On The Origin of Supernova-less Long Gamma-Ray Bursts

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Abstract

The fraction of long duration gamma-ray bursts (GRBs) without an associated bright supernova (SN-less GRBs) at low redshifts is comparable to that of GRBs associated with bright supernovae (SN-GRBs). The prompt emission and its fast decline phase in both types of GRBs are well described by the cannonball model of GRBs, where inverse Compton scattering of ambient light is the dominant $\gamma$-ray production mechanism. However, in SN-less GRBs, the fast decay of the prompt emission appears to be overtaken by an afterglow powered by a millisecond pulsar, while, in SN-GRBs, the late-time X-ray afterglow is well described by synchrotron radiation from the decelerating jet in the interstellar medium. We use their different X-ray light curves to determine the ratio of SN-less GRBs/SN-GRBs at very high redshifts. We find that at $z > 4$, this ratio is the same as that at small redshifts. Such a $z$-independent ratio suggests that the origin of SN-less GRBs is a phase transition of neutron stars to quark stars in high-mass X-ray binaries, rather than the merger of neutron stars.

Key words: gamma-ray burst: general – stars: jets – stars: neutron

1. Introduction

Gamma-ray bursts seem to be divided into two distinct classes, long duration soft gamma-ray bursts (SHBs) that usually last more than 2 s and short hard bursts (SHBs) that usually last less than 2 s (Norris et al. 1984; Kouveliotou et al. 1993). While there is clear photometric (e.g., Dado et al. 2002; Zeh et al. 2004) and spectroscopic evidence (e.g., Della Valle et al. 2006 and references therein) that a large fraction of the long duration GRBs are produced in very bright stripped envelope supernova (SN) explosions of type Ic (Galama et al. 1998), there is also evidence that supernova explosions are not the only source of long duration GRBs (e.g., Della Valle et al. 2006; Fynbo et al. 2006; Gal-Yam et al. 2006). Moreover, in the local universe, the rate of SN-less GRBs is comparable to that of SN-GRBs, as can be seen from Table 1 where all the GRBs with known redshift $z < 0.15$ are listed. If that is valid universally, then the fraction of SN-less GRBs is comparable to that of SN-GRBs. The origin of such a large population of SN-less GRBs, which we shall show seems to extend to very large redshifts, is still unknown.

Thirty years ago, Goodman et al. (1987) suggested that GRBs are not Galactic in origin, as was widely believed, but may be produced at cosmological distances by highly relativistic $e^+e^-\gamma$ fireballs (Goodman 1986) formed by neutrino-neutrino annihilation at merging neutron stars (NSM) in close binaries due to gravitational wave emission and/or around compact stars undergoing gravitational collapse due to mass accretion. However, shortly after the launch of the Compton gamma-ray burst observatory (CGRO), it became clear that such neutrino-annihilation fireballs are not powerful enough to produce observable GRBs at the very large cosmological distances, which were indicated by the CGRO observations (Meegan et al. 1992). Consequently, Meszaros & Rees (1992) suggested that the $e^+e^-\gamma$ fireballs produced in the merger of neutron stars and of neutron stars and stellar black holes may be collimated into $e^+e^-\gamma$ jets by funneling through surrounding matter. Instead, Shaviv & Dar (1995) suggested that GRBs are produced at large cosmological distances by inverse Compton scattering (ICS) of ambient light by narrowly collimated jets of plasmoids (cannonballs) of ordinary matter rather than by collimated fireballs, launched in neutron star mergers, in phase transition of neutron stars to quark stars in compact binaries due to mass accretion, and in stripped envelope SN explosions. To date, there is direct photometric and spectroscopic evidence for production of GRBs in stripped envelope SN explosions (see, e.g., Della Valle 2016 and references therein), but only indications that SHBs and perhaps SN-less GRBs may be produced in neutron star mergers (Berger et al. 2013; Fong & Berger 2013; Hotokezaka et al. 2013; Tanvir et al. 2013; Berger 2014 and Jin et al. 2015, respectively). The first indubitable SHB-NSM association (SHB170817A/GW170817) was reported (von Kienlin et al. 2017; Abbott et al. 2017a, 2017b, 2017c; Goldstein et al. 2017) after this paper was submitted for publication.

