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CONVERSION OF NEUTRON STARS TO STRANGE STARS AS THE CENTRAL ENGINE OF GAMMA-RAY BURSTS

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ABSTRACT

We study the conversion of a neutron star to a strange star as a possible energy source for gamma-ray bursts. We use different recent models for the equation of state of neutron star matter and strange quark matter. We show that the total amount of energy liberated in the conversion is in the range of (1–4) × 10^{53} ergs (1 order of magnitude larger than previous estimates) and is in agreement with the energy required to power gamma-ray burst sources at cosmological distances.

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

1. INTRODUCTION

There is now compelling evidence to suggest that a substantial fraction of all gamma-ray bursts (GRBs) occur at cosmological distances (with a redshift $z \sim 1$–3). In particular, the measured redshifts of $z = 3.42$ for GRB 971214 (Kulkarni et al. 1998) and $z \sim 1.6$ for GRB 990123 (Kulkarni et al. 1999) imply energy releases of 3×10^{53} and 3.4×10^{54} ergs, respectively, in the gamma rays alone, assuming isotropic emission. The latter energy estimate could be reduced substantially if the energy emission is not isotropic but instead displays a jetlike geometry (Dar 1998; Kulkarni et al. 1999). Models in which the burst is produced by a narrow jet are able to help us explain the complex temporal structure observed in many GRBs (Sari & Piran 1997; Sari, Piran, & Halpern 1999). In any case, a cosmological origin for GRBs leads to the conclusion of a huge energy output. Depending on the degree of burst beaming and on the efficiency of gamma-ray production, the central engine powering these extraordinary events should be capable of releasing a total energy of a few times 10^{53} ergs.

Many cosmological models for GRBs have been proposed. Among the most popular is the merging of two neutron stars (or a neutron star and a black hole) in a binary system (Paczyński 1998). Recent results (Janka & Ruffert 1996) within this model indicate that, even under the most favorable conditions, the energy provided by $\nu\bar{\nu}$ annihilation during the merger is too small by at least an order of magnitude, and more probably 2 or 3 orders of magnitude, to power typical GRBs at cosmological distances. An alternative model is the so-called "failed supernova" (Woosley 1993) or "hypernova" model (Paczyński 1998).

In the present work, we consider the conversion of a neutron star to a strange star (hereafter the NS → SS conversion) as a possible central engine for GRBs. In particular, we focus on the energetics of the NS → SS conversion and not on the mechanism by which gamma rays are produced. A previous estimate of the total energy $E^{\rm conv}$ released in the NS → SS conversion (Olinto 1987; Cheng & Dai 1996) or in the conversion of a neutron star to a hybrid star (Ma & Xie 1996) gave $E^{\rm conv} \sim 10^{52}$ ergs, which is too low to power GRBs at cosmological distances. These calculations did not include the various details of the neutron star and strange star structural properties, which go into the binding-energy release considerations. Here we present accurate and systematic calculations of the total energy released in the NS → SS conversion using different models for the equation of state (EOS) of neutron star matter (NSM) and strange quark matter (SQM). We show that the total amount of energy liberated in the conversion is in the range $E^{\rm conv} = (1$–$4) \times 10^{53}$ ergs, in agreement with the energy required to power GRB sources at cosmological distances.

The existence of strange stars (made up of degenerate u, d, and s quarks in equilibrium with respect to the weak interactions) is allowable within uncertainties inherent in our present theoretical understanding of the physics of strongly interacting matter (Bodmer 1971; Witten 1984; Farhi & Jaffe 1984). Thus, strange stars may exist in the universe, but until now, these have remained purely speculative entities. This situation changed in the last few years, thanks to the large amount of new observational data collected by the new generation of X-ray satellites. In fact, recent studies have shown that the compact objects associated with the X-ray bursters GRO J1744−28 (Cheng et al. 1998) and SAX J1808.4−3658 (Li et al. 1999a) and with the X-ray pulsar Hercules X-1 (Dey et al. 1998) are good strange star candidates. Recently, Li et al. (1999b) have shown that the observed high- and low-frequency quasi-periodic oscillations (QPOs) in the atoll source 4U 1728−34 (Méndez & van der Klis 1999) are more consistent with a strange star compared with a neutron star, if the model of Osherovich & Titarchuk (1999a, 1999b) correctly interprets the QPO phenomena.

