

Gamma-ray Bursts and Hypernovae

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October 18, 2004

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Abstract

In these proceedings, I discuss recent progress in understanding the nature of cosmic gamma-ray bursts (GRB), with the focus on the apparent relation of several GRBs with an energetic subclass of stellar explosions, type Ib/c core-collapse supernovae. This relation provides the strong case that the GRB phenomenon is connected with the final stages of massive star evolution and possibly with the formation of neutron stars and black holes. I speculate that intrinsically faint, apparently spherically symmetric nearby GRB 980425 and 031203 associated with bright hypernovae SN 1998bw and SN 2003lw, respectively, can signal the formation of a neutron star in the end of gravitational collapse, while the bulk of cosmological GRBs with a universal energy release of $\sim 10^{51}$ ergs in narrow-collimated jets are produced when a black hole is formed. In the former case, the energy source of GRB is the neutron star rotational energy; in the latter case the GRB energy is due to non-stationary accretion onto the black hole.

1 Introduction

GRBs have remained in the focus of modern astrophysical studies for more than 30 years. After the discovery of GRB afterglows in 1998 (Costa et al. 1998), the model of GRB as being due to a strong explosion with isotropic energy release of 10^{53} ergs in the interstellar medium (originally proposed

by Rees and Meszaros (1992)) became widely recognized. Various aspects of GRB phenomenology are discussed in many reviews: observational and theoretical studies are summarized in Hurley et al. (2003), first observations of afterglows are specially reviewed in van Paradijs et al. (2000), GRB theory is extensively discussed in Meszaros (2002).

A widely used paradigm for GRBs is the so-called fireball model (e.g. Piran 2004 and references therein). In this model, the energy is released in the form of thermal energy (its initial form is usually not specified) near the compact central source (at distances and is mostly converted into leptons and photons (the fireball itself). The outflow is formed driven by the high photon-lepton pressure (generically in the form of two oppositely directed narrow collimated jets). The fireball internal energy is converted to the bulk motion of ions so that relativistic speed with high Lorentz-factors (typically, $\Gamma > 100$) is achieved during the initial stage of the expansion; the ultrarelativistic motion is in fact dictated by the need to solve the fireball compactness problem (see Blinnikov 2000 for a detailed discussion and references). The kinetic motion of ions is reconverted back into heat in strong collisionless relativistic shocks at typical distances of 10^{12} cm. Assuming the appropriate turbulence magnetic field generation and particle acceleration in the shocks, energy thermalized in the shocks is emitted via synchrotron radiation of accelerated electrons (see Waxman 2003), which is identified with the GRB emission. A shell of ultrarelativistically moving cold protons produce a blast wave in the surrounding medium, forming an external shock propagating outward and reverse shock propagating inward the explosion debris. Most energy of explosion is now carried by the external shock which decelerates in the surrounding medium. Assuming magnetic field generation and particle acceleration in the external shock, the afterglow synchrotron emission of GRB is produced. Note that at this stage the memory of the initial explosion conditions is cleaned, and the dynamical evolution of the external shock is well described by the Blandford-McKee (1975) self-similar solution, a relativistic analog of the Sedov-von-Neumann-Taylor solution for strong point-like explosion. This explains the success in modeling the GRB afterglow spectral and temporal behavior in the framework of the synchrotron model (Wijers et al. 1997), irrespective of the actual nature of the GRB explosion.

Indeed, there is no consensus thus far about the origin of the GRB emission itself. The fireball model meets some important problems (for example, baryon contamination of the fireball, the microphysics of magnetic field gen-

eration and particle acceleration in collisionless ultrarelativistic shocks etc., see a more detailed list in Lyutikov and Blandford (2003)). In the last paper an alternative to the fireball model was proposed in which large-scale magnetic fields are dynamically important. Whether the GRB jets are hot (fireball model) or cold (electromagnetic model) remains to be determined from future observations. Here crucial may be spotting the very early GRB afterglows and measuring polarization of prompt GRB emission (see Lyutikov (2004) for the short-list of the electromagnetic model predictions).

Here we focus on the observed association of GRBs with an energetic subclass of core-collapse supernovae (SNe), type Ibc SNe, which with each new finding provides an increasing evidence that the GRB phenomenon is related to the evolution of most massive stars and formation of stellar-mass black holes (BH).

2 Supernova - GRB connection

2.1 Theoretical grounds: the collapsar model

The connection of GRBs with stellar explosions was first proposed theoretically. Woosley (1993) considered a model of accretion onto a newly formed rotating black hole to power the GRB fireball. The progenitor to GRB in this model is a rapidly rotating Wolf-Rayet (WR) star deprived of its hydrogen and even helium envelop due to powerful stellar wind or mass transfer in a binary system. Dubbed by Woosley himself as "failed type Ib supernovae", this model is now called the collapsar model (MacFadyen and Woosley, 1999). In this model, a massive ($\gtrsim 25M_{\odot}$) rotating star with a helium core $\gtrsim 10M_{\odot}$ collapses to form a rapidly rotating BH with mass $\gtrsim 2 - 3M_{\odot}$. The accretion disk from the presupernova debris around the BH is assumed to be the energy source for GRB and is shown to be capable of providing the prerequisite $10^{51} - 10^{52}$ ergs via viscous dissipation into neutrino-antineutrino fireball. The energy released is assumed to be canalized in two thin antiparallel jets penetrating the stellar envelop. Another possible energy source in the collapsar model could be the electromagnetic (Poynting-dominated) beamed outflow created via MHD processes, much alike what happens in the active galactic nuclei powered by accretion onto a supermassive BH. The estimates show that the Blandford-Znajek (BZ) (1977) process in the collapsar model (e.g. Lee et al. 2000) can be a viable candidate for the central engine mech-

anism for GRBs, provided somewhat extreme values for BH spin (the Kerr parameter $a \sim 1$) and magnetic field strength in the inner accretion disk around the BH ($B \sim 10^{14} - 10^{15}$ G). In that case the rotating energy of BH (up to $0.29M_{bh}c^2$ for $a = 1$) is transformed to the Poynting-dominated jet with energy sufficient to subsequently produce GRB.

