

GRBs in Pulsar Wind Bubbles: Observational implications

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Abstract. We present the main observational features expected for Gamma-Ray Bursts (GRBs) that occur inside pulsar wind bubbles (PWBs). This is the most natural outcome of the supranova model, where initially a supernova (SN) explosion takes place, leaving behind a supra-massive neutron star, which loses its rotational energy over a time t_{sd} and collapses to a black hole, triggering a GRB. We find that the time delay, t_{sd} , between the SN and GRB events is the most important parameter that determines the behavior of the system. We consider the afterglow, prompt GRB and PWB emission. Constraints on the model are derived for a spherical PWB, from current afterglow observations and the lack of direct detection of the PWB emission. We find that a simple spherical model cannot account for the X-ray features detected in some afterglows, together with the typical afterglow emission that was observed for the same GRBs. The discrepancies with observations may be reconciled by resorting to a non-spherical geometry, where the PWB is elongated along the polar axis. Finally, we predict that the inverse Compton upscattering of PWB photons by the relativistic electrons of the afterglow (external Compton) should lead to high energy emission during the early afterglow that may explain the GeV photons detected by EGRET for a few GRBs, and should be detectable by future missions such as GLAST.

1. Introduction

Despite the large progress in GRB research over the last few years, the identity of their progenitors is still perhaps the most interesting open question. GRB Progenitor models are divided into two main categories: (i) a merger of two compact stars, (ii) the death of a massive star. Short GRBs (lasting $\lesssim 2$ s) are usually attributed to the category (i), while long GRBs are attributed to category (ii), which includes the failed SN (Woosley 1993) or hypernova (Paczynski 1998) models, and the supranova model (Vietri & Stella 1998), where a massive star explodes in a SN leaving behind a supra-massive neutron star (SMNS) which after a time delay, t_{sd} , loses its rotational energy and collapses to a black hole (BH), triggering the GRB. All these models have the same final stage (large accretion rate onto a newly formed BH) and a similar energy budget ($\lesssim 10^{54}$ ergs).

This work concentrates on the supranova model, focusing on its possible observational signatures. The original motivation for this model was to provide a relatively baryon clean environment for the GRB jet. As it turned out, it also seemed to naturally accommodate the later detection of iron lines in several X-ray afterglows (Lazzati, Campana, & Ghisellini 1999; Piro et al. 2000; Vietri et al. 2001). Recently, it has been suggested that the most natural mechanism by which the SMNS can lose its rotational energy is through a strong pulsar type wind, between the SN and the GRB events, which creates a pulsar wind bubble (PWB), also referred to as a plerion (Königl & Granot 2002, KG hereafter; Inoue, Guetta & Pacini 2002). Here we report the main results of Guetta & Granot (2002a, GG hereafter), and refer the reader to this work for more details.

The most important parameter that determines the behavior of the system is the time delay, t_{sd} , between the SN and GRB events. The value of t_{sd} is set by the timescale on which the SMNS loses its rotational energy due to magnetic dipole radiation (see Eq. 2 of GG) and depends mainly on the strength of the SMNS magnetic field; it can range anywhere between weeks to years. Another important parameter is the Lorentz factor, γ_w , of the pulsar wind, emanating from the SMNS, which is expected to be in the range $\sim 10^4 - 10^7$ (KG). An important difference between our analysis and previous works (KG; Inoue, Guetta & Pacini 2002) is that we allow for a proton component in the pulsar wind, that carries a significant fraction of its energy. In the standard model, the external medium is composed of cold protons and electrons (in equal numbers), and has a density profile that scales with the distance from the source as r^{-k} , where $k = 0$ for an ISM and $k = 2$ for a stellar wind. In our scenario, the external medium is made up of hot protons and cold e^\pm pairs, where there are $\sim 10^3$ times more pairs than protons. Nevertheless, the protons hold most of the energy in the PWB due to their large internal energy, which also dominates the effective density that is responsible for the deceleration of the afterglow shock. The value of k for our model ranges between $k = 0$, that is similar to an ISM, and $k = 1$, that is intermediate between an ISM and a stellar wind (KG).

2. The Behavior of the System for Different Time Delays

In this section we go over the main observational signatures of the PWB model, following the different regimes in t_{sd} (for the detailed calculations on how these results are derived we refer the reader to GG):

1. For extremely small values of $t_{\text{sd}} < t_{\text{col}} = R_\star / \beta_b c \approx 0.9 R_{\star,13} \beta_b^{-1}$ hr, where $R_\star = 10^{13} R_{\star,13}$ cm is the radius of the progenitor star (before it explodes in a SN), the stellar envelope does not have enough time to increase its radius considerably before the GRB goes off, and the supranova model reduces to the collapsar model. In this respect, the collapsar model may be seen as a special case of the supranova model.
2. If $t_{\text{sd}} < t_\tau \sim 0.4$ yr, the SNR shell is optically thick to Thomson scattering, and the radiation from the plerion, the prompt GRB and the afterglow cannot escape and reach the observer. If the SNR shell is clumpy (possibly due to the Rayleigh-Taylor instability, see §2 of GG), then the Thomson optical depth in the under-dense regions within the SNR shell may decrease below unity at t_{sd} somewhat smaller than t_τ , enabling some of the radiation to escape. The only

signatures that we expect for this range of t_{sd} are the neutrino emission due to p-p collisions or photo-meson interactions, and high energy photons above $0.5 (t_{\text{sd}}/t_{\tau})^{-2}$ MeV (Guetta & Granot 2002b and Granot & Guetta 2002b).