Originally, the idea that GRBs could be powered by the conversion of a neutron star to a strange star was proposed by Alcock, Farhi, & Olinto (1986; see also Olinto 1987) and was recently reconsidered by other authors (Cheng & Dai 1996). A similar model has been discussed by Ma & Xie (1996) for the conversion of a neutron star to a so-called hybrid star (a neutron star with a SQM core).

A number of different mechanisms have been proposed for the NS → SS conversion. All of them are based on the formation of a "seed" of SQM inside the neutron star. For example, (1) a seed of SQM enters in an NS and converts it to an SS (Olinto 1987). These seeds of SQM, according to Witten (1984), are relics of the primordial quark-hadron phase transition microseconds after the big bang. (2) A seed of SQM forms in the core of a neutron star as a result of a phase transition from neutron star matter to deconfined strange quark matter (the NSM → SQM phase transition). This could possibly happen when an NS is a member of a binary stellar system. The NS accretes matter from the companion star. The central density of the NS increases, and it may overcome the critical

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density for the NSM → SQM phase transition. The NS is then converted to an SS. In the case of an accretion-induced conversion in a binary stellar system, the conversion rate has been estimated (Cheng & Dai 1996) to be in the range of (3–30) × 10^{-10} conversions per day per galaxy. This rate is consistent with the observed GRB rate.

However, once there is a seed of SQM inside a neutron star, it is possible to calculate the rate of growth (Olinto 1987; Horvath & Benvenuto 1988). The SQM front absorbs neutrons, protons, and hyperons (if present), liberating their constituent quarks. Weak equilibrium is then reestablished by the weak interactions. As shown by Horvath & Benvenuto (1988), the conversion of the whole star will then occur in a very short time (the detonation mode), in the range of 1 ms–1 s, which is in agreement with the typical observed duration of GRBs. A detailed simulation of the conversion process is still lacking, and only rough estimates of the total energy liberated in the conversion have been made.

As we show below, the dominant contribution to $E^{\rm conv}$ arises from the internal energy released in the conversion, i.e., in the NSM → SQM phase transition. Moreover, the gravitational mass of the star will change during the conversion process, even under the assumption that the total number of baryons in the star is conserved.

The total energy released in the NS → SS conversion is given by the difference between the total binding energy of the strange star BE(SS) and the total binding energy of the neutron star BE(NS):

$$E^{\rm conv} = {\rm BE(SS)} - {\rm BE(NS)}. \tag{1}$$

In the present work, we assume that the baryonic mass M_B of the compact object is conserved in the conversion process; i.e., $M_B({\rm SS}) = M_B({\rm NS}) \equiv M_B$. Then $E^{\rm conv}$ is given in terms of the difference between the gravitational mass of the NS and SS: $E^{\rm conv} = [M_G({\rm NS}) - M_G({\rm SS})]c^2$.

In general, the total binding energy for a compact object can be written as ${\rm BE} = {\rm BE}_I + {\rm BE}_G = (M_B - M_P)c^2 + (M_P - M_G)c^2$, where ${\rm BE}_I$ and ${\rm BE}_G$ denote the internal and gravitational binding energies, respectively, and M_P is the proper mass of the compact object defined as

$$M_P = \int_0^R dr\, 4\pi r^2 \left[1 - \frac{2Gm(r)}{c^2 r}\right]^{-1/2} \rho(r), \tag{2}$$

where $\rho(r)$ is the total mass-energy density and $m(r)$ is the gravitational mass enclosed within a spherical volume of radius r. The proper mass is equal to the sum of the mass elements on the whole volume of the star; it includes the contributions of rest mass and internal energy (kinetic and interactive [other than gravitational]) of the constituents of the star.

The total conversion energy can then be written as the sum of two contributions

$$E^{\rm conv} = E_I^{\rm conv} + E_G^{\rm conv} \tag{3}$$

related to the internal and gravitational energy changes in the conversion. These two contributions can be written as

$$E_I^{\rm conv} = {\rm BE}_I({\rm SS}) - {\rm BE}_I({\rm NS}) = [M_P({\rm NS}) - M_P({\rm SS})]c^2, \tag{4}$$

$$E_G^{\rm conv} = {\rm BE}_G({\rm SS}) - {\rm BE}_G({\rm NS}) = [M_P({\rm SS}) - M_G({\rm SS}) - M_P({\rm NS}) + M_G({\rm NS})]c^2, \tag{5}$$

and these can be evaluated by solving the structural equations for nonrotating compact objects (Oppenheimer & Volkoff 1939). To highlight the dependence of $E^{\rm conv}$ on the present uncertainties in the microphysics, we employed different models for the EOS of both NSM and SQM.

