A mini-supernova model for optical afterglows of GRB

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ABSTRACT

An energy deposition of $\sim 10^{50}$ ergs into the exterior $10^{-3} M_\odot$ layers of a red giant is calculated to produce an optical phenomenon similar to afterglows of gamma-ray bursts (GRB) recently observed. This mechanism can be realized if a GRB is generated by some mechanism in a close binary system. In contrast to a “hypernova” scenario for GRB recently proposed by Paczyński (1997), this model does not require a huge kinetic energy of the expanding shell to explain optical afterglows of GRB.

Key words: Gamma-rays: bursts – supernovae: general

1 INTRODUCTION

Recent multiwavelength identification of two BeppoSAX GRB 970228 (van Paradijs et al. 1997; Galama et al. 1997) and GRB 970508 (Piro et al. 1997) became a major astronomical “event of the year”. HST observations of a possible “host galaxy” around a point-like optical transient to GRB 970228 and measurements of a high redshift $z = 0.835$ of the absorption and emission lines in the spectra of optical counterpart to GRB 970508 (Metzger et al. 1997) have provided a strong evidence for the cosmological origin of GRB. If so, the energy deposited in gamma-rays during GRB should be $\sim 10^{51}$ ergs. A power-law brightness decline with time observed in both optical afterglows $\sim t^{-1.1}$ (Galama et al. 1997, Kopylov et al. 1997) has readily been explained by the standard model of a relativistic fireball interacting with adjacent material, either interstellar or intergalactic (Rees and Mészáros 1992; e.g. Wijers et al. 1997, Waxman 1997, and references therein).

However, the apparent success of the relativistic fireball model in explaining the observed optical afterglows of GRB still uses some a priori assumptions about the ultimate source of the fireball itself. A critical consideration of the fireball formation under real astrophysical conditions has recently motivated Paczyński (1997) to suggest an alternative model for GRB, which he calls “a hypernova model” and which involves a huge energy deposit ($\sim 10^{54}$ ergs) into the kinetic energy of the expanding envelope of a type Ib supernova (i.e., originating from the core collapse of a helium star) in a close binary system via extremely strong ($\sim 10^{15}$ G) magnetic field of the nascent rapidly rotating neutron star.

Originally, the idea of magneto-rotational supernova explosion was proposed by Bisnovatyi-Kogan (1970) and further elaborated during three decades, see Ardeljan et al. (1996ab, 1997). A very strong magnetic field of a rapidly rotating neutron star as a source of GRB was proposed by Usov (1992). The possibility of a GRB to appear during a bare core collapse in a binary system was suggested by Dar et al. (1992). The latter model assumed a GRB to be a result of the neutrino-antineutrino pair creation and annihilation during the accretion-induced collapse of a white dwarf in a close binary system, when only a tiny fraction of mass is ejected ($< 10^{-4} M_\odot$).

In this paper, we suggest another conceivable model for optical afterglows to GRB, which involves a mild energy release of the order $10^{50} - 10^{51}$ ergs in gamma-rays in a close binary system. The ultimate source of these gamma-rays may be associated with bare collapse of an accreting white dwarf, perhaps with some unknown mechanism (e.g., exotic particle decays). In principle, this mechanism can be of the same nature as the one leading to a standard supernova type II explosion (when the collapse occurs inside a massive star). However, the precise nature of the GRB is not important for the purpose of the present letter; we wish focus only on the consequences the gamma-ray irradiation would have in a close binary system.

