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A possible model for the supernova/gamma-ray burst connection

X.Y. Wang[1], **Z.G. Dai**[1,2], **T. Lu**[1,2], **D.M. Wei**[3,4], **and Y.F. Huang**[1,2]

[1] Department of Astronomy, Nanjing University, Nanjing 210093, P.R. China
[2] LCRHEA, IHEP, CAS, Beijing, P.R.China
[3] Purple Mountain Observatory, Nanjing 210008, P.R. China
[4] National Astronomical Observatories, Chinese Academy of Sciences, P.R. China

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Abstract. Conversion from neutron stars to strange stars as a possible mechanism of cosmological gamma-ray bursts (GRBs) has been discussed in previous works, although the existence of strange stars is still an open question. On the basis of this mechanism, we here outline an explanation of the connection between supernovae (SNe) and GRBs, which has got increasing evidence recently. An asymmetric but normal SN explosion leaves a massive ($\geq 1.8\mathrm{M}_{\odot}$) and rapidly rotating neutron star, which then converts to a strange star few days later, due to its rapid spindown. The accompanied fireball, which can be accelerated to ultra-relativistic velocity ($\Gamma_0 \sim 100$) due to the very low baryon contamination of the strange star, flows out along the direction of the high-velocity SN jet and subsequently produces a GRB and the following low energy afterglows by interacting with the surrounding stellar wind. We will also expect a very luminous supernova like SN1998bw, if a large fraction of the conversion energy finally turns into the kinetic energy of the supernova ejecta.

Key words: gamma rays: bursts – shock waves – stars: neutron – stars: supernovae: general

1. Introduction

More than a year ago, Galama et al. (1998) reported the detection of a very luminous Type Ic supernova (SN) SN1998bw in the error box of GRB980425. The estimated chance probability of the coincidence is 10^{-4}, suggesting a connection between these two events. From the radio observations of GRB980425/SN1998bw, Kulkarni et al. (1998) concluded that there exists a relativistic shock (bulk Lorentz factor $\gamma \equiv (1-\beta^2)^{-1/2} \geq 2$) even 4 days after the supernova explosion. Li & Chevalier (1999) modelled the radio light curves and inferred that the late rise observed at days 20–40 is the result of energy input from a central engine. These both strengthen the link between SN1998bw and GRB980425. More recently, Bloom et al. (1999) and Reichart (1999) revisited GRB980326 and GRB970228, respectively, and found the evidence for a supernova in the light curve and late spectral energy distribution of the afterglow. Galama et al. (1999) reached the same conclusion for GRB970228 by the reanalysis of its optical and near-infrared afterglow. It appears that some GRBs, if not all, are connected with SNe. Now the proposed models include "collapsar" (Woosley 1993; MacFadyen & Woosley 1998; Woosley et al. 1999) or "hypernova" (Paczyński 1998) models, in which the GRBs and SNe are powered by the accretion process into the black hole. Some authors (e.g. Wang & Wheeler 1998; Cen 1998; Nakamura 1998;) also proposed that the MHD process in the core of an asymmetric SN may be responsible for the connection, based on the idea that the core-collapse process is intrinsically strongly asymmetric.

Conversion from neutron stars to strange stars as a possible source of cosmological GRBs has been suggested by some authors (e.g. Cheng & Dai 1996; Ma & Xie 1996). Witten (1984) speculated some time ago that strange quark matter may be the true ground state for hadrons (i.e. the energy of strange matter is lower than that of matter composed of nucleus). Farhi & Jaffe (1984) computed the zero temperature thermodynamics of strange matter and found that it may indeed be stable if the parameters of the MIT bag model take values inside a wide "stability window" they found. If this hypothesis were true, the conversion from neutron stars to strange stars may liberate a large amount of energy ($\sim 10^{52}\mathrm{erg}$). Strange stars, composed of this kind of quark matter, have been used to explain some astronomical phenomena (e.g. Cheng et al. 1998; Cheng & Dai 1998; Xu et al. 1999), although some arguments against the existence should also be kept in mind (e.g. Caldwell & Friedman 1991; Kluzńiak 1994). The conversion of a neutron star to a strange star may require the formation of a strange matter seed, which is produced through the deconfinement of neutron matter at a density (Baym 1991) of $\sim$ 7–9ρ_0 (where ρ_0 is the nuclear matter density), much larger than the central density of a $1.4M_{\odot}$ neutron star with a moderately stiff to stiff equation of state(EOS). (For a soft EOS, the deconfinement density is lower; but we here assume that the EOSs in neutron stars are moderately stiff or stiff, as required by some astrophysical processes; for details please see Cheng & Dai (1996)). Cheng & Dai (1996) proposed that some neutron stars in low-mass X-ray binaries can accrete sufficient mass ($\geq 0.4\mathrm{M}_{\odot}$) and undergo a phase transition to become strange stars. In this paper, we suggest that a normal SN explosion may leave a massive and