Recently, a microscopic EOS of dense stellar matter has been calculated by Baldo, Bombaci, & Burgio (1997) and used to compute the structure of static (Baldo et al. 1997) as well as rapidly rotating neutron stars (Datta, Thampan, & Bombaci 1998). In this model for the EOS, the NS core is composed of asymmetric nuclear matter in equilibrium, with respect to the weak interactions, with electrons and muons (β-stable matter). In particular, we consider their EOS based on the Argonne $v14$ nucleon-nucleon interaction implemented by nuclear three-body forces (hereafter BBB1 EOS).

At the high densities expected in the core of a neutron star, additional baryonic states besides the neutron and the proton may be present, including the hyperons Λ, Σ, Ξ, and Ω and the isospin 3/2 nucleon resonance Δ. The EOS of this hyperonic matter is traditionally investigated in the framework of Lagrangian field theory in the mean field approximation (Glendenning 1985; Schaffner & Mishustin 1996; Prakash et al. 1997). According to this model, the onset for hyperon formation in β-stable–charged neutral dense matter is about 2–3 times the normal nuclear matter density ($n_0 = 0.17$ fm^{-3}). The latter result has been confirmed by recent microscopic calculations based on the Brueckner-Hartree-Fock theory (Baldo, Burgio, & Schulze 1998). The appearance of hyperons, in general, gives a softening of the EOS with respect to the pure nucleonic case. In the present work, we considered one of the EOSs for hyperonic matter given in Prakash et al. (1997).

For SQM, we consider a simple EOS (Farhi & Jaffe 1984) based on the MIT bag model for hadrons. We begin with the case of massless noninteracting ($\alpha_c = 0$) quarks and with a bag constant $B = 60$ MeV fm^{-3}: we denote the corresponding EOS as $B60_0$. Next we consider a finite value for the mass of the strange quark within the same MIT bag model EOS. We take $m_{\rm s} = 200$ MeV (and $m_{\rm u} = m_{\rm d} = 0$, $B = 60$ MeV fm^{-3}, and $\alpha_c = 0$; hereafter EOS $B60_{200}$). To investigate the effect of the bag constant on the energy released in the NS → SS conversion, we take (almost) the largest possible value of B for which SQM is still the ground state of strongly interacting matter, according to the so-called *strange matter hypothesis* (Witten 1984). For massless noninteracting quarks, this gives $B = 90$ MeV fm^{-3}; we denote the corresponding EOS as $B90_0$.

Recently, Dey et al. (1998) derived an EOS for SQM using a different quark model with respect to the MIT bag model. The EOS by Dey et al. has asymptotic freedom built in, shows confinement at zero baryon density, deconfinement at high density, and, for an appropriate choice of the EOS parameters entering in the model, gives absolutely stable SQM according to the strange matter hypothesis. In this model, the quark interaction is described by a screened interquark vector potential

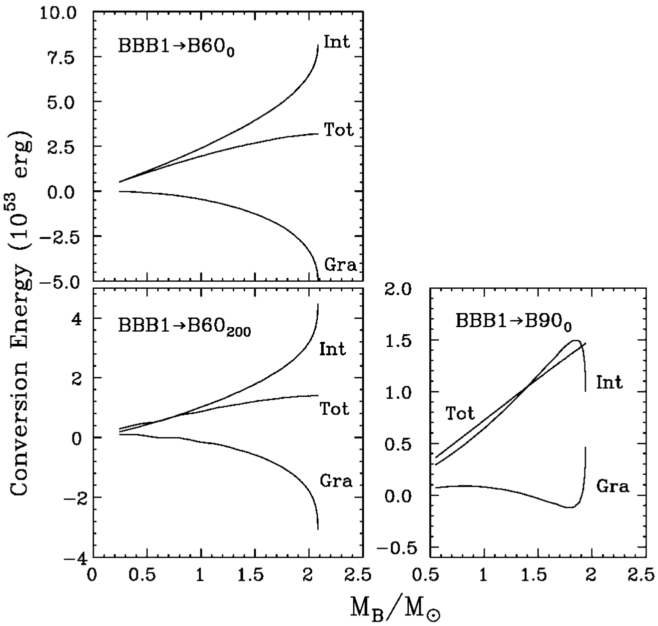

FIG. 1.—The total energy liberated in the conversion of a neutron star to a strange star and the partial contributions from internal energy E_I^{conv} (curves labeled "Int") and from gravitational energy E_G^{conv} (curves labeled "Gra") as a function of M_B. See text for details on the equations of state for NSM and SQM.

