Fast Extragalactic X-ray Transients
From Binary Neutron Star Mergers

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Abstract

The observed light curves and the estimated full sky rate of the extragalactic fast x-ray transients, recently discovered with the Chandra x-ray observatory, indicate that they are early time x-ray afterglows of short gamma ray bursts (SGRBs) which point away from Earth. Their light curves are indistinguishable from those of the early time X-ray afterglows of SGRBs which point to Earth. Their full sky rate is consistent with the estimated rate of newly born millisecond pulsars in binary neutron stars mergers whose spin down seems to power an early time isotropic afterglow of SGRBs.
I. INTRODUCTION

There is mounting evidence [1] that gamma ray bursts (GRBs) and their late time afterglows are produced by highly relativistic jets, which point in the direction of Earth [2]. Distant observers outside their beaming cone miss such GRBs and their early-time afterglow if their angular location $\theta$ relative to the jet axis satisfies $\theta - \theta_j \gg 1/\gamma$, where $\gamma \gg 1$ is the bulk motion Lorentz factor of the jet and $\theta_j$ is its opening angle. However, the deceleration of jets in the interstellar medium decreases $\gamma(t)$ as a function of time after burst and widens the beaming cone of their afterglow radiation. Once $\theta - \theta_j$ becomes smaller than $1/\gamma(t)$, the afterglow of a GRB, which initially is beamed away from Earth, may become visible from Earth. Until recently, however, such orphan GRB afterglows [3] have not been detected. That could be for various reasons, such as lack of a clear signature, luminosity below detection threshold by the time their beaming cone has expanded enough to include Earth, small full sky rates, very small sky coverage in very deep searches, and a small signal to background ratio. However, some of these obstacles may not be present if the early time afterglow of GRBs is not beamed, as seems to be the case in short duration gamma ray bursts (SGRBs) produced by merger of neutron stars in compact neutron star binaries (NSBs).

The production of GRBs in compact NSBs was first suggested in 1984 [4] to be due to explosion of the lighter neutron star after tidal mass loss (so called kilonova), and later in 1987, to be due to neutrino annihilation fireball [5] around the newly born neutron star remnant of the NSB merger due to gravitational wave (GW) emission [6]. But shortly after the launch of the Compton Gamma-Ray Observatory (CGRO) in 1991, its observations of GRBs indicated that neither one of these two mechanisms were powerful enough to produce observable GRBs at the very large cosmological distances of GRBs, which were indicated by the CGRO observations [7]. Thus, in 1994, the fireball mechanism for production of prompt emission in GRBs was replaced by inverse Compton scattering of external light by a highly relativistic jet of plasmoids of ordinary plasma, launched by fall back ejecta on the remnants of NSB mergers and stripped envelope supernova explosions [2]. Following the 1997 discovery by the Italian-Dutch BeppoSAX satellite that GRBs are followed by a long-lived X-ray afterglow [8], the jet model of GRBs [2] has been extended to predict also
the properties of GRBs’ afterglow [9], while the spherical fireball model, which predicted single power-law afterglow light curves [10], had to be replaced by conical fireball models in order to explain the observations.

The first indisputable evidence that NSB mergers due to gravitational wave emission produce SGRBs was provided by GW170817, the first NSB merger detected in gravitational waves by the Ligo-Virgo detectors [11]. GW170817 was followed 1.74±5 s later by the short duration gamma ray burst SHB170817A [12]. Its early-time optical afterglow had a bolometric light curve which was claimed to be produced by a kilonova [13]. But, actually, it could have been an afterglow produced by a pulsar wind nebula (PWN) powered by the spin down of a newly born millisecond pulsar [14], as indicated by the similarity of its bolometric light curve [15] to the ”universal” afterglow [16] of all well sampled early time x-afterglow of SGRBs measured with the Swift x-ray telescope (Swift XRT) [17].

Moreover, the observations of GW170817/SHB170817A not only confirmed the NSB-merger origin of SGRBs, but very large base interferometry (VLBI) radio measurements provided the first direct observational evidence [18] that the late time afterglow of SHB170817A was produced by a narrowly collimated ”superluminal” jet launched in the GW170817 merger event. However, the early time optical afterglow of the low luminosity SHB170817A [12] which was viewed from far off axis, and of almost all well sampled early time x-ray afterglows of ordinary SGRBs viewed near axis, which were measured with the Swift XRT [17], had a ”universal shape” expected from a pulsar wind nebulae powered by the spin down of highly magnetized newly born millisecond pulsars (MSPs) in NSB mergers [16]. This suggests that the early time afterglows of SGRBs are not beamed.