There is, however, compelling evidence that both GRBs and SHBs are produced by ICS of light by highly relativistic jets (Shaviv & Dar 1995). It includes a large linear polarization of the prompt emission, pulse shape, and spectral evolution during its fast decline phase, and various correlations among burst properties (see, e.g., Dar & De Rujula 2000, 2004; Dado et al. 2009a, 2009b; Dado & Dar 2017 and references therein). The main suggested sources of such highly relativistic jets, other than SN explosions, include merger of neutron stars (Goodman et al. 1987), neutron star–black hole mergers (Meszaros & Rees 1992), phase transition of neutron stars to more compact objects (quark stars or black holes) following mass accretion from a companion star (Dar et al. 1992), “failed supernovae” (FSN), i.e., direct collapse of massive stars to black holes without a supernova (e.g., Woosley 1993a, 1993b), or collapsars (MacFadyen & Woosley 1999), i.e., direct collapse of massive stars to black holes with a hypernova, i.e., a bright supernova of type Ic akin to SN1998bw (Pian et al. 2000; Galama et al. 1998; Iwamoto et al. 1998).

An FSN origin of SN-less GRBs seems to be ruled out; the afterglows of FSN-GRBs, like those of SN-GRBs, are produced by highly relativistic jets emitted in the core collapse of massive stars, which takes place mostly within dense molecular clouds. Their late-time afterglows are dominated by synchrotron...
radiation from the decelerating jets in a relatively dense interstellar environment. Their late-time spectral and temporal behaviors satisfy characteristic closure relations (Dado & Dar 2013, 2016). Their shape and closure relations distinguish them from the late-time afterglows of SN-less GRBs (e.g., Cano et al. 2016), which may be powered by nascent millisecond pulsars (MSPs) in mergers (Dai & Lu 1998a, 1998b; Zhang & Meszaros 2001; Dai et al. 2006; Metzger et al. 2008), or in phase transition of neutron stars to quark stars (Dar 1998), within star clusters of high density stellar light, but a low density interstellar medium (ISM).

In this paper, we show that the light curves of the X-ray afterglow of the well sampled nearby SN-less GRBs measured with the Swift X-ray telescope (Evans et al. 2007, 2009) are well explained by ICS of light by relativistic jets launched in the birth of MSPs, which is taken over by an X-ray afterglow powered by the spindown of the newly born MSP (Dai & Lu 1998a, 1998b; Zhang & Meszaros 2001; Dai et al. 2006; Metzger et al. 2008). Late-time afterglows powered by MSPs rule out neutron star–black hole mergers and phase transition of neutron stars to black holes as the origin of SN-less GRBs. However, such afterglows do not distinguish between neutron stars’ merger origins and the collapse of neutron stars to quark stars following mass accretion.

We also show that the SN-GRB/SN-less GRB ratio among GRBs with well sampled X-ray afterglow seems to be redshift independent. For example, among the GRBs with known $z \leq 0.15$, 5 are SN-GRBs and 5 are SN-less GRBs, while out of the 24 GRBs with a very large measured redshift ($z > 4$), and a well sampled X-ray afterglow, 12 have “MSP-like” late-time afterglow, and the other 12 have a jet-like late-time afterglow. Moreover, the energy supply by a phase transition of millisecond neutron stars to quark stars is sufficient to power even the most energetic GRBs with known redshifts.

The $z$-independent ratio SN-GRBs/SN-GRBs suggests that the production rate of SN-less GRBs, like that of SN-GRBs and FSN GRBs, is proportional to the star formation rate (Dado & Dar 2014). This favors a phase transition of neutron stars to quark stars following mass accretion (Dar 1998) in short-lived high-mass X-ray binaries (HMXBs) as the origin of SN-less GRBs rather than formation of binary neutron stars followed by merger through gravitational wave emission, which takes a very long time, compared to the age of the universe (e.g., Kalogera et al. 2007).

### Table 1

| SN     | z     | SN-less GRB | References               |
|--------|-------|-------------|-------------------------|
| 1998bw | 0.0085| 1.11005A    | Galama et al. (1998)     |
| 2006ag | 0.0331| 1.05119B    | Perley et al. (2006)     |
| 2010bb | 0.059 |             | Starling et al. (2011)   |
| (uncertain) |    |             |                         |
| 0.080  | 0.060505| Fynbo et al. (2006) |
| 0.0890 | 0.080517| Stanway et al. (2015) |
| 0.125  | 0.060614| Fynbo et al. (2006) |
| 2013dx | 1.10702A| 0.145       | D’Elia et al. (2015)     |
| 2016jca| 0.1475| 1.161219B   | Cano et al. (2017)       |