originating from gluon exchange and by a density-dependent scalar potential that restores the chiral symmetry at high density. The density-dependent scalar potential arises from the density dependence of the in-medium effective quark masses M_q, which, in the model by Dey et al. (1998), are taken to depend on the baryon number density n_B according to $M_q = m_q +$ 310 MeV × sech $(\nu n_B/n_0)$, where n_0 is the normal nuclear matter density, q(=u, d, s) is the flavor index, and ν is a parameter. The effective quark mass $M_q(n_B)$ goes from its constituent masses at zero density to its current mass m_q as n_B goes to infinity. Here we consider two different parameterizations of the EOS by Dey et al. that correspond to a different choice for the parameter ν. The equation of state SS1 (SS2) corresponds to $\nu = 0.333$ ($\nu = 0.286$).

2. RESULTS AND CONCLUSIONS

To begin with, we fix as a "standard" EOS for neutron star matter the BBB1 EOS (Baldo et al. 1997), in order to explore how the energy budget in the NS → SS conversion depends on the details of the EOS for strange quark matter. First we consider the $B60_0$ equation of state. The NS → SS conversion based on this couple of EOSs will be referred to as the BBB1 → $B60_0$ conversion model. Similar notation will be employed according to the EOS of NSM and SQM. The total conversion energy, together with the partial contributions, is shown in the upper panel of Figure 1. As we can see, for M_B larger than ~1 $M_\odot$ (i.e., values of the baryonic mass compatible with the measured NS gravitational masses), the total energy released in the NS → SS conversion is in the range of (1–3) × 10^{53} ergs, which is 1 order of magnitude larger than previous estimates (Olinto 1987; Cheng & Dai 1996; Ma & Xie 1996). Moreover, contrary to a common expectation, the gravitational conversion energy E_G^{conv} is negative for this couple of EOSs. To make a more quantitative analysis, we consider a neutron star with a baryonic mass $M_B = 1.574\ M_\odot$ (see Table 1), which

TABLE 1

CONVERSION TO STRANGE STAR OF A NEUTRON STAR WITH $M_G \sim 1.4\ M_\odot$ FOR DIFFERENT EOSS FOR NSM AND SQM

NSM → SQM	M_B	M_G(NS)	M_G(SS)	E_G^{conv}	E_I^{conv}	E^{conv}
BBB1 → $B60_0$	1.574	1.409	1.254	−1.436	4.215	2.779
BBB1 → $B60_{200}$	1.574	1.409	1.340	−0.677	1.920	1.243
BBB1 → $B90_0$	1.573	1.409	1.343	−0.057	1.241	1.184
BBB1 → SS1	1.558	1.397	1.235	0.580	2.308	2.888
BBB1 → SS2	1.566	1.403	1.268	1.604	0.800	2.404
Hyp → $B60_0$	1.530	1.401	1.223	−0.617	3.802	3.185
Hyp → SS1	1.530	1.401	1.217	1.291	2.002	3.293

NOTE.—M_B is the baryonic mass (which is conserved in the conversion process), M_G(NS) is the neutron star gravitational mass, and M_G(SS) is the gravitational mass of the corresponding strange star. All masses are in the unit of the solar mass $M_\odot$ = 1.989 × 10^{33} g. E_G^{conv}, E_I^{conv}, and E^{conv} are, respectively, the gravitational, internal, and total conversion energy (× 10^{53} ergs).

has a gravitational mass $M_G = 1.409\ M_\odot$, a radius R(NS) = 11.0 km, and a gravitational binding energy BE$_G$(NS) = 4.497 × 10^{53} ergs. After conversion, the corresponding strange star has $M_G = 1.254\ M_\odot$, R(SS) = 10.5 km, and BE$_G$(SS) = 3.061 × 10^{53} ergs. The NS → SS conversion is energetically possible in this case, thanks to the large amount of (internal) energy liberated in the NSM → SQM phase transition.

