Accretion-Induced Conversion of High-Velocity Neutron Stars to Strange Stars in Supernovae and Implications for Gamma-Ray Bursts

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**ABSTRACT**

We present a new model for gamma-ray bursts (GRBs) that are not only associated with supernovae but also have small baryon contamination. In this model, we assume a newborn neutron star to move outward at a kick velocity of $\sim 10^3\text{ km s}^{-1}$ in the supernova ejecta. We find that such a neutron star still hypercritically accretes its surrounding supernova matter. Once the stellar mass increases to some critical mass, the neutron star will undergo a phase transition to become a strange star, leading to an energy release of a few $10^{52}$ ergs. The phase transition, if possibly occurring just near the supernova front, will first result in an ultra-relativistic fireball and then a GRB. This provides a plausible explanation for the GRB-supernova association. We estimate the burst rate to be $\sim 10^{-6}$ per year per galaxy. Our model also predicts other possibilities. For example, if the resulting fireballs have a Lorentz factor of the order of a few, they will produce X-ray GRBs observed by BeppoSAX. We find the rate of such bursts to be $\sim 10^{-5}$ per year per galaxy.

*Subject headings:* gamma-rays: bursts — stars: neutron — supernovae: general

1. Introduction

Gamma-ray bursts (GRBs) emit an amount of isotropic-equivalent energy $E_{\text{iso}} \geq 10^{52}$ ergs in $\gamma$-rays and X-rays in a few seconds and subsequently emit afterglows at X-ray (Costa et al. 1997), optical (van Paradijs et al. 1997) and radio bands (Frail et al. 1997), which generally last days to months (van Paradijs, Kouveliotou & Wijers 2000). The energetics of GRBs, which is comparable to that of supernovae, and their rapid variability strongly suggest compact objects involving black holes, neutron stars and strange stars as the energy source for GRBs. Two popular models satisfying this energetics are explosive events of very massive stars, also named hypernovae (Paczyński 1998) or collapsars (Woosley 1993; MacFadyen & Woosley 1999), and mergers of neutron-star binaries (Eichler et al. 1989; Narayan, Paczyński & Piran 1992). Other possible models include phase transitions of neutron stars to strange stars (Cheng & Dai 1996; Dai & Lu 1998a; Bombaci & Datta 2000; Wang et al. 2000), births of magnetars (Usov 1992; Kluźniak &
There has been considerable evidence linking the progenitors of GRBs with massive stars. First, the sources of GRBs with known redshifts lie within the optical radii and central regions of the host galaxies rather than far outside the disks of the galaxies (Bloom, Kulkarni & Djorgovski 2001), which seem to rule out mergers of neutron-star binaries as the GRB central engine. Second, the brightness distribution of GRBs is in agreement with the models in which the GRB rate tracks the star formation rate over the past 15 billion years of cosmic history (Totani 1997; Wijers et al. 1998; Kommers et al. 2000). Third, the supernova SN1998bw with an unusual brightness was discovered in the error box of GRB 980425 (Galama et al. 1998) and a supernova-like component was detected in the afterglows from GRB 980326 (Bloom et al. 1999) and GRB 970228 (Reichart 1999; Galama et al. 2000b). These detections provide the most direct evidence for the relation between GRBs and a specific type of supernova. Finally, the recent discovery of a transient absorption edge in the X-ray spectrum of GRB 990705 (Amati et al. 2000) and the observations of X-ray lines from GRB 991216 (Piro et al. 2000) and GRB 000214 (Antonelli et al. 2000) provide new evidence that GRBs are related to the core collapse of massive stars. Therefore, it has been widely believed that long duration GRBs arise from the explosions of massive stars.

However, it seems theoretically difficult to understand the association of GRBs with supernovae. This is because the rapid variability of GRBs and their nonthermal spectra (Woods & Loeb 1995) requires that the Lorentz factor of a GRB fireball be $\Gamma \geq 100$. This conclusion was also recently drawn by Lithwick & Sari (2001), who derived the lower limits on $\Gamma$ due to annihilation of photons and scattering of photons by pair-created electrons and positrons. Thus, the mass of the baryons contaminating the fireball must be less than $M_0 \sim 10^{-5} M_\odot (\Gamma/500)^{-1} (E_{\text{iso}}/10^{52}\text{ergs})$. On the other hand, too many baryons in the stellar envelope exist in the vicinity of the collapsing core in a massive star so that an ultrarelativistic fireball or jet forming during the collapse of the core is easy to become non-relativistic and then a bubble due to sideways expansion of the jet. A choked fireball (or jet) has been found numerically by MacFadyen & Woosley (1999).