2. The Fast Decline of Prompt Emission

In the cannonball (CB) model (Dar & De Rujula 2004), the production mechanism of GRBs is the ICS of photons of a glory (light ball) of radius $R$ surrounding the launch site of a highly relativistic jet of plasmoids (CBs). Consider a jet that is a succession of highly relativistic plasmoids (cannonballs), which are launched inside a light ball (glory) formed by presupernova ejections in the case of SN-GRB, a plerion or a collapsed core (cc) of a globular cluster (GC) in the case of a neutron star merger, or the light from an accretion disk around the neutron star in HMXB. The ICS of glory photons, which have a broken power-law spectrum $dn/d\epsilon \sim \epsilon^{\alpha} \exp(-\epsilon/\epsilon_{p})$, with $-1 \leq \alpha \leq 1$ yields a fast rise–exponential decay (FRED) pulse shape of photons above a detection threshold $E_{\text{min}}$.

A simple derivation of the exponential decay proceeds as follows. Let $\gamma$ be the bulk Lorentz factor of a cannonball (CB) and $\delta = 1/\gamma (1 - \beta \cos \theta)$ be its Doppler factor when viewed from an angle $\theta$ relative to its direction of motion. At early times, when the CB is opaque to photons, its effective cross section for ICS of glory photons increases like $\pi R_{CB}^{2} \sim \tau^{2}$. Outside the glory of radius $R$, at a distance $r = \gamma \delta c t/(1 + z) > R$ from its launch site, the number density of ambient photons intercepted by the CB decreases with distance as $1/r^{2} \sim \tau^{2}$. In the CB’s rest frame, the longitudinal momentum of the intercepted photons is reduced by a factor of 1/2$\gamma$. Thus, in that frame, the photon’s parallel momenta are negligible compared to their transverse momenta, unchanged by the Lorentz boost. Let $b$ be the transverse distance of an emitted photon relative to the CB’s direction of motion, which is intercepted at $r > R$. Its energy in the CB rest frame becomes $\epsilon' \approx \epsilon b/r$. After ICS within the CB, it arrives with $E \approx \epsilon b / r(1 + z) = \epsilon b / \gamma c t$ in the observer frame. Hence, the energy flux above the detection threshold $E_{\text{min}}$, as seen by the distant observer, is given by

$$F(t, E > E_{\text{min}}) \propto R_{CB}^{2} \int_{E_{\text{min}}}^{\infty} \epsilon \frac{dn}{d\epsilon} \frac{de}{dE} 2\pi b \, db \, dE.$$  \hspace{1cm} (1)

It yields an approximate fast decline shape

$$F(t, E > E_{\text{min}}) \propto t^{-1} \exp(-t/\tau),$$  \hspace{1cm} (2)

where $\tau = (R / \gamma c) (\epsilon_{p}/E_{\text{min}})$ for $t \gg t_{es}$, where $t_{es}$ is the plasmoid crossing time of the glory, as seen by a distant observer from a viewing angle $\theta \approx 1/\gamma$. The $E$-dependence of $\tau$ produces the observed (Evans et al. 2007, 2009) fast spectral softening as a function of time during the exponential decline of the prompt emission for $t > t_{es}$. Due to time aberration, $t_{es} \approx (1 + z) R_{c} / \gamma \delta c$. The median value of the observed radii of ccs of GCs is $R_{c} \sim 1$ pc. Hence, $t_{es} \approx (1 + z) 50$ s, for a plasmoid with $\delta \approx \gamma \approx 700$, which is similar to the typical time that the Swift–XRT usually begins its follow-up observations.

The successive emission of plasmoids during a GRB and/or a bumpy light density in the GC yields a bumpy light curve, with resolved peaks at early times because of large photon statistics. Later, when the luminosity decreases, the larger time bins (and perhaps merger of CBs) yield smoothly appearing light curves. A smoothed X-ray light curve during the fast decay phase of the prompt emission is expected to be described
roughly by
\[ F(t, E > E_{\text{min}}) \approx \frac{a F(t)}{a + (t/\tau)^{1-\alpha}\exp(t/\tau)}, \]  
where \( a \) is an adjustable parameter, \( \alpha = -1 \) for bremsstrahlung-like glory and \( \alpha = 2 \) for gray body glory.

The radius of large GCs can reach \( R \approx 25 \) pc. If the GRB occurred within the cc of such a large GC, the ICS of the quasi-isotropic GC light by the CB inside the GC can take over during the fast decay of the contribution from the cc and produce a second bump with a shape also given by Equation (2), but with a much smaller \( F_0(t) \), \( \tau_{cc} \gg \tau_{ec} \), and \( \tau_{es} \approx (1 + z) \times 10^4(R/25 \text{pc})(\gamma/700)^2 \), which is taken over during its fast decay phase by the MSP contribution.