Send offprint requests to: T. Lu (tlu@nju.edu.cn)

rapidly rotating neutron star, which can convert to a strange star in quite a short time ($\sim 1\mathrm{days}$) due to its rapid spindown and subsequently produce a GRB. We will place emphasis on examining the connection between SNe and GRBs. If the GRBs can be successfully produced few days after the SN explosion, then the SN-GRB connection can be reasonably explained.

2. Ultra-relativistic jet from the strange star as GRB

Let us consider a massive progenitor with mass greater than $20M_\odot$ on the main sequence that undergoes a Type Ib/c or Type II supernova explosion and leaves a rapidly rotating neutron star with mass about 1.8–$2.1M_\odot$[1]. (But, for very massive progenitors with masses larger than $30M_\odot$, the collapsing iron cores may possibly implode to black holes rather than neutron stars before the explosions develop, which is just the "collapsar" model of GRBs.) Static neutron star with such a large mass may have undergone phase transition to become a strange star, but for a very rapidly rotating one (close to the break-up angular speed), its central density may be much lower than the deconfinement density. Indeed, for moderately stiff EOSs, rapid rotation can sustain an extra mass up to $0.3M_\odot$ for a given central density (Cook et al. 1994). However, due to the rapid loss of angular momentum through magnetic dipole radiation, the newborn, massive neutron star spins down and its central density becomes larger and larger and finally may reach the deconfinement density and converts to a strange star. The computation of Cook et al. (1994), in which they numerically study the rapidly rotating neutron stars in the frame of general relativity and based on the realistic modern EOSs, has given quantitative evidence for reaching such a high density in the core of massive neutron stars as the angular velocities decrease. Moreover, these findings hold for a wide range EOSs, from moderate to stiff. To illustrate more clearly, we here give an example from their computation. For the modern EOS named FPS (Lorenz et al. 1993), the maximum angular velocity of a $1.8629M_\odot$ (gravitational mass) neutron star is $\omega = 0.88749 \times 10^4 \mathrm{s}^{-1}$. The corresponding central density is $\rho_c = 1.4835 \times 10^{15}$ g cm^{-3}. When it spins down to a slow motion, its central density is close to $\rho_c = 3.3900 \times 10^{15}$ g cm^{-3}, having reached the deconfinement density of neutron matter.

Modelling of the optical light curve of SN1998bw shows that the time of core collapse coincides with that of GRB980425 to within a few days (Iwamoto et al. 1998). This means that the newborn, rapidly rotating neutron star should spin down in this timescale. If we adopt the usual magnetic dipole radiation with the spin-down timescale $T = \omega/\dot{\omega} \sim 2\ \mathrm{days}\ (\omega/10^4\ s^{-1})^{-2}(B/3.9\times10^{13}\mathrm{G})^{-2}$ for typical neutron star values (where I, B and R are, respectively, the moment of inertia, magnetic field strength and stellar radius of the neutron star), a nascent magnetic field larger than $B \geq 3.9 \times 10^{13}$ Gauss is needed. If the initial angular velocity of the newborn neutron star is very close to the maximum (Kepler) value, $\Omega_K \simeq \frac{2}{3}\sqrt{\pi G\bar{\rho}} \simeq 8185 s^{-1}(M/1.5M_\odot)^{1/2}(R/10\mathrm{Km})^{-3/2}$, its rotational kinetic energy $E_{rot} \sim \frac{1}{2}I\omega^2$ can be as large as 8×10^{52} erg for a neutron star with $I \sim 2\times10^{45}$ g cm^2. This energy, if released in the form of electromagnetic waves, will be absorbed by the supernova ejecta (Pacini 1967; Dai & Lu 1998a) and increase the kinetic energy of the ejecta above what has been claimed for the SN 1998bw (Iwamoto et al. 1998). Fortunately, recent studies (e.g. Andersson 1998; Lindblom et al. 1998) show that the emission of gravitational radiation due to r-mode instabilities in hot, young neutron stars can spin down the stars efficiently. Their calculations show that such stars can spin down to a few per cent of the Kepler-limit within one year. Recently, Ho & Lai (1999) show that the spin-down may depend on the combined effect of both the r-mode instability and the magnetic dipole radiation, if the nascent magnetic field is sufficiently high. The exact time when the phase transition occurs is difficult to be determined, but in principle, it can be as short as a few days. Thus, the large initial rotational energy is supposed to be lost mainly in the form of gravitational waves rather than the usual electromagnetic waves.

