Universal Afterglow Of Supernova-Less Gamma Ray Bursts

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The well-sampled afterglows of gamma ray bursts (GRBs) not associated with a supernova (SN) explosion, can be scaled down to a simple dimensionless universal formula, which describes well their temporal behavior. Such SN-less GRBs include short hard bursts (SHBs) and long SN-less GRBs. The universal temporal behavior of their afterglows is that expected from a pulsar wind nebula powered by the rotational energy loss of the newly born millisecond pulsar.

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Introduction. Gamma-ray bursts (GRBs) are brief flashes of gamma rays lasting between few milliseconds and several hours [1] from extremely energetic cosmic explosions [2]. They were first detected in 1967 by the USA Vela spy satellites. Their discovery was published in 1973 after 15 such events were detected [3]. GRBs fall roughly into two classes [4], long duration ones (Long GRBs) that last more than $\sim 2$ seconds, and short hard bursts (SHBs) that typically last less than 2 seconds. For 3 decades after their discovery, the origin of both types were completely unknown. This has changed dramatically by the first X-ray localization of GRBs and the discovery of their X-ray afterglow with the BeppoSAX satellite, which led also to the discovery of GRBs’ afterglow at longer wave lengths, their host galaxies and their redshifts [5], and to the detailed measurements with ground and space based telescopes of the properties of the prompt and afterglow emissions of GRBs, of the environments of GRBs and of their host galaxies.

The late-time afterglow of GRB970228, the first localized GRB by BeppoSAX, also included photometric evidence of an associated supernova [6] which met skepticism, as did [7] the original suggestions of a GRB-SN association [8] long before this first observational evidence. Only when photometric and spectroscopic evidence [9] for other SN-GRB associations has been accumulated over a few years from relatively nearby long GRBs, the SN-GRB association became widely accepted. Moreover, it was also believed (e.g. [10]) that in all ordinary long duration GRBs where an associated supernova of type Ic akin to 1998bw was not seen, it was because it was too distant, and/or overshadowed by the GRB afterglow and/or by the light of the host galaxy, or simply was not looked for.

However, deep optical searches of SNe associated with several relatively nearby long GRBs have failed to detect an associated SN [11]. They provided compelling evidence that SN explosions are not the only source of long duration GRBs. But their origin has not been established beyond doubt and is still debated.

As for SHBs, until recently they were widely believed to be produced in merger of neutron stars [12] in compact binaries, as first suggested three decades ago [13], and perhaps in neutron star-black hole (n*bh) mergers [14]. But, this wide belief was based on indirect evidence [12]. Recently, however, SHB170817A that followed $\sim 1.7s$ after GW170817 [15], the first direct detection of gravitational waves emitted from a neutron stars merger (NSM), with the Ligo-Virgo GW detectors [16], has shown beyond doubt that neutron star mergers do produce SHBs.

In this letter, we show that all the well sampled X-ray afterglows of SN-less GRBs within the first couple of days after burst, have a temporal behavior, which can be scaled down to a simple dimensionless universal form. This simple form, is expected if the afterglows of SHBs and long SN-less GRBs during the first couple of days after burst are dominated by the emission of a pulsar wind nebula (PWN) powered by the newly born millisecond pulsar [17]. Several implications of this observation are shortly discussed.

Universal MSP Afterglows. As long as the spin-down of a pulsar with a period $P(t)$ satisfies $PP = \text{const}$, 

$$P(t) = P_{i}(1 + t/t_{b})^{1/2}, \quad (1)$$

where $P_{i} = P(0)$ is the initial period of the pulsar, $t$ is the time after its birth, and $t_{b} = P_{i}/2\dot{P}_{i}$. If a constant fraction $\eta$ of the rotational energy loss of such pulsar is reradiated by the PWN, then, in a steady state, its luminosity satisfies $L = \eta I w w$, where $w = 2\pi/P$ and $I$ is the moment of inertia of the neutron star. Hence, in a steady state, the luminosity emitted by a PWN satisfies

$$L(t) = L(0)/(1 + t/t_{b})^{2}. \quad (2)$$

Eq.(2) can be written as

$$L(t)/L(0) = 1/(1 + t_{s}/t_{b})^{2}, \quad (3)$$

where $t_{s} = t/t_{b}$. Thus, the dimensionless luminosity $L(t)/L(0)$ has a simple universal form as function of the scaled time $t_{s}$. For each afterglow of an SN-less GRB (long or short) powered by a pulsar, $L(0)$ and $t_{b}$ can be obtained from a best fit of Eq.(2) to the light curve of their measured afterglow.