The pulse shape, or a "flare" during the decline of the prompt emission, which is produced by the ICS of ambient light with a bremsstrahlung spectrum by a CB launched at a time \( t_{0,0} \), is given approximately by interpolation between the \( \sim t_i^2 \) rise of a pulse and its exponential decay,
\[ N_i(t_i, E > E_{\text{min}}) \approx F_0 \frac{4(t_i/\Delta t)^2}{((t_i/\Delta t)^2 + 1)^2} \exp(-t_i/\tau), \]  
where \( t_i = t - t_{0,0} \) is the time after \( t_{0,0} \) the beginning time of pulse \( i \).

### 3. Afterglows Powered by MSPs

Newly born neutron stars seem to be surrounded by nearby plerions, which absorb their emitted radiation, winds, and highly relativistic particles, and convert them to luminous energy, mostly in the X-ray band. If the power source is the spindown of a newly born neutron star with a period \( P \), then, in a steady state it generates a plerion luminosity \( L(t) = 2\pi^2 I P^2/P^3 \). For canonical neutron stars of a constant density, a radius \( R = 10^6 \) cm, and a mass \( M \approx M_{\text{Ch}} \), where \( M_{\text{Ch}} \approx 1.4 M_\odot \) is the Chandrasekhar mass limit of white dwarfs, \( I = (2/5)M_{\text{Ch}}R^2 \approx 1.12 \times 10^{45} \) g cm².

Observations of young X-ray pulsars indicate that the change of their period during their spindown satisfies to a good approximation,
\[ P\dot{P} = K, \]  
where \( K \) is time independent constant (with time-dimension). Such a behavior is expected from pulsars that spindown by magnetic dipole radiation (MDR) from a magnetic dipole aligned at an angle \( >0 \) relative to the rotation axis, and stays constant in time (in the pulsar rest frame) during spindown (e.g., Manchester & Taylor 1977). Observations, however, indicate that \( P \dot{P} \) remains constant to a good approximation also when other spindown mechanisms, such as emission of winds and/or highly relativistic particles, contribute, or even dominate, the spindown of pulsars. This follows from the fact that the age estimate \( t = [P^2(t) - P^2(0)]/2K \) and the braking relation \( d^2P/dt^2 \approx -K^2/P^3 \) (Manchester & Taylor 1977) also seem to be satisfied by young X-ray pulsars: the age relation has been tested by comparing the age obtained from measurements of \( P \) and \( P \) of young pulsars to the known ages of their parent supernovae (historical supernovae) or to their ages obtained from measurements of the distance and proper motion of the young pulsars relative to the centers of the supernova remnants where they were born. The braking relation, which is very difficult to test over a human timescale, has been verified only in a few young X-ray pulsars, where it yielded a braking index near the expected value of 3 (see, e.g., Archibald et al. 2016 and references therein).

We shall assume that Equation (5) is valid approximately for the power supply by the newly born millisecond neutron stars in SN-less GRBs during the first few days after their birth. It then follows from Equation (5) that
\[ L_{ps}(t) = L_{ps}(0)(1 + t/t_b)^{-2}, \]  
with \( t_b = P_0/2P_0 \) and \( P_0 = P(t = 0) \). The afterglow of a GRB at redshift \( z \) that is powered by such a luminosity has a local energy flux density \( F(t) = L(t)/4\pi D_L^2 \), where \( D_L \) is the luminosity distance of the GRB at redshift \( z \), i.e.,
\[ F_{ps}(t) = F_{ps}(0)(1 + t/t_b)^{-2}. \]  
If only a fraction \( \eta \) of the rotational energy is converted to X-rays, then
\[ P_0 = \frac{1}{D_L \sqrt{2F_{ps}(0)t_b}} \left( \frac{1 + z}{\pi}\right) \left( \frac{\eta I}{2F_{ps}(0)} \right), \]  
and its time derivative is \( P_0 = P_0/2t_b \).