Once the deconfinement density is reached, strange matter seeds are formed in the interiors of the star and the strange matter will begin to swallow the neutron matter in the surroundings. While it has been proposed that the combustion corresponds to the slow mode (Olinto 1987), later work (Horvath & Benvenuto 1988) shows that this mode is hydrodynamically unstable. Thus the conversion should more likely proceed in a detonation mode (Lugones et al. 1994) (at a speed of sound) and the timescale for the conversion is about 0.1 millisecond. Although neutron star is composed of outer crust, inner crust and core, only the outer crust will not convert into strange matter because it does not contain free neutrons. Then the resulting strange star has a thin crust with mass $M_0 \sim 2\times10^{-5}M_\odot$ (strictly say, this mass corresponds to a $1.4M_\odot$ strange star; for a more massive strange star, it may increase slightly; Glendenning & Weber 1992; Huang & Lu 1997). It has been pointed out (Cheng & Dai 1996) that the energy deposition of this phase transition is mainly through the process of $n+\nu_e \to p+e^-$ and $p+\bar{\nu}_e \to n+e^+$ and the phase transition energy released (E_0) is of the order of 10^{52} ergs. The process, $\gamma\gamma \leftrightarrow e^+e^-$, will inevitably lead to the creation of a fireball, which expands outward, carrying the baryonic matter in the thin crust of the strange star. Finally, an ultra-relativistic shell is formed with a high Lorentz factor

$$\Gamma_0 \sim \frac{E_0}{M_0c^2} \sim 300(E_0/10^{52}\mathrm{ergs})(M_0/2\times10^{-5}M_\odot)^{-1}. \quad (1)$$

In addition, there's also another important process that could sometimes act as the central engine of GRBs after the birth of the strange stars: differential rotation may occur in the interiors of these newborn strange stars due to the fact that the density profile of a strange star is much different from that of a neutron star with the same mass (Glendening 1997). According to the basic idea of the Kluźniak & Ruderman (1998), Dai & Lu (1998b) argued that such differentially rotating strange stars could lead to a series of subbursts of GRBs by the following mechanism: as one part of the star rotates around the other part, internal poloidal magnetic field will be wound up into a toroidal configuration and linearly amplified. When the toroidal field increases up to a critical field

[1] This mass has included that of the accretion matter from the possible supernova fallback, see the section Discussions.

value, it will be able to float up to break through the stellar surface. Reconnection of the newborn surface magnetic field will arise a quickly explosive event with a large amount energy, which could lead to a subburst of a GRB. The obvious advantage in these two scenarios is that the baryon contamination in the fireball is small due to the low mass of the crust of strange stars.

