Fast extragalactic x-ray transients from binary neutron star mergers

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The observed light curves and other properties of the two extragalactic fast x-ray transients, CDF-S XT1 and CDF-S XT2, which were discovered recently in archival data of the Chandra Deep Field-South (CDF-S) observations, indicate that they belong to two different populations of x-ray transients. XT1 seems to be an x-ray flash, i.e., a narrowly beamed long duration gamma ray burst viewed from far off axis, while XT2 seems to be a nebular emission powered by a newly born millisecond pulsar in a binary neutron stars merger.

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I. INTRODUCTION

The first detection of neutron star binary (NSB) merger GW170817, in gravitational waves, by the Ligo-Virgo detectors [1], was followed 1.74 ± 0.5 s later by a short duration gamma ray burst (SGRB) 170817A [2]. They provided the first indisputable evidence that NSB mergers produce SGRBs [3]. Moreover, the follow-up observations of the radio afterglow of GRB170817A with very large base interferometry provided the first direct observational evidence [4] that NSB mergers launch narrowly collimated jets of "superluminal" plasmoids which produce narrowly beamed SGRBs [5] with narrowly beamed afterglow [6]. Such electromagnetic counterparts of NSB mergers are mostly beamed away from the direction of the Earth and are not observable. However, a good fraction of the observed near axis SGRBs have a well sampled x-ray afterglow right after the prompt emission (and extended emission, when present), which shows a "universal" temporal behavior [7] and a power-law spectrum. This x-ray emission, most probably is produced by a newly born millisecond pulsar (MSP), which powers an isotropic nebular emission [8]. It is the smoking gun of NSB mergers with MSP remnant, which is detectable up to very large cosmological distances [8].

Recently, two extragalactic fast x-ray transients, CDF-S XT1 [9] associated with a faint galaxy at a photometric redshift $z_{ph} \sim 2.2$ and CDF-S XT2 associated with a galaxy at redshift $z = 0.738$ [10], were discovered in archival data of the Chandra Deep Field-South (CDF-S) observations. It was suggested by their discoverers that both are x-ray nebular emission powered by the spin-down of newly born magnetars in NSB mergers [10,11]. In this paper, we provide supportive evidence that CDF-S XT2 was an early time nebular x-ray emission powered by remnant MSP [10,11,12] born in NSB merger [13]. However, the light curve of CDF-XT1 indicates that, more likely, it was an x-ray flash (XRF), i.e., a prompt emission pulse of a narrowly beamed long duration gamma ray burst (LGRB) viewed from far off axis [14,15], rather than a nebular emission powered by the spin-down of a newly born MSP in NSB merger.

II. ORPHAN X-RAY AFTERGLOWS OF GRBS

There is mounting observational data indicating [16] that LGRBs and SGRBs are narrowly beamed along the direction of motion of highly relativistic jets of plasmoids which produce them [5]. Distant observers located outside the beaming cone of such jets miss their prompt gamma ray emission and their beamed afterglows [5]. However, the deceleration of jets in the circumburst medium decreases their bulk motion Lorenz factor $\gamma(t)$ and widens the beaming cone of their radiation. Once their beaming cone includes the distant observer, their afterglow radiations become visible. However, so far, no such orphan GRB afterglows [17] have been detected. That could have been because of various reasons, such as lack of a unique signature, a luminosity below detection threshold by the time their beaming cone has expanded enough to include the Earth, a very small sky coverage in very deep searches, and a small signal to background ratio.

Another type of orphan x-ray transients, which can be seen from large cosmic distances, is an isotropic nebular emission powered by the spin-down of a newly born MSP in NSB mergers which do not produce SGRBs or produce narrowly beamed SGRBs which do not point to the Earth [7]. In that case, both the fast x-ray transient and the x-ray afterglow of SGRBs after the prompt, and extended emission if present, have the same universal shape light curve and a spectrum expected from a nebular emission powered by a newly born MSP [8,10,11,12]. Such an MSP powered emission can be seen from very large cosmological distances [8]. Moreover, even if the birth of an MSP in NSB merger is not accompanied by SGRB, the x-ray nebular emission powered by the spin-down of the MSP is expected to be like that present in a large fraction of the SGRBs [8] whose early time x-ray afterglow was well sampled.