Under the assumptions that the spindown of the newly born neutron star is dominated by radiation from a magnetic dipole \( m \), which is constant in time and is aligned at a fixed angle \( \alpha \) relative to its rotation axis, the peak surface value of the dipole magnetic field \( B_p = 2m/R^3 \) is at the magnetic poles and it satisfies (Manchester & Taylor 1977)
\[ B_p \sin \alpha \approx 6.8 \times 10^{19} \left| \frac{P \dot{P}}{\alpha^3} \right|^{1/2} \text{ Gauss}. \]  

However, the wide use of Equation (9) for estimating \( B_p \) cannot be trusted because it assumes that there is no magnetic field decay, that the spindown is in a perfect vacuum, that there are no other spindown mechanisms in operation, such as emission of a wind, relativistic particles, and gravitational waves, and that other sources, such as thermal energy, stress energy, phase transition and gravitational contraction, can be ignored.

### 4. Comparison with Observations

Equations (2) and (7) can be combined to yield the canonical light curve of the decay of the prompt emission phase of SN-less GRBs taken over by an MSP powered afterglow,
\[ F(t) \approx \frac{a F(0)}{a + (t/\tau)^{1-\alpha} \exp(t/\tau)} + \frac{F_{ps}}{(1 + t/t_b)^2}. \]  

Figures 1–4 show the X-ray light curves of the four nearest SN-less GRBs, 051109B, 080517, 060614, and 050826, with known redshifts and well sampled X-ray afterglows, which were measured with the Swift-XRT and are reported in the Swift-XRT GRB light-curve repository (Evans et al. 2007, 2009). Also shown are their best-fit light curves as given by Equation (10) with the minimal number of parameters. The best-fit values of these parameters (two for the late-time MSP contribution and two or three for the jet contribution) are listed in Table 2.
Figure 1. X-ray light curve of the SN-less GRB 051109B at the (uncertain) redshift $z = 0.08$ measured with Swift-BAT and -XRT telescopes and reported by Troja et al. (2006) and in the Swift-XRT GRB light-curve repository (Evans et al., 2007, 2009). The line is the best-fit light curve as given by Equation (10) with the parameters listed in Table 2.

Figure 2. X-ray light curve of the SN-less GRB 080517 at redshift $z = 0.0809$ reported in the Swift-XRT GRB light-curve repository (Evans et al., 2007, 2009). The line is the best-fit light curve, as given by Equation (10) with the parameters listed in Table 2.

Figure 3. X-ray light curve of the SN-less GRB 060614 at redshift $z = 0.125$ reported in the Swift-XRT GRB light-curve repository (Evans et al., 2007, 2009). The line is the best-fit light curve, as given by Equation (10) with the parameters listed in Table 2.

Figure 4. X-ray light curve of the SN-less GRB 050826 at redshift $z = 0.297$ reported in the Swift-XRT GRB light-curve repository (Evans et al., 2007, 2009). The line is the best-fit light curve, as given by Equation (10) with the parameters listed in Table 2.
We have also verified that all other well sampled X-ray afterglows of GRBs with redshift \( z < 1 \), which were reported in the *Swift-*XRT GRB light-curve repository and have no evidence for an associated SN, despite their relative proximity, could be well fit by Equation (10) (18 additional GRBs in Figures 5–7), or by Equation (4) plus Equation (7) (6 additional GRBs in Figure 8) with flaring activity during the decay phase of their prompt emission. Moreover, Figures 9 and 10 show the X-ray afterglows of the 12 GRBs, out of 24 with a known large redshift (\( z > 4 \)) and a well sampled afterglow reported in the *Swift-*XRT GRB light-curve repository (Evans et al. 2007, 2009), that could be well fit by a jet + MSP light curve with the parameters listed in Table 4.

### 5. Can \( n^* \) Collapse to \( q^* \) Power GRBs?

Neutron stars (\( n^* \)s), which are spun-up by mass accretion in HMXBs to millisecond periods may undergo a gravitational collapse to a quark star (\( q^* \)) or a black hole when their mass increases beyond a critical limit. In such stars, the gravitational pressure is balanced by short-range interactions and Fermi degeneracy pressure of neutrons or quarks, respectively. The equations of state at supernuclear densities in \( n^* \)s, and at densities below asymptotic freedom in \( q^* \)s, are not known well enough to obtain reliable estimates of the energy release in \( n^* \) to \( q^* \) transitions, if such transitions take place. At present, approximate but simple estimates suggest that \( n^* \) collapse to \( q^* \) can provide the energy required in the CB model to power even the most energetic SN-less GRBs. Such an estimate is presented below.