Can this ultra-relativistic shell(s) produce a detectable γ-ray burst inside the dense SN ejecta of supernova? It depends on the scattering optical opacity of ejecta. The scattering optical depth is $\tau = \sigma_T nl \sim 9.4(M_{ej}/M_\odot)(t/10\mathrm{days})^{-2}(v/3 \times 10^9 \mathrm{cm\,s}^{-1})^{-2}$. For Type II supernova with a ejecta of mass greater than $10M_\odot$, τ is less than unity about 100 days after the explosion. Since the rise time of Type II supernova is quite long, we think that if the time of core collapse is more than 100 days earlier than that of the phase transition, the γ-ray burst resulting from the fireball shock can then be detected. This may apply to GRB980326 and GRB970228, as the Types of SNe associated with them are unknown. Since in this case, the corresponding distance that the ejecta has reached is not large ($\sim$ 1–3 $\times$ 10^{16}cm), the fireball shock will definitely run into the dense ejecta not long after the burst and transit to a non-relativistic expansion regime (Mészáros et al. 1998; Dai & Lu 1999a,b), leading to a steeply decaying or even non-detectable afterglow, very similar to the "SupraNova" model (Vietri & Stella 1998) of γ-ray bursts. This agrees with the observations of GRB980326, whose optical afterglow decays as $t^{-2.1}$ (Bloom et al. 1999). Recent analysis (Galama et al. 1999) of the optical and near-infrared afterglow of GRB970228 also shows a steep temporal decay ($F_\nu \propto t^{-1.73}$). On the other hand, the rise time of Type Ib/c supernova is much shorter ($\sim$2—3 weeks). So, even at the time that the luminosity of the supernova begins to decline, the scattering optical depth is still much greater than unity and no significant amount of gamma-rays can escape, unless there is a hole in the ejecta, which in fact implies a high-velocity moving jet in that direction resulted from a highly asymmetric supernova explosion. Since a Type Ib/c supernova SN1998bw has already been identified to be associated with GRB980425, next we will discuss in more detail this scenario.

In their models to explain the SN/GRB connection, Wang & Wheeler (1998), Cen (1998) and Nakamura (1998) assumed that the highly asymmetric explosion of Type Ib/c supernova makes the material in a small cone of the supernova ejecta be preferentially first blown out of the deep gravitational potential well of the star. Immediately (about a few seconds after the explosion), a tightly collimated jet from the core collapse rushes through the preferred "hole" and becomes an ultra-relativistic jet after an expansion phase. However, because the preexpelled material may still run in the direction of the small cone, we speculate that the fireball jet formed *immediately* after the explosion should be slowed down (viz. $\Gamma_0 \ll 100$) by the material before the fireball itself becomes optically thin, and difficult to produce a γ-ray burst. (Anyway, the mass in the small cone is about $10^{-3}M_\odot$ even for $\frac{\Omega}{4\pi} \sim 10^{-3}$.) But we think that this process may accelerate the preexpelled material in the small cone to mildly relativistic velocity ($\sim 0.8c$) and leaves a preferred exit for the fireball formed *a few days later* by the conversion of a newborn neutron star to strange star or from the differentially rotating strange star. *In this case, the fireball jet can reach a large radius and produce a γ-ray burst before catching up with the preexpelled material.* Moreover, at this time, the preexpelled material will not scatter the gamma-ray photons significantly, because the scattering optical depth has decreased below unity. In fact, there are some observational and theoretical evidences favouring the existence of mildly relativistic jet in the supernova explosion: 1)The mysterious spot in SN1987A which appeared 5–7 weeks after the explosion at ~ 0.06 arc-second away from the center, implies a relativistic velocity (Rees 1987; Piran & Nakamura 1987) of $v \simeq (0.6 \pm 0.15)c/\sin\alpha$, where α is the angle between the velocity and the line of sight. The new analysis of SN1987A data provided stronger evidence for the original "mystery spot" and in addition a second spot on the opposite side of the supernova, suggesting relativistic jets (Nisenson & Papaliolios 1999). 2) General relativistic numerical simulations (Piran & Nakamura 1987) have demonstrated that collapse of the rapidly rotating core bounces along the rotation axis to form jets moving with mildly relativistic velocity; 3)Superstrong magnetic field formed immediately after the core collapse is claimed to be able to punch a hole in the supernova ejecta and the preexpelled jet can also reach a relativistic velocity (Nakamura 1998). Moreover, because the newborn rapidly rotating neutron star may have a strong magnetic field, the energy released through the magnetic dipole radiation can be as large as $\dot{E} \sim B^2R^6\omega^4/c^3 \sim 4\times10^{46}\mathrm{ergs\,s}^{-1}(B/10^{13}\mathrm{G})^2(R/10^6\mathrm{cm})^6(\omega/10^4\mathrm{s}^{-1})^4$. Since a large fraction of this energy will be converted to photons, the ensuing luminosity in fact exceeds the Eddington luminosity for a neutron star by about 8 orders of magnitude. This high energy flow and the inherent rotation of the ejecta (if the jet moves along the rotation axis) may maintain the emptiness of the "hole".