Below, we first show that the extragalactic fast x-ray transient CDF-S XT2 discovered in the Chandra Deep Field-South observations [10] and a large fraction of the well sampled early time x-ray afterglow of SGRBs share the same universal shape light curves [8] powered by newly born MSPs. Next, we show that the estimated full sky rate of CDF-S XT2-like events [18] is consistent with that expected from the local cosmic rate of neutron star mergers [19]. Together, they provide supporting evidence to the suggestion [10,11,12] that CDF-S XT2 [10] probably was the early time nebular emission powered by the spin-down of a newly born pulsar in NSB merger.

III. NEBULAR EMISSION POWERED BY NEWLY BORN MSPS

The spin-down energy release by a pulsar with a constant moment of inertia I is given by

$$\dot{E} = 4\pi^2 \nu\dot{\nu} I, \tag{1}$$

where ν is its spin frequency. For a pulsar with braking index n defined by

$$\dot{\nu} = -k\nu^n, \tag{2}$$

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

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

with

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

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

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

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

where $L(t) = \dot{E}$. As long as the early time x-ray afterglows of SGRBs from NSB mergers are pulsar wind nebula (PWN) emission powered by a constant fraction η 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,

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

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

In Fig. 1, the reported x-ray light curve of CDF-S XT2 [10], reduced to the dimensionless universal form given by Eq. (6), is compared to the early time light curves of the x-ray afterglow after the prompt and extended emission (if present) of about half of the SGRBs with a well sampled x-ray afterglow measured with the Swift XRT and reported

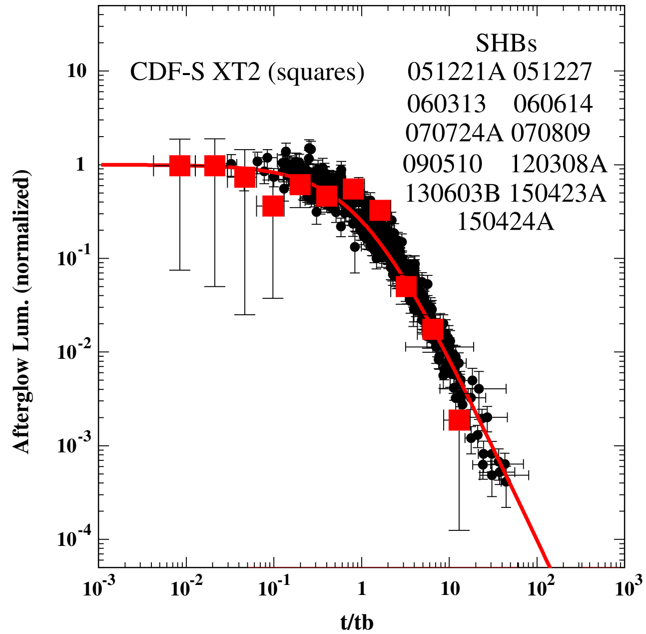

FIG. 1. Comparison between the scaled 0.3–10 keV light curves of the well sampled x-ray afterglow of SGRBs during the first couple of days after burst and extended emission (when present) measured with the Swift XRT [20] and the 0.3–10 keV light curve of CDF-S XT2 [10]. The line is the expected universal behavior given by Eq. (6) of a PWN afterglow powered by a newly born millisecond pulsar with a braking index $n = 3$.

in the Swift-XRT Light Curves Repository [20]. 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 measured light curves. Their values were reported in Table I of [7]. A best fit of Eq. (6) to the 0.3–10 keV x-ray light curve of CDF-S XT2 [10] has yielded the best fit values, $F_x(0) = 8.8 \times 10^{-13}$ erg/cm^2 s and $t_b = 1705$ s.

IV. LOWER BOUND ON MSP MAGNETIC FIELD

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 [21]

$$B \sin\alpha \approx 6.8 \times 10^{19} [P\dot{P}]^{1/2} \text{ Gauss}, \tag{7}$$

where P is in seconds and α is the angle of the magnetic poles relative to the rotation axis.