Here we propose a scenario for the formation of GRBs when a newborn neutron star accretes sufficient mass to undergo a phase transition to a strange star. Cheng & Dai (1996), Dai & Lu (1998a), Bombaci & Datta (2000), and Wang et al. (2000) have proposed the conversion from neutron stars to strange stars as a cosmological origin of GRBs, but have not investigated the association of GRBs with supernovae, the burst rate, and other interesting implications, e.g., X-ray GRBs. The purpose of this paper is to discuss these questions. We assume the neutron star to move outward at an initial kick velocity of $\sim 10^3 \text{km s}^{-1}$ in the supernova ejecta. In section 2, we analyze and calculate hypercritically accreted mass. In section 3, we discuss implications for GRBs. In order to produce a GRB, the phase transition is required to occur near the supernova front. We estimate the burst rate to be $\sim 10^{-6}$ per year per galaxy. Our model explains the GRB-supernova connection. In section 4, we discuss other implications of the model.
2. Accretion of High-Velocity Neutron Stars in Supernovae

It is known that the core collapse of massive stars with $10 - 25M_\odot$ produces Type II supernovae accompanying neutron stars whose initial mass is likely near the Chandrasekhar limit $\sim 1.4M_\odot$. The neutron stars are believed to have proper velocities. Gunn & Ostriker (1970) first recognized that Galactic pulsars have much larger random velocities than their progenitor massive stars. Modern observations and analysis on the proper motion of pulsars even give $\sim 450\text{ km s}^{-1}$ as an average 3-dimension velocity of neutron stars at birth (e.g., Lyne & Lorimer 1994; Lorimer et al. 1997; Hansen & Phinney 1997; Cordes & Chernoff 1998), with possibly a significant population having velocities greater than $1000\text{ km s}^{-1}$. Direct evidence for pulsar velocities $\geq 1000\text{ km s}^{-1}$ is provided by observations of the bow shock produced by PSR B2224 + 65 in the interstellar medium (Cordes, Romani & Lundgren 1993). The studies of the associations of neutron stars with supernova remnants have, in many cases, indicate large velocities (e.g., Frail et al. 1994).

In particular, the associations of soft gamma-ray repeaters (SGRs) with supernova remnants imply that SGR 0526 — 66 and SGR 1900 + 14 have velocities of $\sim 2900(3\text{ kyr}/t_{\text{SNR}})\text{ km s}^{-1}$ and $\sim 1800(10\text{ kyr}/t_{\text{SNR}})\text{ km s}^{-1}$ respectively where $t_{\text{SNR}}$ is the supernova remnant age, although the associations seem problematic. Since many isolated pulsars have such large proper velocities, it appears necessary to invoke “natal kicks” imparted to newborn neutron stars due to asymmetrical processes during supernovae. Several mechanisms have been suggested for natal kicks: local hydrodynamical instabilities, neutrino - magnetic field driven asymmetry, local high-order gravity mode instabilities, and electromagnetic radiation of an off-centered rotating magnetic dipole (for a recent review see Lai 2000). Owing to these mechanisms, we assume a newborn neutron star to have an initial kick velocity of $v_{\text{ns}} \sim 10^3\text{ km s}^{-1}$.

The supernova explosion scenarios involve an outgoing shock wave that initially travels with speed of $\sim 10^4\text{ km s}^{-1}$. However, when the initial outgoing shock wave enters hydrogen envelope, a deceleration of matter is formed (Woosely 1988). This deceleration sharpens into a reverse shock. As a result, the final velocity of the supernova ejecta may be slowed down to $v_{\text{sn}} \sim 10^3\text{ km s}^{-1}$.