The initial period of the pulsar enshrouded within a PWN can be estimated from its locally measured energy flux $F(0)$ corrected for absorption along the line of sight to the PWN, its redshift $z$, and its luminosity distance $D_{L}$.

$$P_{i} = \frac{1}{D_{L}} \sqrt{(1+z)\frac{\eta \pi I}{2 F(0) t_{b}}}, \quad (4)$$

$$F(0) = \frac{\eta \pi I}{2 \dot{I} t_{b}} \left(1 + \frac{1}{2\dot{P}_{i}} \right) = \frac{\eta \pi I}{2 \dot{P}_{i}} \omega, \quad (5)$$
where $F = L/4 \pi D_L^2$, $I \approx (2/5) M R^2 \approx 1.12 \times 10^{45} \text{ g cm}^2$, for a canonical pulsar with $R = 10 \text{ km}$ and $M \approx 1.4 M_\odot$, and $q < 1$. The period derivative can be obtained from the relation $P_i = P_i/2 t_b$.

**Comparison with experiments.** In [18], we have fitted the X-ray lightcurves of all SHBs with a well sampled afterglow measured with the Swift XRT [19], assuming the cannonball model for the prompt and extended emission and Eq.(2) for the taking-over afterglow. Figure 1 demonstrates such a fit for SHB150424A.

Eqs.(2),(3) are expected to be valid only after the last accretion episode on the newly born pulsar, and after the PWN emission powered by the pulsar's power supply has reached a steady state. Since the exact times of both are not known, and in order to avoid a contribution from the prompt emission, we have fitted the observed afterglows of SHBs and long SN-less GRBs with Eq.(2) only well after the fast decline of the prompt emission (last pulse/flare or extended emission). This also made unimportant the lack of knowledge of the exact birth time/power supply of the MSP. In Figure 2 we plotted the dimensionless X-ray afterglow of 12 SHBs with the best sampled afterglows measured with the Swift XRT [20] in the first couple of days after burst and the universal behavior given by Eq.(3). The values of $L(0)$ and $t_b$ needed to reduce each measured lightcurve to the dimensionless form, were obtained for each SHB, from a best fit of Eq.(2) to the observed plateau followed by a fast decline phase of the X-ray afterglow.

The predicted universal behavior of the afterglow of long SN-less GRBs as given by Eq.(2) is compared in Figure 3 to the observed afterglow lightcurves of the long duration GRB990510, in the X-ray [21] and optical I, R, V, B bands, [22] rescaled according to Eq.(3) to dimensionless values, and plotted as a function of $t/t_b$.

Unlike SHBs, long GRB seem to be divided to two classes [23], SN-GRBs and SN-less GRBs. Only in relatively near by long GRBs the GRB class can be identified by deep searches of an associated SN. However, long SN-GRBs are produced mostly in star formation regions within molecular clouds of relatively high density. In such cases the GRB afterglow seems to be dominated by the synchrotron radiation emitted from the deceleration of the highly relativistic jet in the dense ISM. The spectral energy density of the emitted afterglow is well described by a smoothly broken power-law with a spectral index $\beta$ and a temporal decay index $\alpha$ which well after the ”break” satisfies the closure relation $\alpha = \beta + 1/2$ predicted by the CB model of GRBs [24]. This relation seems to be well satisfied by long SN-GRBs but not by SN-less GRBs. It was used to identify long SN-GRBs whose afterglow was produced by synchrotron emission from a decelerating highly relativistic jet [25].

The dimensionless afterglow of 12 long SN-less GRBs with the best sampled afterglows during the first couple of days after burst measured with the Swift XRT [19] in 2005, the first year of GRB observations with Swift, and in first half of 2018, are compared in Figure 4 to the universal behavior given by Eq.(3). The parameters $L(0)$ and $t_b$ needed to reduce each measured lightcurve to the dimensionless form were obtained from a best fit of Eq.(2) to the plateau and the following fast decline...
FIG. 3: Comparison between the observed afterglow of GRB990510 in the X-ray \cite{21} and optical I, R, V, B bands \cite{22} rescaled according to Eq.(2) and plotted as function of $t/t_b$, and their predicted universal form as given by Eq.(3).

FIG. 4: Comparison between the normalized light curve of the X-ray afterglow measured with Swift XRT \cite{19} of 12 SN-less GRBs with a well sampled afterglow in the first couple of days after burst and their predicted universal behavior as given by Eq.(3)

phase of the X-ray afterglow of each SHB.

Tables I,II summarize the parameters in Eq.(2) which best reproduce the X-ray afterglow of the 26 SN-less GRBs listed in Figures 1-4, and the pulsar periods derived from them using Eq.(4) and assuming $\eta=1$.

**Discussion and conclusions:** All the well sampled afterglows of SHBs within a few days after burst are well described by Eqs.(2),(3) as shown in Figures 1,2. That, and the detection of SHB170817A \cite{15}, which followed the detection of gravitational waves (GWs) from the $n^*n^*$ merger GW170817 by the Virgo-Ligo GW detector \cite{16}, indicate that SHBs are produced mainly by merger of binary neutron stars \cite{13} and not by neutron star - black hole mergers \cite{14}.