If the gravitational collapse of \( n^* \) to \( q^* \) changes the radius of \( n^* \) by \( dR = R_{n^*} - R_{q^*} \), the moment of inertia of the star changes roughly by \( dl \approx d [(2/5)M R^2] \approx 2l(dR/R) \), where \( l \approx 1.12 \times 10^{45} \text{ g cm}^2 \) for the canonical values \( M_{n^*} \approx 1.4 M_\odot \) and \( R(n^*) \approx 10^6 \text{ cm} \). If the angular velocity of the \( n^* \) is retained during the fast collapse and the angular momentum loss is converted to kinetic energy of a bipolar jet, which powers the SN-less GRB, then for a canonical MSP with initial period \( P \approx ms \), each jet has an energy

\[
E_j \approx 2(\pi/P)^2 I \ dR/R \approx 2.2 \times 10^{52} dR/R \ \text{erg.} \tag{11}
\]

In the cannonball model of GRBs, the kinetic energy of the electrons \( E_k(e) = (m_e/m_p)E_j \) in a highly relativistic narrowly collimated jet of plasmoiids of ordinary matter with kinetic energy \( E_j \) is converted to the energy of a narrowly beamed GRB by ICS of glory photons. The column density of glory photons is usually large enough for the electrons to loose their entire initial energy, or even more energy if they extract energy from interactions with protons and other nuclei within the jet. Hence, in the CB model, the equivalent isotropic energy \( E_{iso} \) of a beamed GRB satisfies (e.g., Dar & De Rujula 2004):

\[
E_{iso} \sim (m_e/m_p)E_k(e) \delta^2 /4, \tag{12}
\]

where \( \delta \) is the Doppler factor of the jet. The most energetic GRBs are GRBs viewed near axis with \( \gamma^2 \theta^2 < 1 \), i.e., \( \delta \approx 2 \gamma > 2(\gamma) \). The minimal kinetic energy required to produce such GRBs is

\[
E_k(jet) \sim (m_e/m_p)(E_{iso}/\gamma^2). \tag{13}
\]

The CB model best estimate of \( \langle \gamma \rangle \) (Dado & Dar 2014) from the entire data on GRBs, has yielded \( \langle \gamma \rangle \approx 700 \). The measured mean equivalent isotropic energy of SN-less GRBs with \( z > 4 \), i.e., that of presumably the observed population of most energetic GRBs, which have \( \langle E_{iso} \rangle \approx 5.6 \times 10^{53} \text{ erg} \). Hence, Equation (13) yields \( E_k(jet) \approx 2 \times 10^{51} \text{ erg} \) for \( z > 4 \) SN-less GRBs, and then Equations (11) and (13) imply that a radius change of \( dR \approx -0.10R \) can power even the most energetic population of SN-less GRBs.

### 6. Discussion

Fast rotating millisecond neutron stars can be produced in SN explosions, in merger of neutron stars and through spin-up of neutron stars by mass accretion in compact binaries. We have conjectured that the spindown of such newly born young millisecond neutron stars satisfies, to a good approximation, \( P \dot{P} = K \) where \( K \) is constant in time during the first few days after birth. This conjecture was motivated by the fact that the braking relation \( d^2P/dt^2 \approx -P^2/P \approx -K^2/P^3 \) and the age estimate \( t_{age} \approx P^2/2 \dot{P} \), which follow from the relation \( P \dot{P} \approx const \), seem to be satisfied to a good approximation by young X-ray pulsars: their braking index derived from precise measurements of \( P(t) \) of a few young pulsars is near 3, and the age relation \( t_{age} = (P^2 - P_0^2)/2 P \) of young pulsars seem to agree with the age of their parent historical supernovae or their age extracted from their observed distance and proper motion relative to the centers of their parent supernovae.