3. Time scale and afterglows of GRBs associated with SNe

It is very likly that the ultra-relativistic radiation-dominated fireball, produced by the phase transition or/and from the differentially rotating strange stars, becomes beamed to some extent by the MHD effect due to the anisotropy of the configuration of the magnetic field surrounding the strange stars. As an estimate, we assume the enhancement factor is about 10 and thus the equivalent isotropic energy E_i of the fireball is of the order of 10^{53} erg or even more.

How much of this fireball energy can flow out through the "hole" is also difficult to be determined. It may depend on the size of the "hole" and the jet dynamics. But from the inferred total energy associated with GRBs, which ranges from 10^{50} erg to $10^{51.5}$ erg (Freedman & Waxman 1999), we estimate that only less than ten per cent of the fireball energy flowed out the supernova ejecta and produced the observed gamma-ray burst. For the case that only the phase transition occurs, the γ-ray burst is more likely to be produced by the external shocks (Dermer 2000 and references therein) rather than internal shocks because the conversion of neutron stars to strange stars is very quick and the energy deposition is impulsive. The jet-like outflow expands outward in a way similar to a homogeneous fireball, sweeping up more and more external matter. We expect the existence of a stellar wind environment surrounding the massive star GRB progenitor (Chevalier & Li 1999). External shocks will occur when the observer-frame energy of the swept-up external matter equals the initial energy of the fireball jet at a radius (Mészáros 1999)

$$r_{dec} \sim 2\times 10^{15}\ \mathrm{cm}\ E_{i,53}\Gamma_{0,2}^{-2}(\dot{M}_{-5}/v_{w,3})^{-1}, \qquad (2)$$

where $E_i = 10^{53}E_{i,53}\mathrm{erg}$, $\Gamma_0 = 10^2\Gamma_{0,2}$, $\dot{M} = 10^{-5}\dot{M}_{-5}M_\odot\ \mathrm{yr}^{-1}$ and $v_w = 10^3 v_{w,3}\mathrm{km\ s}^{-1}$. Here, $\dot{M}$ and v_w are the mass-loss rate and velocity of the wind, respectively. The duration of the GRBs in the observer's frame is

$$\Delta t \sim \frac{r_{dec}}{\Gamma_0^2 c} \sim 10\ \mathrm{s}\ E_{i,53}\Gamma_2^{-4}(\dot{M}_{-5}/v_{w,3})^{-1}. \qquad (3)$$

This time scale is consistent with the durations of those bursts that are thought to connect with supernovae. Variability on time scales shorter than Δt may occur on the cooling time scale of electrons or on the dynamic scale for inhomogeneities in the external medium, but generally this is not ideal for reproducing highly variable profiles. Therefore, in this case we will generally see bursts with simple profiles, agreeing well with GRB980425 and GRB980326 (Soffitta et al. 1998; Celidonio et al. 1998). On the other hand, for GRB970228 that have a relatively complex time structure, we think it may be produced by internal shock resulting from the differentially rotation process of the newborn strange star, in which the faster shells catch up and collide with the slower ones.

The afterglows are generally expected to decay rapidly as the result of the wind-shaped circumburst environment (Chevalier & Li 1999), which is consistent with the observations of the GRB980329 and GRB970228. For the case of GRB980425, it is natural to think that the jet geometry (i.e. we observe this jet from the lateral direction) makes us detect a weak gamma-ray intensity and its weak optical afterglow emission is supposed to be suppressed by the luminous optical radiation of SN1998bw and therefore not seen by us. However when the radio afterglow dominates (we suggest the radio emission is from the afterglow of GRB980425 rather than SN1998bw), its emission angle $\theta \sim \frac{1}{\gamma} \sim \frac{1}{2}$ is quite large (Wang et al. 1999) and at this time the observer may be inside this angle; hence, the radio emission we received should be bright, considering the short distance of the source from us.