Moreover, in this paper we show that the extragalactic fast X-ray transients (XTs) discovered in the Chandra Deep Field-South (CDF-S) observations [19,20] and the well sampled early time X-ray afterglow of SGRBs [17] share the same ”universal shape” light curves [16] powered by newly born MSPs with a braking index 3. Furthermore, the estimated full sky rate of CDF-S XT2 like events [21] is consistent with that expected from the local cosmic rate of neutron star mergers [22]. They provide solid support to the suggestions that the electromagnetic smoking guns of NSB mergers, whose SGRBs do not point to Earth, are orphan afterglows with a ”universal” shape [16], powered by pulsars born in NSB mergers, and that the light curve of CDF-S XT2 [20] probably is the early time orphan afterglow of such SGRB [19,20,23,24].
II. SGRB AFTERGLOW POWERED BY PULSARS

The early time X-ray afterglows of SGRBs seem to have a universal temporal behavior expected from a pulsar wind nebula powered by a newly born pulsar in neutron star merger (NSM) [14,16]. The spin down energy of a pulsar with a constant moment of inertia $I$, is given by

$$\dot{E} = 4 \pi^2 \nu \dot{\nu} I$$  \hspace{1cm} (1)$$

where $\nu$ is its spin frequency. For a pulsar with braking index $n$ defined by

$$\dot{\nu} = -k \nu^n$$  \hspace{1cm} (2)$$

where $k$ is a time independent constant, the rate of its rotational energy loss is given by

$$\dot{E}(t) = \dot{E}(0)((1 + t/t_b)^{-(n+1)/(n-1)},$$  \hspace{1cm} (3)$$

with

$$t_b = -\nu(0)/(n - 1)\dot{\nu}(0) = P(0)/(n - 1)\dot{P}(0),$$  \hspace{1cm} (4)$$

where $P = 1/\nu$ is the pulsar’s period.

For a spin down dominated by the emission of magnetic dipole radiation (MDR) in vacuum $n=3$ and

$$L(t) = L(0)/(1 + t/t_b)^2,$$  \hspace{1cm} (5)$$

where $L(t) = \dot{E}$. As long as the early time x-ray afterglows of SGRBs from NSB mergers are powered by a constant fraction $\eta$ of the spin down energy of a newly born pulsar with a braking index $n = 3$, the early time x-ray afterglow of both a visible and an invisible SGRBs have the universal behavior,

$$F_x(t)/F_x(0) = [1 + t_s]^{-2}$$  \hspace{1cm} (6)$$

where $F_x(t)$ is the measured energy flux of the X-ray afterglow of the SGRB and $t_s = t/t_b$.

In Figure 1 the reported x-ray light curve of CDF-S XT2 [20], reduced to the dimensionless universal form given by Eq.(6), is compared to the early time light curves of the x-ray afterglow of all SGRBs with a well sampled x-ray afterglow measured with the Swift XRT and reported in the Swift-XRT Light Curves Repository [17]. For each SGRB afterglow the values of the parameters $F_x(0)$ and $t_b$ were obtained from a best fit of Eq.(6) to the the measured light curves. Their values were reported in Table I of [16]. A best fit of
Eq.(6) to the 0.3-10 keV X-ray light curve of CDF-S XT2 [20] has yielded the best fit values, 
\[ F_x(0) = 8.8 \times 10^{-13} \text{erg/cm}^2 \text{s} \text{ and } t_b = 1705 \text{ s}. \]

If the spin down of the newly born pulsar is dominated by magnetic dipole radiation, the 
magnetic field \( B_p \) at the pulsar’s magnetic poles satisfies [25]

\[ B \sin \alpha \approx 6.8 \times 10^{19} [P \dot{P}]^{1/2} \text{ Gauss}, \]  

(7)

where \( P \) is in seconds and \( \alpha \) is the angle of the magnetic poles relative to the rotation axis.