3. For $t_{\tau} < t_{\text{sd}} < t_{\text{Fe}} \sim 1$ yr the SNR shell has a Thomson optical depth smaller than unity, but the optical depth for the iron line features is still $\gtrsim 1$ so that detectable X-ray line features, like the iron lines observed in several afterglows, can be produced. In this range of t_{sd} we expect a very large effective density ($\sim 10^5 \text{ cm}^{-3}$) and electron number density ($\sim 10^3 \text{ cm}^{-3}$). This effects the afterglow emission in a number of different ways: i) The self absorption frequency of the afterglow is typically above the radio, implying no detectable radio afterglow, while radio afterglows were detected for GRBs 970508, 970828, and 991216, where the iron line feature for the latest of these three is the most significant detection to date ($\sim 4\sigma$, Piro et al. 2000). We also typically expect the self absorption frequency of the plerion emission to be above the radio in this case, so that the radio emission from the plerion should not be detectable, and possibly confused with that of the afterglow. ii) A short jet break time t_j and a relatively short non-relativistic transition time t_{NR} are implied, as both scale linearly with t_{sd} and are in the right range inferred from observations

4. Finally, for $t_{\text{sd}} > t_{\text{Fe}}$, we expect no iron lines. When t_{sd} is between ~ 2 yr and ~ 20 yr the radio emission of the plerion may be detectable for $\gamma_w \lesssim 10^5$. The lack of detection of such a radio emission excludes values of t_{sd} in this range, if indeed $\gamma_w \lesssim 10^5$, as is needed to obtain reasonable values for the break frequencies of the afterglow (see Fig.1 of GG and the relevant discussion there).

3. High energy emission

An interesting new ingredient of the PWB model, is that the GRB and its afterglow occur inside a photon rich plerionic environment. These photons can be upscattered by the relativistic electrons behind the afterglow shock, producing a high energy emission (external Compton, EC). Fig. 2 of GG and Fig. 1 of Granot & Guetta (2002a) show that the EC emission can account for the high energy emission detected by EGRET for GRB 940217 (Hurley et al. 1994), and is consistent with the flux level and moderate time decay observed in this case.

4. Conclusions

In this work we have presented the main results obtained in GG and Granot & Guetta (2002a) regarding the observational implications for GRBs that occur inside pulsar wind bubbles (PWBs), as expected in the supranova model. We find that a simple spherical model cannot produce the iron line features observed in several afterglows together with the other, more conventional, features of the afterglow emission from these bursts. However, if the iron lines are not real, then a simple spherical model can explain all other observations for $t_{\text{sd}} \gtrsim 20$ yr. The latter is required in order to explain typical afterglow observations and the lack of direct detection of the plerion emission in the radio during the afterglow.

If the iron line detections are real, then in the context of the PWB model, this requires deviations from a simple spherical geometry. The most straightforward variation of the simple model is a PWB that is elongated along its polar

axis. Such a geometry may arise naturally within the context of this model (KG; GG). With an elongated geometry, the PWB model can account for all the observed features in the afterglow, and it offers a number of advantages in comparison to other models: i) It provides a relatively baryon clean environment for the GRB jet, which is required in order to produce a highly relativistic outflow. This arises as the initial SN expels most of the stellar envelope to a large distance from the site of the GRB, and the strong pulsar wind effectively sweeps up the remaining baryonic matter. ii) An important advantage of this model is that it can naturally explain the large values of ϵ_B and ϵ_e that are inferred from fits to afterglow data (KG), thanks to the large magnetic fields in the PWB and the large relative number of electron-positron pairs. This is in contrast with standard environment that is usually assumed to be either an ISM or the stellar wind of a massive progenitor, that consists of protons and electrons in equal numbers. In this case, the pre-existing magnetic field, that is amplified due to the compression of the fluid in the shock, is too small to explain the values inferred from afterglow observations, and further magnetic field amplification or generation at the shock is required. iii) All the detections of GRB afterglows to date are for the long duration sub-class of GRBs (with a duration $\gtrsim 2$ s), that are believed to arise from a massive star progenitor, which according to the collapsar model should imply a stellar wind environment ($k = 2$). However, a homogeneous external medium ($k = 0$) provides a better fit to the observational data for most GRB afterglows. This apparent contradiction is naturally explained in the context of the PWB model, where k ranges between 0 and 1, while we still have a massive star progenitor.

Another advantage of the PWB model is its capability of explaining the high energy emission observed in some GRBs. We find that the high energy emission during the early afterglow at photon energies $\gtrsim 100$ keV is dominated by the EC component. We predict that such a high energy emission may be detected in a large fraction of GRBs with the upcoming mission GLAST.

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