For simplicity, we assume that, since this time, the expanding supernova ejecta is spherical, its mass $M_{\text{ej}} \sim 10M_\odot$ is constant with time, its density $\rho$ is uniform in space and decreases with time, and the supernova front radius $R$ increases at the fixed velocity of $v_{\text{sn}}$. Therefore, the density throughout is given by

$$\rho = \frac{3M_{\text{ej}}}{4\pi R^3} = 4.8(R_{0,11} + v_{\text{sn},8}t_3)^{-3} \text{ g cm}^{-3},$$

where $v_{\text{sn},8} = v_{\text{sn}}/10^8\text{ cm s}^{-1}$, $R_0 = R_{0,11} \times 10^{11}\text{ cm}$ is the initial radius of the ejecta, and $t_3$ is the time after the explosion in units of $10^3\text{ s}$. Since the ejecta is radiation dominated, its temperature $T$ scales as $\propto R^{-3/4}$. From this scaling law, we have $T = 6.5 \times 10^7(R_{0,11} + v_{\text{sn},8}t_3)^{-3/4}\text{ K}$ (Brown & Weingartner 1994), and the sound speed of the ejecta

$$c_s = \left(\frac{5kT}{12n_{\text{HH}}}\right)^{1/2} = 0.47 \times 10^8(R_{0,11} + v_{\text{sn},8}t_3)^{-3/8}\text{ cm s}^{-1}.$$  

The initial outgoing supernova shock may produce a hole with radius of $R_{\text{in}} \sim 2 \times 10^4\text{ km}$.
(Bethe 1993). So, no matter is accreted by the neutron star in a time of $t_0 \equiv R_{\text{in}}/v_{\text{ns}} = 20R_{\text{in},s}v_{\text{ns},s}^{-1}$ s where $R_{\text{in},s} = R_{\text{in}}/(2 \times 10^4 \text{km})$. Subsequently, the neutron star will enter the supernova ejecta. We want to calculate the accretion rate as follows. If the effect of the neutron star magnetic field is neglected (in fact, an initial strong magnetic field can rapidly decay due to hypercritical accretion, cf. Geppert, Page & Zannias 1999), the accretion rate of the neutron star at radius $r \equiv v_{\text{ns}}t$ is given by the Bondi-Hoyle accretion formula,

$$\dot{M} = \frac{\rho R_s^2 c^4}{v_{\text{tot}}^2} \equiv \frac{\rho R_s^2 c^4}{\left(\left|v_{\text{ns}} - v_{\text{sn}}(r,t)\right|^2 + c_s^2\right)^{3/2}},$$

(3)

where $R_s = 2GM_{\text{ns}}/c^2$ is the Schwarzschild radius of the neutron star with $M_{\text{ns}} \sim 1.4M_\odot$, and $v_{\text{sn}}(r,t) = v_{\text{sn}}r/(R_0 + v_{\text{sn}}t) = v_{\text{sn}}v_{\text{ns}}t/(R_0 + v_{\text{sn}}t)$ is the velocity of the supernova matter (not front) at radius $r$ (Chevalier 1989). Here we have defined $v_{\text{tot}} \equiv \left\{\left|v_{\text{ns}} - v_{\text{sn}}(r,t)\right|^2 + c_s^2\right\}^{1/2}$. We first estimate the accreted mass. To do this, $v_{\text{tot}}$ is assumed to be approximately constant. Thus, at early times $t_0 \ll t \ll 10^3(R_{0,11}/v_{\text{sn}},s)\text{ s}$, the accretion rate is approximated by

$$\dot{M} \sim 3.2 \times 10^{-4}(M_{\text{ns}}/1.4M_\odot)^2R_{0,11}^{-3}v_{\text{tot},8}^{-3} M_\odot \text{ s}^{-1};$$

(4)

at late times $t \gg 10^3(R_{0,11}/v_{\text{sn}},s)\text{ s}$, the accretion rate becomes

$$\dot{M} \sim 3.2 \times 10^{-4}(M_{\text{ns}}/1.4M_\odot)^2v_{\text{tot},8}^{-3}t^{-3} M_\odot \text{ s}^{-1}.$$  

(5)

This accretion rate is at least ten orders of magnitude larger than the Eddington accretion rate for a solar-mass star. The gravitational energy released during such a hypercritical accretion is carried away by neutrinos. It is neutrino emission that allows accretion of the star at a much higher rate than the Eddington rate. From simple analytical arguments, Chevalier (1989) and Brown & Weingartner (1994) estimated a lower limit to steady neutron star accretion with neutrino losses assuming spherical symmetry: $\dot{M}_c \sim 2 \times 10^{-5}M_\odot \text{ yr}^{-1}$. Our estimated accretion rate exceeds $\dot{M}_c$ for $t \leq 10^6 \text{ s}$. We estimate the accreted mass

$$\Delta M_{\text{acc}} = \int_{t_0}^{t} \dot{M} dt = \int_{t_0/10^6}^{t_3} \frac{0.32M_\odot(M_{\text{ns}}/1.4M_\odot)^2}{(R_{0,11} + v_{\text{sn}},st_3)^3v_{\text{tot},8}} dt_3$$

$$\sim 0.32M_\odot(M_{\text{ns}}/1.4M_\odot)^2v_{\text{tot},8}^{-3}(0.5 + R_{0,11}^{-3} - 0.5t_3^{-2}),$$