III. LOWER BOUND ON MSP MAGNETIC FIELD

The initial period of the pulsar could be estimated [16] from the best fit parameters \( F_x(0) \), 
\( t_b \) and the luminosity distance of the PWN only when the fraction \( \eta \) of entire spin down 
energy of the pulsar, which has been converted by the PWN to the observed afterglow of 
the SGRB, is known. However, usually the exact geometry of the PWN and the fraction of 
the pulsar spin energy converted to X-ray emission in the PWN are not known. As a result 
the value of \( \eta \) is usually unknown. Moreover there is no reliable evidence that millisecond 
pulsars spin down by the emission of magnetic dipole radiation. That, and the lack of 
reliable evidence that MSPs spin down by magnetic dipole radiation [26] prevents the use of 
Eq.(7) to obtain a reliable estimate of the magnetic field of the neutron star at the magnetic 
poles.

However, if the widespread assumption that MSPs spin down mainly by magnetic dipole 
radiation is correct, then a lower bound on the magnetic field at the poles can be estimated 
from the best fit value of \( t_b \) obtained from the best fit of Eq.(6) to the early X-ray afterglow 
of SGRBs powered by newly born pulsars, as follows. Substitution of the lower classical 
limit \( P \geq 2\pi R/c \approx 0.2 \text{ ms} \) for a canonical pulsar with a radius \( R \approx 10 \text{ km} \) and a surface 
velocity equal to the speed of light, and substituting it in Eq. (6), and the use of the relation 
\( \dot{P}(0) = P(0)/2 t_b \) valid for a braking index \( n = 3 \), which is valid for a constant magnetic field 
in vacuum, imply the lower limit,

\[ B_p(0) \gtrsim 10^{16} \sqrt{(1 + z)/(t_b/s)} \text{ Gauss}. \]  

(8)

Eq.(8) yields \( B_p(0) \gtrsim 3 \times 10^{14} \text{ Gauss} \) for CDF-S XT2 at its redshift \( z = 0.735 \) [20].
FIG. 1: Comparison between the scaled 0.3-10 keV light curves of the well sampled X-ray afterglow of SGRBs during the first couple of days after burst measured with the Swift XRT [17] and the 0.3-10 keV light curve of CDF-S XT2 [20]. The line is the expected universal behavior given by Eq.(6) of a PWN afterglow powered by a newly born millisecond pulsar with a braking index $n = 3$. 

**SHBs**

CDF-S XT2 (squares)

- 051221A 051227
- 060313 060614
- 070724A 070809
- 090510 120308A
- 130603B 150423A
- 150424A 170817A
IV. THE FULL SKY RATE OF ORPHAN SGRB AFTERGLOWS

If the cosmic rate of NSB mergers in a comoving volume as a function of redshift \( z \) is proportional to the star formation rate, \( SFR(z) \), e.g., if they are produced mainly by fission of fast rotating cores in core collapse supernova explosions of massive stars, then the production rate of pulsar powered afterglows by NSB mergers in a comoving volume is given by [27]

\[
\frac{d\dot{N}}{dz} \propto SFR(z) \frac{dV_c(z)}{dz} \frac{1}{1+z}
\]  
(9)

where \( dV_c(z)/dz \) is the comoving volume at redshift \( z \). In a standard ΛCDM cosmology, \( dV_c(z)/dz \) is given by

\[
\frac{dV_c(z)}{dz} = \frac{c}{H_0} \frac{4 \pi [D_c(z)]^2}{\sqrt{(1+z)^3 \Omega_M + \Omega_\Lambda}},
\]  
(10)

where \( H_0 \) is the current Hubble constant, \( \Omega_M \) and \( \Omega_\Lambda \) are, respectively, the current density of ordinary energy and of dark energy, in critical energy-density units, and \( D_c(z) \) is the comoving distance at a redshift \( z \), which satisfies

\[
D_c(z) = \frac{c}{H_0} \int_0^z \frac{dz'}{(1+z')^{3 \Omega_M + \Omega_\Lambda}}.
\]  
(11)

In order to estimate the full sky rate of NSB mergers, \( \dot{N}(z) \), as given by Eqs.(9-11) we have adopted the current best values of the cosmological parameters obtained from the combined WMAP and Planck data [28]: a Hubble constant \( H_0 = 67.4 \text{ km/s Mpc}^{-1} \), \( \Omega_M = 0.315 \) and \( \Omega_\Lambda = 0.685 \) and the SFR\((z)\) compiled and standardized in [29] and [30] from optical measurements. This standardized SFR\((z)\) is well approximated [27] by a log-normal distribution,

\[
SFR(z) \approx 0.25 e^{-[\ln((1+z)/3.16)]^2/0.524} \text{ M}_\odot \text{Mpc}^{-3} \text{y}^{-1}.
\]  
(12)

