosion, in a few cases the mass of the proto–neutron star will be low enough not to allow the immediate production of QM inside the star. Only when the star acquires enough mass can the process of QM formation take place. Due to the surface tension between the hadronic matter and the QM the star will become metastable. The later collapse into a stable HyS or QS will generate a powerful GRB. It can be interesting to notice that, in order not to have too small a value for $M_\odot$, a relatively large value for the bag constant $B$ has to be chosen, $B^{1/4} \approx 170$ MeV, which turns out to be the preferred value in many hadronic physics calculations (see, e.g., Steffens et al. 1995). In this situation the final state is an HyS and not a QS.

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6 Dramatic effects of a time-dependent magnetic field have been discussed, e.g., by Kluzniak & Ruderman (1998).

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