In contrast to Paszyński’s hypernova scenario, we need no a huge kinetic energy of the expanding envelope to produce a prolonged optical afterglow. We show that deposition of the energy of gamma-ray burst into the exterior envelope of a red supergiant in a close binary system could be sufficient to explain optical afterglow decaying with time in a way similar to that observed in GRB 970228.
2 THE MODEL

Consider the following model. Let a GRB phenomenon with the energy of the order of a SN explosion occur in a close binary system, e.g. as a result of accretion-induced collapse of a WD in a symbiotic binary system. This process is currently one of the favoured mechanisms for SN type Ia explosions (Nomoto et al. 1997). In our model we do not specify the detailed mechanism of the GRB; for example, it can be associated with a ‘failed’ SN (Woosley 1993) or something else. Let the secondary red giant companion be close enough to intercept a significant fraction of gamma-rays emitted. Let pose the question: What is the consequence of such immediate gamma-ray irradiation of the red giant atmosphere? For simplicity, we consider a spherically symmetric energy deposition in the red giant atmosphere. To calculate the afterglow, we used a multi-energy group radiation-hydro-code STELLA (Blinnikov & Bartunov 1993; Blinnikov et al. 1997). The method uses the time-dependent equations for the angular moments of intensity averaged over fixed frequency bands and solves the non-relativistic equations of hydrodynamics implicitly coupled to them.

We consider a red supergiant with a mass of $15\, M_\odot$ and radius $r \sim 4000 R_\odot$. Actually, the mass of the star is of minor importance since the energy was deposited only into the exterior layers with a mass of $10^{-3} M_\odot$. The deposition of $1.5 \times 10^{50}$ ergs of gamma-ray energy into these layers during 10 seconds, assumed in our model calculation, heats them up to $\sim 5 \times 10^5$ K. The thermal energy thus stored is orders of magnitude higher than the initial thermal energy of the exterior layers of the red giant star. The energy budget is spent twofold: a part of it is transferred as a heat wave into deeper layers (down to $\sim 0.1 M_\odot$ during $\sim 0.1$ day) and another part goes into the thermal and kinetic energy of the outermost layers. All layers out of $10^{-4} M_\odot$ acquire speed of $\sim 2 \times 10^4$ km/s during a few hours, while the layers interior to $10^{-3} M_\odot$ remain almost at rest with the speed less than $10^3$ km/s. By this time the temperature of the outer layers falls down by an order of magnitude, to $\sim 5 \times 10^4$ K. The inward moving heat wave dies out during $\sim 10$ days reaching around $1 M_\odot$. By that time the kinetic energy of the expanding shell is about 2% of the initial energy deposited into envelope. The resulting light curve is shown in Fig. 1. We assumed a 1 Gpc distance to the source. No redshift corrections were made, so in fact the apparent R-magnitudes are close to the intrinsic V-magnitudes.

The observed magnitudes of the optical transient of GRB 970228 are taken from Galama et al. (1997). It is seen from Fig. 1 that the resulting light curve follows well the observed behaviour of the optical transient associated with GRB 970228, especially during first 10 days. At later epoch, near 30 days, the calculated optical fluxes becomes two magnitudes smaller than the observed ones (the second HST point for the day 39, $R = 25.5$, is not shown in Fig. 1). However, we can say that taking into account of the mini-blast wave interaction with circumstellar medium (pre-supernova wind) at later stages could increase the fluxes and make the agreement with observations better.

If more energy is deposited the effect would be more dramatic – the afterglow would be brighter and longer.

In the case of a GRB occurring in a classical high-mass X-ray binary (due to, for example, collapse of a neutron star to a black hole) with an O/B supergiant as the companion, the consequences would change significantly. The star being more compact, the mass of the outer shell heated by gamma-rays is smaller, scaling as square of the radius (e.g., for $R \approx 50 R_\odot$ the heated mass is $\sim 10^{-7} M_\odot$). The energy deposition per unit mass is correspondingly higher, so the speed and temperature of the matter increase as well whereas the duration of the afterglow decreases. For the case of a $R \approx 50 R_\odot$ supergiant we obtain $T \sim 5 \times 10^6$ K and $v \sim c$. Currently, the code STELLA is unable to treat relativistic problems; nevertheless, it is conceivable that the prolonged afterglows to GRBs could be explained by the interaction of the relativistic ejecta with the surrounding ISM. In this respect our model converges with the Rees and Mészáros (1992) relativistic fireball model.