(6)

(7)

where equation (7) is obtained by substituting equations (4) and (5) into (6). Next, we numerically calculate equation (6). Figure 1 presents the accreted mass as a function of time. It can be seen from this figure that the neutron star will be able to accrete considerable matter (with mass of $\geq 0.5M_\odot$) before its conversion to a strange star.

3. Conversion of Accreting Neutron Stars to Strange Stars and Gamma-Ray Bursts

Since conversion of neutron stars to strange stars was suggested as a possible origin of cosmological GRBs by Cheng & Dai (1996), resulting rotating strange stars with strong magnetic
fields have been proposed to explain the observed features of some GRB afterglows by some authors (Dai & Lu 1998a, 1998b, 2000, 2001; Zhang & Mészáros 2001). Bodmer (1971) and Witten (1984) conjectured that strange quark matter may be the true ground state of hadrons. Detailed calculations based on the zero-temperature thermodynamics of strange matter show that strange matter is indeed more stable than $^{56}$Fe for a wide range of the parameters of the MIT bag model (Farhi & Jaffe 1984). If this hypothesis is true, strange stars as a kind of compact object may exist in the Universe. How are strange stars produced? One natural way is direct collapse of the core of a massive star to a strange star. If this way is possible, a binary including a strange star and a more massive compact object imaginably exists. During the coalescence of such a binary, the strange star is disrupted by its companion. As a result, the entire galaxy can be contaminated and all “neutron stars” become strange stars (Madsen 1988; Caldwell & Friedman 1991; Kluźniak 1994), which is referred to as the Madsen-Caldwell-Friedman (MCF) effect. This effect conflicts with the post-glitch behavior of pulsars, which is well described by the neutron-superfluid vortex creep theory, and current strange star models cannot explain the observed pulsar glitches (Alpar 1987; Alpar, Pines & Cheng 1990). Another way to produce strange stars is that a neutron star in a low-mass X-ray binary accretes sufficient mass to undergo a phase transition to a strange star (Cheng & Dai 1996). This way can avoid the MCF effect. In this paper, we propose a third way to produce strange stars, i.e., a newborn “unbound” neutron star with a kick velocity of $\sim 10^3$ m s$^{-1}$ will catch up with the outgoing supernova ejecta and will accrete considerable matter so that the neutron star can convert to a strange star (see section 2). If such a rapidly moving neutron star arises from the supernova explosion of a massive star in a binary, the neutron star must be able to escape from the binary system because of its too large kick velocity, and thus the resulting strange star will have no companion. If a newborn neutron star does not have an enough large proper velocity to catch up with the supernova ejecta, the star may accrete only a mass of $\sim 0.1M_\odot$ (Chevalier 1989) so that it cannot undergo a phase transition to become a strange star. Therefore, the third way can also avoid the MCF effect. Cheng & Dai (1998, 2001) have argued that such a strange star, if it has a strong magnetic field and a superconducting core, may produce soft gamma-ray repeaters in an age of $\sim 10^4$ yrs. Here we discuss its implications for GRBs.