Apart from the fraction of the fireball energy that flows out along the directions of the high-velocity SN jets, the remaining, large portion of the ultra-relativistic shell(s) will catch up and collide with the ejecta of the supernova that moves with a lower velocity and be immediately decelerated to a non-relativistic speed, heating the ejecta and producing super-Mev gamma-rays at the same time. However, no significant amount of gamma-rays can escape due to a high scattering optical depth of the dense ejecta, i.e. $\tau = \sigma_T nl > 1000$ (for the ejecta with $\sim 5M_\odot$) at the time two days after the explosion. Therefore, a large fraction of the energy of the fireball shell will turn into the expansion energy of the massive ejecta, leading to a supernova with very bright optical luminosity and broad line emission, which are the very characteristics of SN1998bw.

4. Discussions

We have suggested a possible explanation of the puzzling SN/GRB connection, based on the conversion of a newborn, massive neutron star to a strange star few days after the supernova explosion. This suggestion is based on a basic hypothesis that strange matter is the true ground state, which is entirely possible but not conclusive at present. Thus we should only regard strange stars as possible stellar objects. We think that the ultra-relativistic shell(s) responsible for GRBs could not be produced by the supernova itself, but possibly by the phase transition process or the differentially rotation process of the newborn strange star. The formation of a strange star requires that the total mass of the preconversion neutron star should exceed $\sim 1.8M_\odot$ for slowly rotating ones. According to the numerical simulation (Woosley et al. 1999), when supernova occurs, some matter may fail to escape and fall back onto the neutron star. For example, as they show, if the kinetic energy at infinity is set to be about 1.2×10^{51} erg for a $25M_\odot$ presupernova star, about $0.48M_\odot$ matter falls back onto the neutron star in about 1000 seconds. Therefore, it is reasonable to believe that some supernova explosions, especially for the progenitors with moderately massive mass (perhaps in the range 20–$30M_\odot$), could produce massive neutron stars. But, for very massive progenitors (perhaps with mass higher than $30M_\odot$), it is very likely that more than $1M_\odot$ matter falls back and then the massive neutron star will promptly collapse to a black hole, which then points to the "collapsar" model or the two-step model (Cheng & Dai 1999) of GRBs associated with supernovae.

Our scenario clearly differs from previous discussions about the effects of strange quark matter on SN explosion (e.g. Benvenuto & Horvath 1989; Dai et al. 1995; Gentile et al. 1993). In their works, the authors assumed a lower deconfinement density ($\sim$ 2–3ρ_0) for soft EOSs and strange stars were born during the core collapse phase of the SN progenitors. The energy released during the conversion may be a help to the SN explosion because of the increase of the shock-wave energy. But, we think that this case is not appropriate for the production of GRBs due to the baryon contamination of the massive envelope surrounding the strange star. In our scenario, we suggested a model involving the delayed birth of strange stars, in which the baryon contamination in this case is smaller and the mass of the newborn neutron stars can reach the critic value by accretion from the supernova fallback matter. Thus, we speculate that the SN explosion is normal while the associated GRBs are powered by the phase transition which occurs only when the neutron stars have spun down sufficiently.

After all, note that this scenario has some distinct features or predictions. First, a strange star, rather than a black hole or neutron star, is left after a SN/GRB event. Since all non-strange matter is ejected during the burst, a bare strange star is left. Thus in our galaxy, there may exist bare strange stars left by past GRBs. Discovery of this kind of interesting stellar objects will be a good indication of our proposed model. Certainly, if at later time the bare strange stars accreted matter from outside, it may again be "dressed" in a shell of ordinary matter. Second, as the major part of the fireball shell collides with the supernova ejecta, a large fraction of the energy released in the conversion will finally turn into the kinetic energy of the ejecta, therefore the supernova should be very bright and show broad emission lines. Thirdly, the afterglows of supernova-related γ-ray bursts in this scenario will generally decay faster than usual ones as the result of dense medium effect (Type II SNe) or interaction with the surrounding stellar wind (Type Ib/c SNe). Finally, prior to the phase transition, the spin-down of the hot, newborn neutron stars driven by the r-mode instability involves emission of up to 8×10^{52} erg of gravitational waves, making the gravitational radiation potentially observable.

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