Long GRBs seem to consist of two distinct populations, SN-less GRBs and SN-GRBs. An SN-less identity was established observationally only for relatively nearby GRBs by very deep searches \cite{11}. In more distant GRBs, an SN-less identity could not be established because the SN could have been overshadowed by the GRB afterglow and/or the host galaxy, or simply was not looked for.

An indirect way of identifying SN-less GRBs is the characteristic universal afterglow of SN-less GRBs, which is very different from the afterglow of of SN-GRBs: The late-time afterglow of long SN-GRBs seems to have a spectral energy flux density, which is well described by $F_\nu \propto t^{-\alpha} \nu^{-\beta}$ with $\alpha = \beta + 1/2$, as predicted \cite{24} by the cannonball (CB) model of SN-GRBs, where a highly relativistic jet of CBs ejected in an SNeIc explosion produces the afterglow by synchrotron radiation emitted from the decelerating jet in the interstellar medium (ISM).

The afterglow of SN-less GRBs seems to be quite different. It has a simple temporal behavior, which is well described by Eq.(2) and can be scaled down to the universal dimensionless behavior given by Eq.(3). We have verified that almost all the well sampled afterglows of long GRBs without an identified associated SNe, and which do not satisfy the above late time closure relation of SN-GRBs, seem to satisfy Eqs.(2),(3). But, due to space limitation and clarity, this is demonstrated in Figure 3 for GRB990510 and in Figure 4 for all the GRBs with well sampled afterglows measured with the Swift XRT during its first year after launch, and in the present year 2018 until the submission date of this letter. Such an afterglow behavior is expected from a PWN emission powered by a newly born MSP \cite{18,23} in SN-less GRB.

Figure 3 is included in order to demonstrate that the claims in the title of \cite{21} ”BeppoSAX confirmation of beamed afterglow emission from GRB 990510” and in \cite{22} ”Optical and Radio Observations of the Afterglow from GRB990510: Evidence for a Jet” were misleading and based on arbitrary parametrizations of beliefs rather than on solid evidence and critical science.

Figure 4 clearly demonstrates that although the relation $\dot{P} \propto \dot{P} = const$ has been derived \cite{26} for pulsars which spin down by magnetic dipole radiation (MDR) (in vacuum, assuming time-independent magnetic field and moment of inertia during spin down), the GRB data suggests that it may be more general. For instance, it is satisfied to a good accuracy by the Crab pulsar, despite the fact that the total luminosity of the Crab PWN which is powered by the Crab pulsar, is much higher than its MDR luminosity, estimated from its current $P$ and $\dot{P}$. Addi-
tional power supply to the PWN can come, e.g., from cosmic ray particles and relativistic winds emitted from the newly born MSP.

Indeed, relativistic wind (RW) particles and high energy cosmic rays (CRs) with $E \approx pc$, which spiral out along the open magnetic field lines and escape at the light cylinder (of a radius $c/w$ around the rotation axis) carry out energy and angular momentum at a rate \( \dot{E} = \text{Lum(CR)} + \text{Lum(RW)} \) and \( \dot{l} = I \dot{\omega} = \text{Lum}/w \), respectively, where $\text{Lum}=\text{Lum(CR)}+\text{Lum(RW)}$ is the energy loss rate by CRs and RW. If this loss of angular momentum dominates the spin down of an MSP, then the estimate [26] of its magnetic field at the magnetic poles, $B_p = 6.4 \times 10^{19} \sqrt{P \dot{P}}$ Gauss, is an over estimate. Moreover, the estimate assumes a vacuum environment and a time-independent magnetic field [26] of the newly born MSP, and cannot be trusted as solid evidence that MSPs which seem to power the afterglows of SN-less GRBs are magnetars [27].

If the afterglow of SN-less GRBs is powered by a newly born MSP, then the period which is obtained from best fits of Eq.(2) to its afterglow must yield a periods well above the classical Newtonian lower limit $P > 2\pi R/c \approx 0.2$ ms for canonical neutron stars. So far, all the fitted SN-less GRBs have yielded much larger periods than 0.2 ms, despite the fact that $\eta < 1$.

It is however, quite remarkable that the inferred MSP periods in SHBs are typically order of magnitude larger than those inferred in long SN-less GRBs. That may be due to different $\eta$ or loss of angular momentum by gravitational wave emission in neutron stars mergers compared to the spin up of neutron stars in high mass X-ray binaries (HMXB) by mass accretion. It may indicate that core collapse supernova explosions of massive stars are driven mainly by transport out of excessive rotational energy from infalling layers on the proto neutron star, which cannot be spun up to a surface velocity exceeding the speed of light light. This may be even more important than energy momentum deposition by neutrinos and shock waves in the envelope of the star, which so far, in numerical simulations, could not produce consistently core collapse SN explosions of massive stars with kinetic energy $E_k \sim 10^{51}$ erg [29].

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