Assuming that the cosmic rate of neutron star mergers (NSMs) as a function of redshift is proportional to the star formation rate \( SFR(z) \) given by Eq.(12), and that the rate of NSMs in a comoving volume of Gpc\(^3\) is \((1540 + 3200/ - 1200) \text{ Gpc}^{-3} \text{y}^{-1}\), as estimated in [11] from the Ligo-Virgo GW observations, then the expected full sky rate \( \dot{N}(\leq z) \) of NSMs in the standard cosmological model with the updated values of the cosmological parameters measured with Planck [28], is shown in Figure 2. This rate, to a good approximation, is also the expected rate of orphan early time afterglows produced by the majority of SGRBs which
point away from Earth. Their full sky rate obtained from their estimated rate \(\frac{59 + 77}{-38}\) event \(\text{yr}^{-1} \text{deg}^{-2}\) in [21] from the CDF-S observations of XT1 and XT2 [19] is also indicated in Figure 2.

V. CONCLUSIONS

The observed light curve of CDF-S-XT2 recently discovered with the Chandra x-ray observatory [20] and the estimated full sky rate [21] of such extragalactic fast x-ray transients seem to support the conclusion that they are early time orphan afterglows of short gamma ray bursts powered by the newly born millisecond pulsars in neutron star mergers. The estimated strength of the dipole magnetic field of these newly born pulsars from the afterglow which they power depends on the assumption that their spin down is dominated by magnetic dipole radiation, which may or may not be true. The typical signature of orphan afterglows of SGRBs - a fast rise after burst followed by a short plateau phase of a few thousands seconds which turns into a fast temporal decline may explain why such transients have not been found so far in searches of electromagnetic afterglows of SGRBs from the nearby binary neutron star merger candidates detected recently in gravitational wave by Ligo-Virgo [31]. Fast extragalactic x-ray transients, such as XRT 000519 and XRT 110103 [32], and CDF-S XT1 [19], which unlike CDF-S XT2 [20] did not have the "universal shape" of early time light curves of SGRBs, could have been LGRBs viewed far off axis and appear as X-ray flashes [33].

Acknowledgements: We thank Peter Jonker and Yongquan Xue for useful comments.
FIG. 2: The expected full sky rate of neutron stars merger (NSM) with redshift $\leq z$, as a function of $z$. The calculated rate is based on the standard cosmological model and the assumption that the NSM rate as a function of redshift $z$ is proportional to the observed star formation rate, SFR($z$), as parametrized in Eq.(12). The full and thin lines correspond to the estimated rate and its errors in a comoving $Gpc^3$ volume reported in [11] by the Ligo-Virgo collaboration. The inserted point is the full sky rate estimated in [21] from the CDF-S XT1 and XT2 events.
[1] S. Dado & A. Dar, arXiv:1810.03514 and references therein.

[2] N. Shaviv, A. Dar, ApJ, 447, 863 (1995). arXiv:astro-ph/9407039.

[3] J.E. Rhoads, ApJ, 525, 737 (1999) arXiv:astro-ph/9903399.

[4] S.I. Blinnikov, et al., PAZh, 10 (1984) 422.

S.I. Blinnikov, et al. SvAL, 10 (1984) 177 arXiv:1808.05287.

[5] J. Goodman, A. Dar, S. Nussinov, ApJ, 314 (1987) L7.

[6] J. H. Taylor, J. M. Weisberg, ApJ, 253, 908 (1982).

[7] C. A. Meegan, et al., Nature, 355, 143 (1992).

[8] E. Costa, et al., Nature, 38, 783 (1997) arXiv:astro-ph/9706065.

[9] A. Dar, ApJ, 500, L93, (1998) arXiv:astro-ph/9709231.

[10] R. A. M. J. Wijers, M. J. Rees, P. Meszaros, MNRAS, 288, L51 (1997) arXiv:astro-ph/9704153.

[11] B. P. Abbott, et al. [Ligo-Virgo Collaboration], PRL, 119, 161101 (2017) arXiv:1710.05832.

ApJ, 848, L12 (2017) arXiv:1710.05834; ApJ, 851, L16 (2017) arXiv:1710.09320.

[12] A. Goldstein, et al., ApJ, 848, L14 (2017) arXiv:1710.0544.

[13] LX. Li, B. Paczynski, ApJ, 507, L59 (1998) arXiv:astro-ph/9807272.

[14] S. Dado & A. Dar, NCC, 41, 131 (2018) arXiv:1708.04603.