The conversion of a neutron star to a strange star requires the formation of a strange matter seed, which is produced through the deconfinement of neutron matter at a density of $(7 - 9)\rho_0$ (where $\rho_0$ is the saturation nuclear matter density) (Baym 1991), much larger than the central density of a $1.4M_\odot$ neutron star with a moderately stiff to stiff equation of state (as implied by some astrophysical processes, cf. Dai & Lu 1998a). To reach the deconfinement density, Cheng & Dai (1996) suggested, a $1.4M_\odot$ neutron star with a moderately stiff to stiff equation of state should accrete matter with mass of $\Delta M_{\text{acc}} \geq 0.5M_\odot$ before its phase transition to a strange star. Once the accreted mass is $\Delta M_{\text{acc}}$, a strange matter seed may appear in the core of the neutron star, and subsequently the strange matter will begin to swallow its surrounding neutron matter in a hydrodynamically unstable mode (detonation). Thus, the neutron star will convert to a strange star in a timescale of the order of 0.1 ms. The phase transition includes two processes: (1) the neutron matter converts to two-flavor quark matter, and (2) the two-flavor quark matter
converts to strange (three-flavor) quark matter. The latter process can release the energy per baryon of a few tens of MeV in a timescale of \( \sim 10^{-7} \) s (Dai et al. 1995). Owing to this process, the resulting strange star will be as hot as a few \( 10^{11} \) K. How is the energy release due to the phase transition deposited? One mechanism for the energy deposition is the neutrino-antineutrino annihilation process \( \nu + \bar{\nu} \rightarrow e^- + e^+ \) and the neutrino absorption processes \( \nu_e + n \rightarrow p + e^- \) and \( \bar{\nu}_e + p \rightarrow n + e^+ \) (in the crust). Another mechanism is the creation of electron/positron pairs in an extremely strong electric field at the quark surface (Usov 1998, 2001). The total energy deposition for these two mechanisms, \( E \), is a few \( 10^{52} \) ergs, which will inevitably lead to a fireball composed of \( \gamma \) and electron/positron pairs polluted by a small number of baryons. The contaminating baryon mass is up to the crustal mass of the strange star, \( \sim M_0 \sim 10^{-5} M_{\odot} \). Therefore, the resulting fireball should be accelerated to an ultra-relativistic phase with Lorentz factor of \( \Gamma \geq E/M_0 \sim 500(E/10^{52} \text{ergs})(M_0/10^{-5} M_{\odot})^{-1} \).

The newborn strange star is surrounded by the supernova ejecta matter. If the SN ejecta mass in the solid angle of \( \sim 2\pi \) between the star and the SN front, \( \Delta M_{\text{ej}} \), greatly exceeds \( M_0 \), the resulting fireball cannot still be accelerated to ultra-relativistic. An ultra-relativistic fireball also requires \( \Delta M_{\text{ej}} \leq M_0 \sim 10^{-5} M_{\odot} \). We assume that \( \Delta R \) is the minimum distance of the initial site of the strange star to the supernova front. Assuming \( \Delta R \ll R \), we estimate the ratio of \( \Delta M_{\text{ej}} \) to the total SN ejecta mass \( M_{\text{ej}} \):

\[
\frac{\Delta M_{\text{ej}}}{M_{\text{ej}}} \sim \frac{\pi (\Delta R)^2 R \rho}{\pi R^3 \rho} = \left( \frac{\Delta R}{R} \right)^2.
\]

Since \( \Delta M_{\text{ej}}/M_{\text{ej}} \leq 10^{-6} \), we have

\[
\frac{\Delta R}{R} \leq 10^{-3},
\]

which further requires

\[
\delta_v \equiv \frac{v_{ns} - v_{sn}}{v_{sn}} \leq 10^{-3}.
\]

Because the number of the neutron stars with \( v_{ns} \geq 10^8 \) cm s\(^{-1} \) is \( N_{ns}(v_{ns} \geq 10^8 \) cm s\(^{-1} \) \( \sim 10^7 \) per galaxy in the Hubble time (Lorimer et al. 1997), the number of the strange stars that can produce GRBs are estimated to be \( N_{ss\rightarrow GRB} \sim \delta_v \times N_{ns}(v_{ns} \geq 10^8 \) cm s\(^{-1} \) \( \sim 10^4 \) per galaxy in the Hubble time, where we have assumed that the number distribution of the neutron stars is uniform in the velocity space for \( v_{ns} \geq 10^8 \) cm s\(^{-1} \). The burst rate in our model is approximated by

\[
\mathcal{R} \sim \frac{N_{ss\rightarrow GRB}}{t_{\text{Hubble}}} \sim 10^{-6} \text{ yr}^{-1} \text{ per galaxy}.
\]

This rate is enough to explain the observed GRB rate, \( 10^{-7} /\text{yr/galaxy} \). The latter rate has been estimated due to the evidence that the GRB rate is proportional to the star formation rate (Totani 1997; Wijers et al. 1998; Kommers et al. 2000).

Since the accreted mass \( \Delta M_{\text{acc}} \leq 1.4 M_{\odot} \), accretion of the pre-conversion neutron star should not influence its velocity significantly, we have an approximate relation: \( \Delta R \sim R_0(v_{sn}/v_{ns}) \), and
the ejecta radius $R \geq 10^3 R_0 (v_{\text{sn}} / v_{\text{ms}})$. Thus, the expansion timescale of the SN ejecta is

$$t \sim R / v_{\text{sn}} \geq 10^6 R_{0,11} v_{\text{ms},8}^{-1} \text{ s.}$$

(12)

This implies that the SN explosion might occur a few days before a GRB.