We have shown that all the well sampled light curves of the X-ray afterglows of the nearby SN-less GRBs measured with the *Swift* X-ray telescope are those expected from the launch of highly relativistic jets in the birth of MSPs within an environment of a very dense light and a very low ISM density. Such an environment exists in stellar-rich GCs with or without a cc. We have also shown that roughly half of all GRBs with well sampled X-ray afterglow, where SN-GRB association has not or could not be confirmed, could be well explained by ICS.
Figure 5. X-ray light curve of the nearby (0.15 < z < 1) SN-less GRBs 051022, 060123, 080710, 090814A, 091003, and 091018 reported in the Swift-XRT GRB light-curve repository (Evans et al. 2007, 2009) and their best-fit light curve for a jet contribution taken over by MSP powered emission, as given by Equation (10) with the parameters listed in Table 3.
Figure 6. X-ray light curve of the nearby \((0.15 < z < 1)\) SN-less GRBs 091127, 100418A, 100508A, 110106B, 110918A, and 111225A reported in the Swift-XRT GRB light-curve repository (Evans et al. 2007, 2009) and their best-fit light curve for a jet contribution taken over by MSP powered emission, as given by Equation (10) with the parameters listed in Table 3.
Figure 7. X-ray light curve of the nearby ($0.15 < z < 1$) SN-less GRBs 120729A, 120907A, 141225A, 160623A, 160804A, and 170519A reported in the Swift-XRT GRB light-curve repository (Evans et al. 2007, 2009) and their best-fit light curve for a jet contribution taken over by MSP-powered emission, as given by Equation (10) with the parameters listed in Table 3.
Figure 8. X-ray light curve of the nearby ($0.15 < z < 1$) SN-less GRBs 061110A, 080430, 080916A, 090814A, 100621A, and 151027A, reported in the Swift-XRT GRB light-curve repository (Evans et al. 2007, 2009), and their best-fit light curve for a jet contribution taken over by MSP powered emission, as given by Equation (4) plus Equation (7) with the parameters listed in Table 3.
of light by relativistic jets launched in the birth of an MSP within a GC-like environment.

The late-time behavior of the light curves of the afterglows of SN-less GRBs is very different from that of SN-GRBs. In SN-GRBs, the light curves evolve by synchrotron radiation from the deceleration of highly relativistic jets in dense molecular clouds within spiral galaxies, where most massive star formation and core collapse supernovae of type Ic take place. The late-time light curves of SN-less GRBs can neither be explained well by synchrotron radiation from the deceleration of highly relativistic jets nor do they satisfy the closure relations that are satisfied by the late-time afterglows of SN-GRBs.

The MSP birth periods obtained from our fits to the late-time X-ray afterglows of SN-less GRBs with known redshift are all well above the minimal classical period $2\pi R/c \approx 0.2$ ms of fast rotating canonical neutron stars.

Late-time afterglows powered by MSPs rule out neutron star–black hole mergers or phase transition of neutron stars to black holes as the origin of SN-less GRBs. However, they do not distinguish between the neutron star’s merger origin or collapse of neutron stars to quark stars following mass accretion.

SHBs are observed near/within both spiral and elliptical galaxies (probably within the core of stellar rich GCs), while long soft GRBs seem to take place only in spiral galaxies, mainly within star formation regions. These suggest that SHBs and SN-less GRBs have different origins: we have found that the fraction of GRBs with very large measured redshifts ($z > 4$), which have “MSP-like” late-time X-ray afterglows is not different from that observed at very low redshifts ($z < 0.15$).

This implies a similar redshift dependence on the rate of SN-less GRBs and SN-GRBs that is proportional to the global star formation rate when beaming and threshold effects are taken into consideration. However, formation and merger of neutron stars after the birth of the older neutron star plus the merger time usually takes a very long time, comparable to the age of the universe. If SN-less GRBs were formed by the neutron star merger in compact binaries due to gravitational wave emission, it would have implied a much lower fraction of SN-less GRBs at very large redshifts, i.e., a much smaller fraction of GRBs that have a late-time X-ray afterglow that appears to be powered by MSP. That is not observed. We have found that out of the 24 GRBs with a measured redshift $z > 4$ and well sampled X-ray afterglow, about half have late-time X-ray afterglows similar to those of the SN-less GRBs at low-$z$ ($z < 0.15$), which consist of about half of the low $z$ GRBs. This favors collapse of neutron stars to quark stars due to mass accretion in HMXBs as the origin of SN-less GRBs over merger of neutron stars due to gravitational wave emission in

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**Table 3**

The Parameters Obtained from the Best-fit Light Curves to the Well-sampled X-Ray Afterglows of GRBs of Known Redshift 0.15 < $z$ < 1, without a Confirmed Association with SN