[15] M. R. Drout, A. L. Piro, OB. J. Shappee, et al., Sci. 358, 1570 (2017) arXiv:1710.054431.

[16] S. Dado, A. Dar, PRD, 99, 123 (2019) arXiv:1807.08726.

[17] P. A. Evans et al., MNRAS, 397, 1177 (2009) arXiv:0812.3662.

P. A. Evans et al., A&A, 469, 379 (2007) arXiv:0704.0128.

[18] K. P. Mooley, et al., Nature 561, 355 (2018) arXiv:1806.09693.

[19] F. E. Bauer, E. Treister, K. Schawinski, et al., 2017, MNRAS, 467, 4841 (2017) arXiv:1702.04422.

[20] Y. Q. Xue, et al., Nature, 568, 198 (2019) arXiv:1904.05368.

[21] G. Yang, W. N. Brandt, S. F. Zhu, F. E. Bauer, B. Luo, Y. Q. Xue, X. C. Zheng arXiv:1906.02793.

[22] B. P. Abbott, et al. [Ligo-Virgo Collaboration], PRL, 119, 161101 (2017) arXiv:1710.05832.

[23] D. Xiao, B. B. Zhang, Z. G. Dai, ApJ 879, L7 (2019) arXiv:1904.05480.
Other mechanisms by which newly born MSPs power GRBs and/or their afterglows were suggested, e.g., by

E. Blackman, I. Yi, ApJ, 498, L31 (1998) [arXiv:astro-ph/9802017].
Z. G. Dai and T. Lu, PRL, 81, 4301 (1998) [arXiv:astro-ph/9810332].
Z. G. Dai and T. Lu, A&A, 333, L87 (1998) [arXiv:astro-ph/9810402].
B. Zhang and P. Meszaros, ApJ, 552, L35 (2001) [arXiv:astro-ph/0011133].
Z. G. Dai et al., Science 311, 1127 (2006) [arXiv:astro-ph/0602525].
B. D. Metzger, E. Quataert, T. A. Thompson, MNRAS, 385, 1455 (2008) [arXiv:0712.1233].
A. Rowlinson, et al., MNRAS 409, 531 (2010) [arXiv:1007.2185].
B. D. Metzger, A. L. Piro, MNRAS, 439, 3916 (2014) [arXiv:1311.1519].
B. P. Gompertz, P. T. O’Brien, G. A. Wynn, MNRAS, 438, 240 (2014) [arXiv:1311.1505].
H. Lu, B. Zhang, W. Lei, Y. Li, P. D. Lasky, MNRAS, ApJ, 805, 89 (2015) [arXiv:1501.02589].
S. Gibson, G. Wynn, B. Gompertz, P. O’Brien, MNRAS, 470, 4925 (2017) [arXiv:1706.04802].

Origin ally, magnetars were defined to be pulsars powered by the decay of their ultrastrong magnetic field. Anomalous X-ray pulsars (AXPs) and soft gamma ray repeaters (SGRs), whose observed luminosity was found to exceed their loss of rotational energy [see, e.g., S. Mereghetti, AAR, 15, 225 (2008) [arXiv:0804.0250]], were the first discovered pulsars with a luminosity exceeding their spin down energy release. They were assumed to be powered by the decay of their assumed ultrastrong magnetic field. More recently, the name magnetars was extended to include millisecond pulsars (MSPs) whose spin down was assumed to be dominated by the emission of magnetic dipole radiation. See, e.g., [24].

S. Dado & A. Dar, ApJ, 785, 70 (2014) [arXiv:1307.5556].
N. Aghanim, et al., (Planck Collaboration), 2018 e-Print: arXiv:1807.06209.
A. M. Hopkins, J. F. Beacom, ApJ, 651, 142 (2006) [arXiv:astro-ph/0601463].
N. A. Reddy, & C. C. Steidel, ApJ, 692, 778 (2009) [arXiv:0810.2788].
The Ligo-Virgo Scientific Collaboration, GCN Circulars 24168, 24237, 24442 (2019).
P. G. Jonker, et al., ApJ, 779, 14 (2013) [arXiv:1310.7238].
A. Glennie, P. G. Jonker, R. P. Fender, T. Nagayama, M. L. Pretorius, MNRAS, 450, 3765 (2015) [arXiv:1504.03720].
S. Dado, A. Dar, A. De Rujula, A&A, 422, 381 (2004) [arXiv:astro-ph/0309294].