The initial period of the pulsar could be estimated [7] from the best fit parameters $F_x(0)$, t_b, and the luminosity distance of the PWN only when the fraction η 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 η 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 [22] 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 $P \geq 2\pi R/c \approx 0.2$ ms for a canonical pulsar with a radius $R \approx 10$ km and a surface velocity equal to the speed of light, and substituting it in Eq. (6), and the use of the relation $\dot{P}(0) = P(0)/2t_b$ valid for a braking index $n = 3$, which is valid for a constant magnetic field in vacuum, imply the lower limit,

$$B_p(0) \gtrsim 10^{16}\sqrt{(1+z)/(t_b/s)}\ \text{Gauss}. \tag{8}$$

Equation (8) yields $B_p(0) \gtrsim 3 \times 10^{14}$ Gauss for CDF-S XT2 at redshift $z = 0.738$ [10] and $t_b = 1705$ s from our best fit light curve shown in Fig. 1.

V. THE FULL SKY RATE OF ORPHAN MSP POWERED 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 a fast rotating core in core collapse supernova explosions of massive stars [23], then the production rate of pulsar powered afterglows by NSB mergers in a comoving volume is given [24] by

$$\frac{d\dot{N}}{dz} \propto \text{SFR}(z)\frac{dV_c(z)}{dz}\frac{1}{1+z}, \tag{9}$$

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

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

where H_0 is the current Hubble constant, Ω_M and Ω_Λ 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

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

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 [25]: a Hubble constant $H_0 = 67.4$ km/s Mpc, $\Omega_M = 0.315$, and $\Omega_\Lambda = 0.685$ and the SFR(z) compiled and standardized in [26] and [27] from optical measurements. This standardized SFR(z) is well approximated [24] by a log-normal distribution,

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

Assuming that the cosmic rate of NSB mergers as a function of redshift is proportional to SFR(z) given by Eq. (12), and that the rate of NSB mergers in a comoving volume of Gpc^3 is $(1540 + 3200/-1200)\ \text{Gpc}^{-3}\,\text{y}^{-1}$, as estimated in [1] 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 [25], is shown in Fig. 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 the Earth. Their full sky rate obtained from their estimated rate $59 + 77/-38$ evt $\text{y}^{-1}\,\text{deg}^{-2}$ in [18] from the CDF-S

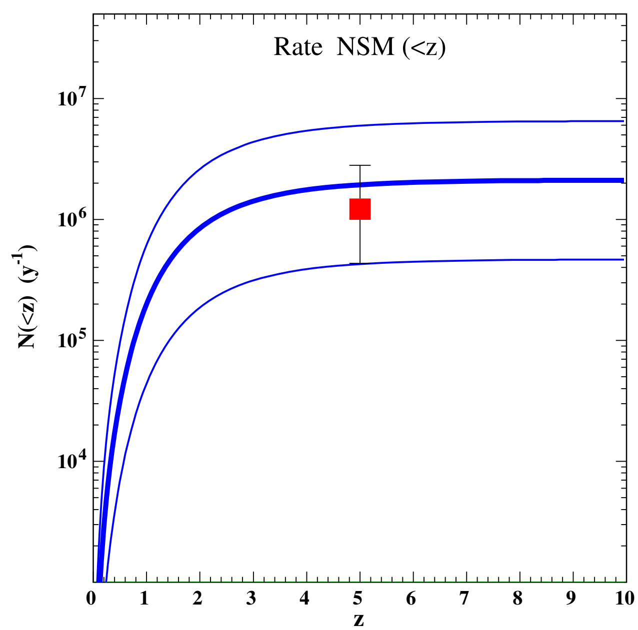

FIG. 2. The expected full sky rate of NSB mergers with redshift $\leq z$, as a function of z. The calculated rate is based on the standard cosmological model and the assumption that the NSB merger rate as a function of redshift z is proportional to the observed star formation rate, SFR(z), as parametrized in Eq. (12). The full and thin lines correspond to the estimated rate and its errors in a comoving Gpc^3 volume reported in [1] by the Ligo-Virgo Collaboration. The inserted point is the full sky rate estimated in [18], after subtracting the contribution of CDF-S XT1.

observations of XT1 and XT2, after subtracting the contribution of XT1, is also indicated in Fig. 2.