4. Discussions

Our model has several implications. First, it can clearly explain the association of GRBs with a special kind of supernova. The phase transition of the neutron star to a strange star is almost isotropic; about one half of the energy release will result in an ultra-relativistic fireball with baryon contamination of $\Delta M_{\text{ej}} + M_0$, and another half will be absorbed by the SN ejecta because the photon-electron scattering depth in the SN ejecta $\tau \sim \sigma_T [M_{\text{ej}} / (m_p \pi R^3)] R \sim 10^5 \gg 1$. So, the phase transition discussed here may also give rise to a hypernova with a high amount of explosive energy ($\sim 10^{52} \text{ ergs}$) and a bright optical luminosity. A hypernova-like component has been observed in several cases, e.g., SN 1998bw (Iwamoto et al. 1998), GRB 980326 (Bloom et al. 1999) and GRB 970228 (Reichart 1999; Galama et al. 2000). Second, the observed breaks in the light curves of some optical afterglows are argued to be due to sideways expansion of collimated fireballs (Rhoads 1999; Sari, Piran & Halpern 1999). However, this argument is still now a matter of considerable theoretical debate (Moderski, Sikora & Bulik 2000; Wei & Lu 2000). Dai & Lu (1999, 2000) have proposed the evolution of a fireball to the non-relativistic regime in a dense medium as an alternative explanation for these observed breaks. Our present model meets the second explanation. Third, if the phase transition occurs at $10^{-3} \ll \Delta R / R \sim 10^{-2}$, then the resulting fireball has the loading baryon mass of $\sim (\Delta R / R)^2 M_{\text{ej}} \sim 10^{-3} M_\odot (10^2 \Delta R / R)^2 (M_{\text{ej}} / 10 M_\odot)$, and its Lorentz factor should be $\sim 5 (E / 10^{52} \text{ ergs}) (10^2 \Delta R / R)^{-2} (M_{\text{ej}} / 10 M_\odot)^{-1}$. Although this fireball cannot produce a classical GRB due to its low Lorentz factor, it may result in a weak GRB like GRB 980425 or an X-ray GRB (or called an X-ray flash) like GRB 991106 observed by BeppoSAX (search http://www.ias.rm.cnr.it/ias-home/sax/xraygrb.html). We predict that the rate of such a kind of GRB is $\sim 10^{-5} (10^2 \Delta R / R)$ per year per galaxy. Finally, the phase transition occurs more possibly at $\Delta R / R \gg 10^{-2}$. All the energy release will be absorbed by the SN ejecta, and the resulting fireball is non-relativistic but much more energetic than a normal supernova. This fireball may only behave as a hypernova but not emit a GRB or even an X-ray GRB.

In summary, we have presented a new model for GRBs with small baryon contamination. A key point of our model is that a newborn neutron star with an initial kick velocity of $\sim 10^3 \text{ km s}^{-1}$ will catch up with the outgoing supernova ejecta, and accrete matter at a hypercritical rate. Once the stellar mass increases to some critical mass, the neutron star will undergo a phase transition to a strange star, resulting in an energy release of a few $10^{52} \text{ ergs}$. The phase transition may produce a GRB when it occurs just near the SN front. The burst rate is $\sim 10^{-6}$ per year per galaxy. In addition, if the phase transition occurs in the interior of the SN ejecta, it may result in an X-ray GRB observed by BeppoSAX or only a burstless hypernova explosion.
In this paper, we have discussed one result for accreting high-velocity neutron stars in supernovae, i.e., the conversion to strange stars as an origin of GRBs. Another result for accreting neutron stars is the collapse to black holes when the stellar mass reaches the maximum mass. If the pre-collapse neutron stars are millisecond pulsars, the resulting black holes must be rapidly rotating. As suggested by Vietri & Stella (1998), such black holes may produce GRBs by extracting their rotational energy or tapping the binding energy of the disk-black hole system.

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Fig. 1.— The accreted mass as a function of time for $R_{0,11} = 1$ and $M_{ej} = 10M_{\odot}$. The dashed, solid and dotted lines correspond to $v_{ns,8} = v_{sn,8} = 1.2, 1.3$ and 1.4 respectively.