3 DISCUSSION

Our simplified calculations of the effect of $\sim 10^{50}$ ergs impinging the atmosphere of a nearby red giant demonstrate a fair correspondence with the observed light curve of the optical transient to GRB 970228. If more energy is released in a binary system (for example, if even 1% of the Paczyński’s hypernova energy, i.e. $10^{52}$ ergs in gamma-rays, and/or kinetic energy), an enormous optical flash similar to a very bright unusual supernova could be produced by interaction of gamma-rays and expanding blast wave with the secondary companion. Impact of $10^{54}$ ergs of kinetic energy on the secondary optical star would probably have really dramatic consequences. However, we think that in order to produce gamma-ray burst and optical afterglow, one needs not to assume such high energies – a bare collapse of an accreting white dwarf in a binary system could produce both gamma-ray and optical emission.

What should be other effects of a 10$^{51}$-erg GRB on the surrounding medium?

The effects must be twofold: first, the impact of 10$^{51}$ ergs in gamma-rays on the surrounding medium and second, the impact of a blast wave expanding in the dense circumstellar medium formed by a strong stellar wind of the pre-supernova.

The first group of effects was recently addressed by Bisnovatyi-Kogan and Timokhin (1997). They showed that a very prolonged optical afterglow lasting for tens of years should result from a cosmological GRB depending on conditions in interstellar or intergalactic medium where the GRB occurred.

The second group of effects has been extensively studied in the context of the interaction of supernova remnants with
surrounding medium. A non-relativistic blast wave produced by supernovae has shown to be capable of producing large superbubbles in the interstellar medium (for example, the well known Cygnus superbubble was suggested by Blinnikov et al. 1982 to be a result of a peculiar supernova explosion; more recently the superbubbles are thought to be the result of a chain of normal SN explosions, e.g. Koo, Heiles and Reach 1992). A superbubble would live for millions years in the dense ISM. If occurred in a star formation region, such a hypernova would likely to stop completely the surrounding star formation. Huge expanding voids in neutral hydrogen that require the energy deposition of 100 supernovae have indeed recently been detected in several nearby dwarf galaxies, with no apparent star formation region and associated stellar clusters inside it (Radice et al. 1995). This possibly may be related to such hypernovae, but with the energy of order $\sim 10^{53}$, not $\sim 10^{54}$ ergs.

Some other difficulties that the hypernova scenario meets include (1) a failure to transfer more than a few per cent of the rotational energy into the kinetic energy of the envelope by the magneto-rotational mechanism, as hydrodynamical calculations show (Ardeljan et al. 1996ab, 1997); (2) troubles with the shock break-out through the exploding star envelope (Blinnikov and Nadyozhin 1990; Blinnikov et al. 1991; Ensmann and Burrows 1992, and references therein).

Therefore we propose another conceivable model for optical afterglow of GRB, which includes a collapse of a "naked" stellar core (Ne-Mg-O, or even iron) in a binary system as a possible source of a moderate (e.g., Dar’s model of the fireball formation by neutrino-antineutrino annihilation is customarily rejected on the grounds of Dar et al. 1992). Although it is hard to reproduce the detailed picture of GRB within the framework of a particular model (e.g., Dar’s model of the fireball formation by neutrino-antineutrino annihilation is customarily rejected on the grounds of being too contaminated by baryonic load, e.g. Woosley 1993), we must note that the present situation even with supernova explosion themselves is far from being completely clear (e.g., Mezzacappa et al. 1997 for a recent review of difficulties with mass ejection in supernova explosions).

Another plausible way of forming GRB at cosmological distances involves binary neutron star merging (as originally proposed by Blinnikov et al. 1984; see Pazyński 1986, Lipunov et al. 1995, etc.). However, as detailed hydrodynamical calculations currently demonstrate, this mechanism also fails in producing powerful fireballs by several orders of magnitude (Janka and Ruffert 1996, Ruffert et al. 1997).