| SHB     | $z$  | $F_i$ (erg s$^{-1}$ cm$^{-2}$) | $t_i$ (s) | $\tau_i$ (s) | $F_{pe}$ (erg s$^{-1}$ cm$^{-2}$) | $t_b$ (s) | $\chi^2$/dof | $P_i/10^{-12}$ (ms) |
|---------|------|-------------------------------|----------|-------------|-------------------------------|---------|-------------|-------------------|
| 051022A | 0.809| ...                           | 0        | ...         | 1.40E-10                      | 13.007  | 1.48        | 2.63              |
| 060123  | 0.56 | ...                           | 0        | ...         | 2.15E-12                      | 146.432 | 0.85        | 9.25              |
| 080710  | 0.845| ...                           | 0        | ...         | 3.42E-11                      | 6740    | 0.85        | 7.07              |
| 090814A | 0.696| 6.88E-9                       | 0        | 125         | 8.46E-13                      | 33274   | 0.90        | 71.2              |
| 091003  | 0.896| ...                           | 0        | ...         | 7.24E-12                      | 83.890  | 1.19        | 4.10              |
| 091127  | 0.49 | 9.61E-9                       | 0        | 4528        | 7.82E-12                      | 27.775  | 1.14        | 6.34              |
| 101106B | 0.618| 2.55E-11                      | 0        | 511         | 1.56E-11                      | 16.076  | 1.42        | 9.32              |
| 110918A | 0.982| ...                           | 0        | ...         | 3.61E-11                      | 82.033  | 1.24        | 1.69              |
| 111225A | 0.297| 9.27E-9                       | 0        | 237         | 1.46E-12                      | 17.838  | 1.91        | 62.2              |
| 120729A | 0.80 | 2.08E-8                       | 0        | 106         | 3.06E-10                      | 864     | 2.65        | 6.98              |
| 120907A | 0.97 | 9.07E-11                      | 0        | 12691       | 2.38E-12                      | 64.579  | 2.65        | 7.54              |
| 141225A | 0.915| 3.04E-8                       | 0        | 542         | 1.63E-12                      | 23.065  | 0.77        | 16.2              |
| 160623A | 0.367| ...                           | 0        | ...         | 2.40E-9                       | 6261    | 1.15        | 2.07              |
| 160804A | 0.736| 2.81E-7                       | 0        | 136         | 3.47E-12                      | 77.312  | 2.09        | 7.57              |
| 170519A | 0.818| 3.06E-7                       | 0        | 52          | 3.05E-11                      | 11.123  | 1.50        | 6.05              |
| 061110A | 0.758| 3.97E-9                       | 0        | 33          | 2.33E-13                      | 15.8697 | 1.26        | 19.7              |
|         |      | ...                           | 7.76E-11 | 0           | 552                           | ...     | ...         | ...               |
| 080430  | 0.768| 2.56E-9                       | 0        | 67          | 3.64E-13                      | 662.118 | 0.89        | 7.61              |
| 080916A | 0.689| 8.32E-8                       | 0        | 264243      | ...                           | ...     | ...         | ...               |
| 090814A | 0.696| 6.88E-8                       | 0        | 40          | 1.22E-12                      | 146.113 | 1.13        | 9.89              |
|         |      | ...                           | 2.19E-7  | 62767       | ...                           | ...     | ...         | ...               |
| 100621A | 0.542| 6.14E-7                       | 0        | 125         | 8.46E-13                      | 33.274  | 0.90        | 40.4              |
|         |      | ...                           | 2.61E-11 | 1332        | ...                           | ...     | ...         | ...               |
| 151027A | 0.81 | 2.64E-6                       | 91       | 19          | 5.37E-10                      | 5563    | 1.84        | 2.05              |
|         |      | ...                           | 2.37E-8  | 173         | 57                            | ...     | ...         | ...               |

Note. The 18 GRBs shown in Figures 5–7 were fit with Equation (10) and the last 6 GRBs were fit with Equation (4) plus Equation (7). Also listed are the periods of the MSPs at birth, as estimated from the best-fit values of $F_{pe}$ and $t_b$. The index $i$ is the pulse number.
Figure 9. X-ray light curve of the SN-less GRBs 050505, 050814, 050922B, 060927, 090205, and 120521B with $z > 4$ reported in the Swift-XRT GRB light-curve repository (Evans et al. 2007, 2009) and their best-fit light curve for a jet contribution taken over by MSP powered emission, as given by Equation (10) or by Equation (4) plus Equation (7) with the parameters listed in Table 4.
Figure 10. X-ray light curve of the SN-less GRBs 130606A, 140311A, 140419A, 140518A, 140614A, and 151027B with $z > 4$ reported in the Swift-XRT GRB light-curve repository (Evans et al. 2007, 2009) and their best-fit light curve for a jet contribution taken over by MSP powered emission, as given by Equation (10) or by Equation (4) plus Equation (7) with the parameters listed in Table 4.
compact binaries. Such HMXBs may be present mostly in GCs and star formation regions in spiral galaxies, where winds and SN ejecta have already swept away the initial high density ISM.

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