Similar qualitative results for the total conversion energy are obtained for other choices of the two EOSs, but as we show below the magnitude of the two partial contributions are strongly dependent on the underlying EOS for NSM and SQM. The total conversion energy for the BBB1 → $B60_{200}$ model is plotted in the lower left-hand panel of Figure 1. Comparing with the previous case, we notice that the strange quark mass produces a large modification of the conversion energy, which is reduced by a factor of between 2 and 3 with respect to the $m_s = 0$ case. The bag constant B also has a sizable influence on the conversion energy. Increasing the value of B reduces E^{conv} and strongly modifies E_G^{conv}. This can be seen by comparing the results for the BBB1 → $B60_0$ conversion model with those in the lower right-hand panel of Figure 1 for the BBB1 → $B90_0$ model. These results are a consequence of the sizable effects of the strange quark mass and of the bag constant mainly on the internal binding energy BE$_I$(SS) for strange stars (see, e.g., Bombaci 1999). In fact, all strange star configurations within the $B60_0$ EOS are self-bound objects [i.e., BE$_I$(SS) > 0]. Strange star configurations within the $B90_0$ ($B60_{200}$) EOS are self-bound objects up to $M_G \sim 0.8\ M_\odot$ ($M_G \sim 1.6\ M_\odot$), compared with the corresponding maximum gravitational mass $M_{max} = 1.60\ M_\odot$ ($M_{max} = 1.75\ M_\odot$).

The results depicted in the two upper panels of Figure 2 have been obtained using the EOS of Dey et al. (1998) for SQM, for two different choices of the parameter ν that controls the rate at which chiral symmetry is restored to the quark masses at high density. For $\nu = 0.286$ (SS2), chiral symmetry is broken up to larger densities with respect to the case of $\nu = 0.333$ (SS1). The parameter ν has a strong influence on the internal binding energy of the strange star. In fact, we found that strange stars within the SS2 (SS1) EOS are self-bound objects up to $M_G \sim 0.7\ M_\odot$ ($M_G \sim 1.4\ M_\odot$), compared with the maximum gravitational mass $M_{max} = 1.33\ M_\odot$ (M_{max} = 1.44 $M_\odot$). This effect is the main source for the differences in the calculated conversion energies for the two conversion models BBB1 → SS1 and BBB1 → SS2.

The next step in our study is to consider a different neutron star matter EOS, which allows for the presence of hyperons in the neutron star core. We consider one of the EOSs (hereafter Hyp) for hyperonic matter given in Prakash et al. (1997). In

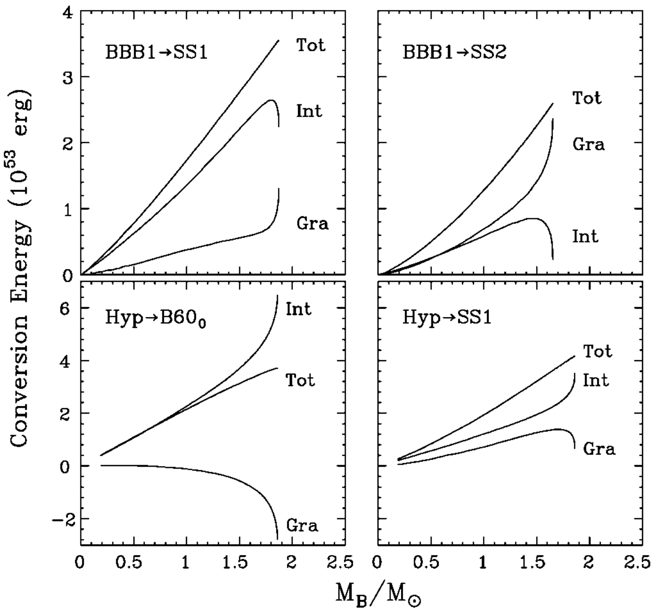

FIG. 2.—Same as in Fig. 1, but for different conversion models

the two lower panels of Figure 2, we plot the total conversion energy, together with the partial contributions, for the Hyp → $B60_0$ and for the Hyp → SS1 conversion models. These results are in qualitative agreement with those reported in the previous figures.

In Table 1, we report the conversion energy together with the partial contributions for the conversion of a neutron star with a gravitational mass M_G(NS) ~ 1.4 $M_\odot$ and for various conversion models. In the present work, we considered the conversion of a neutron star to a strange star as a possible energy source for gamma-ray bursts. Our main focus was to perform an accurate calculation of the total released energy compatible with our current understanding of the microphysics of strong interacting matter. We show that the total amount of energy liberated in the NS → SS conversion is in the range of (1–4) × 10^{53} ergs (1 order of magnitude larger than previous estimates) and is in agreement with the energy required to power GRB sources at cosmological distances.

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