But supernovae do explode and binary neutron stars should coalesce in nature due to gravitational radiation regardless of the present failure to obtain powerful fireballs in numerical calculations. Physics is always richer than we can imagine. For example, taking into account magnetic moment of neutrino can help in producing envelope ejection in supernova explosions (Dar 1987; Voloshin 1988; Blinnikov and Okun’ 1988, Akhmedov et al. 1997). If neutrino magnetic moment indeed plays the role in supernova explosion, its interaction with outer magnetic field (the stronger the magnetic field, the more effective the transformation of the sterile neutrinos to ‘normal’ ones is) in the case of an almost naked presupernova could give rise to gamma-ray emission with temporal features similar to the observed fractal or scale-invariant properties found in gamma-ray light curves of GRB (Shakura et al. 1994; Stern and Svensson 1996). Such a temporal behaviour appears natural if turbulence and magnetic fields are crucial in any mechanism of gamma-ray emission (see Stern and Svensson 1996 and references therein; see also Bykov and Toptygin 1993, Bykov and Mészáros 1996; for a review of the role of fractals, intermittency, etc. in the magneto-hydrodynamic turbulence see Isichenko 1992).

Electromagnetic properties of neutrino or decays of exotic particles (Raffelt 1996) during such a dramatic process as supernova explosions and binary compact star coalescence may directly produce the energies required in gamma-rays ($10^{51}$ erg). We thus may suppose that when this energy is released at the center of a thick envelope, this leads to the phenomenon of supernova explosion; oppositely, when the matter coating is thinner, gamma-rays may be directly observed as a GRB, and when this occurs in a binary system, afterglows at different wavelengths should be produced as a consequence of interaction of gamma-rays with secondary companion and/or local interstellar medium.

Our calculations demonstrate that this may be the case for GRB 970228. Of course, detailed features of the light curve of the optical transient to GRB 970228 cannot be reproduced in our simplified spherically-symmetric calculations. The model in its simplest form gives no explanation to the delayed optical afterglow, as observed in GRB 970508. One can speculate here on the role of 2D effects, on the effects of the shock wave propagation in the circumstellar material, etc. The model also meets difficulties with explaining X-ray afterglows – the latter can be produced either on the surface of the ‘failed’ supernova remnant or connected directly with the mini-supernova shock; some supernovae are known to emit X-rays not connected with radioactive decay.

So other direct consequences of the $10^{51}$ erg energy deposition into the dense pre-supernova wind, e.g. like in SN 1979C, should be considered. For example, taking into account of radiation transport in the presupernova wind was shown to strongly affect the SN 1979C light curve for many years (Bartunov and Blinnikov 1992, Blinnikov and Bartunov 1993); Chugai and Danziger (1993) considered the interaction of the supernova blast wave with dense clumpy wind of the precursor to peculiar SN 1988Z to explain observed properties of its optical emission. As mentioned above, a very prolonged (years and tens of years) optical afterglows may be produced by a gamma-ray burst in interstellar medium (Timokhin and Bisnovatyi-Kogan 1995, 1996). The latest HST observations of GRB970228 of September 5, 1997, which spotted the optical afterglow at $R = 27.7$ (Fruchter et al. 1997) after half a year strongly evidence the interaction of an expanding envelope with the surrounding medium.

We conclude that effects of supernova explosions and a powerful gamma-ray burst on the surrounding medium and
possible binary companion may give rise to a large variety of optical afterglows. Future observations of optical transient to GRB 970228 and GRB 970508 will help in distinguishing these possibilities.

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Figure 1. A mini-supernova U,B,V,R-afterglow produced by depositing $10^{50}$ ergs into the exterior $10^{-3} M_\odot$ of a 15 $M_\odot$ red supergiant with a radius of 4000$R_\odot$, as seen from a distance of 1 Gpc. The observed B,V,R-light curve of the optical transient of GRB 970228 (Galama et al. 1997) are also indicated.