VI. CDF-S XT1 AS FAR OFF AXIS LGRB

In the cannonball model of GRBs, the predicted pulse shape above a minimal energy E_m of prompt emission pulses of GRBs has the behavior [16,28]

$$\frac{dN_\gamma(E>E_m)}{dt} \propto \frac{t^2\exp[-E_m/E_p(t)]}{(t^2+\Delta^2)^2}, \qquad (13)$$

where $E_p(t)$ is the peak energy at time t. For XRFs, i.e., far off axis GRBS, the exponential factor on the right-hand side of Eq. (13) can be neglected, which yields a full width at half maximum FWHM $\approx 2\Delta$, a rise time $RT \approx 0.59\Delta$ from half peak to peak at $t=\Delta$, and a decay time $DT \approx 1.41\Delta$ from peak to half peak. This pulse shape is in good agreement with that observed in resolved, well sampled GRB pulses [28]. Figure 3 shows a comparison between Eq. (13) and the measured light curve of CDF-S XT1. The best fit normalization, a pulse start-up time $t_0 = 38.8$ s, and $\Delta = 50.6$ s yield $\chi^2/\text{d.o.f.} = 4.52/9 = 0.50$.

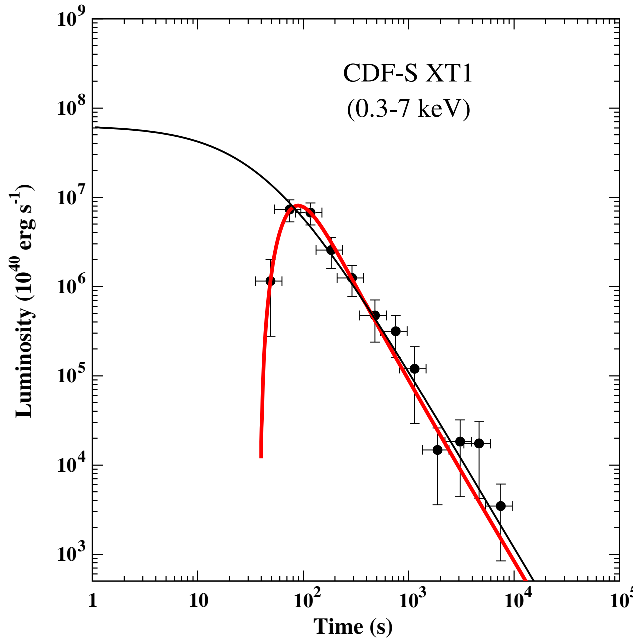

FIG. 3. Comparison between the observed pulse shape of CDF-S XT1 [9] in the 0.3–7 keV x-ray band and (a) the expected pulse shape of far off axis LGRB pulse as given by Eq. (13) (thick red line) with the best fit parameters listed in the text, which yield $\chi^2/df = 0.50$, (b) the best fit universal shape of a nebular x-ray emission powered by the spin-down of a newly born MSP (thin black line), as given by Eq. (5).

VII. CONCLUSIONS

The observed light curve of CDF-S-XT2 recently discovered with the Chandra x-ray observatory [10] and the estimated full sky rate of such extragalactic fast x-ray transients [18] support the conclusion that it was an early time nebular emission powered by a newly born millisecond pulsar with a strong magnetic field, $B \gtrsim 10^{14}$ Gauss in a neutron stars binary merger, which probably produced SGRB beamed away from the direction of the Earth [8,10,11,12]. 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 typically a few thousands of seconds, which turns into a fast temporal decline, may partially 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 in gravitational wave by Ligo-Virgo in run O3 [29]. Fast extragalactic x-ray transients, such as CDF-S XT1 [9], unlike CDF-S XT2 [10], do not have the universal shape of an early time pulsar powered afterglow of SGRB [7]. Its light curve has the shape of well resolved prompt emission pulses of LGRBs viewed far off axis, i.e., of XRFs, and which were discovered in archival CDF data [30] long before the discovery of CDF-S XT1 [9].

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