Another source of energy in the collapsar model could be the rotation energy of a rapidly spinning neutron star with high magnetic field (magnetar), as originally proposed by Usov (1992). As in the BZ-based models, the GRB jets are Poynting-dominated. Lyutikov and Blandford (2003) develop the electromagnetic model, which postulates that the rotating energy of the GRB central engine is transformed into the electromagnetic energy (for example, in a way similar to the Goldreich-Julian pulsar model) and is stored in a thin electromagnetically-dominated "bubble" inside the star. The bubble expands most rapidly along the rotational axis, breaks out of the stellar envelopes and drives the ultrarelativistic shock in the circumstellar material. In contrast to the synchrotron GRB model, here GRB is produced directly by the magnetic field dissipation due to current-driven instabilities in this shell after the breakout. The energy transfer to GRB is mediated all the way by electromagnetic field and not by the ion bulk kinetic energy. As we noted in the Introduction, it remains to be checked by observations whether the EM or fireball model for GRB emission is correct.

2.2 Observational evidence: GRB-supernova associations

First hint on the association of GRBs with SNe came from the apparent time coincidence (to within about a day) of GRB 980425 with a peculiar supernova SN 1998bw (Galama et al. 1998). SN 1998bw occurred in a spiral arm of nearby (redshift $z = 0.0085$, distance ~ 40 Mpc) spiral galaxy ESO 184-G82. Such a close location of GRB 980425 rendered it a significant outliers by (isotropic) energy release $\Delta E_{iso} \approx 10^{48}$ erg from the bulk of other GRBs with known energy release, and even from a beaming-corrected mean value of GRB energies of $\sim 10^{51}$ erg (Frail et al. 2001).

Now the most convincing evidence for GRB-SN association is provided by spectroscopic observations of late GRB afterglows. Among them is a bright GRB 030329 associated with SN 2003dh (Hjorth et al. 2003, Stanek et al. 2003, Matheson et al. 2003, Mazzali et al. 2003, Kawabata et al. 2003).

Spectral observations of the optical afterglow of this GRB revealed the presence of thermal excess above non-thermal power-law continuum typical for GRB afterglows. Broad absorption troughs which became more and more pronounced as the afterglow faded indicated the presence of high-velocity ejecta similar to those found in spectra of SN 1998bw. Despite these strong evidences, there are some facts which cannot be explained by simple combination of the typical SN Ibc spectrum and non-thermal power-law continuum. For example, the earliest spectroscopic observations of GRB 030329 of optical spectra taken on the 6-m telescope SAO RAS 10-12 hours after the burst (Sokolov et al. 2004) showed the presence of broad spectral features which could not be produced by a SN at such an early stage. The complicated shape of the optical light curve of this GRB with many rebrightenings (Lipkin et al. 2004) and polarization observations made by VLT (Greiner et al. 2003) suggest a clumpy circumburst medium and require additional refreshing of shocks (if one applies the synchrotron model, e.g. Granot et al. (2003)).

Another recent example of GRB-SN connection is provided by another nearby GRB 031203. This GRB is one of the closest ($z = 0.105$) known GRBs and is found to be intrinsically faint, $\Delta E_{iso} \sim 10^{50}$ ergs (Watson et al. 2004, Sazonov et al. 2004)¹. The low energy release in gamma-rays is confirmed by the afterglow calorimetry derived from the follow-up radio observations (Soderberg et al. 2004) and allows this GRB to be considered as an analog to GRB 980425. It is important that the low energy release in these bursts can not be ascribed to the off-axis observations of a "standard" GRB jet (unless one assumes a special broken power-law shape of GRB luminosity function, see Guetta et al. 2004). However, a bright type Ib/c supernova SN 2003lw was associated with GRB 031203 as suggested by the rebrightening of the R light curve peaking 18 days after the burst and broad features in the optical spectra taken close to the maximum of the rebrightening (Cobb et al 2004, Thomsen et al. 2004, Malesani et al. 2004, Gal-Yam et al. 2004).

The comparison of radio properties of 33 SNe type Ib/c with those of measured radio GRB afterglows allowed Berger et al. (2003) to conclude that not more than few per cents of SNe type Ib/c could be associated with GRBs, which explains the observed small galactic rate of GRBs. However, it still remains to be studied how much intrinsically faint GRBs like 980425

¹A bright soft X-ray flux was inferred from XMM observations of evolving X-ray halo for this burst (Vaughan et al. 2004), making it an X-ray rich GRB (Watson et al. 2004); this point of view was argued by Sazonov et al. (2004).

and 031203 can contribute to the total GRB rate.

3 Hypernovae

Core-collapse supernovae with kinetic energy of the ejecta $\sim 10 - 30$ times as high as the standard 1 foe ($1\text{foe} = 10^{51}$ erg) are now collectively called "hypernovae". The term was introduced by B. Paczynski shortly after the discovery of first GRB afterglows in 1997 by the Beppo-SAX satellite (Paczynski, 1998) based on qualitative analysis of possible evolutionary ways leading to cosmic GRB explosions.

SN 1998bw was exceptionally bright compared to other Ib/c SNe (the peak bolometric luminosity of order 10^{43} erg/s, comparable to the SN Ia peak luminosities). This points to the presence of a substantial amount of ^{56}Ni isotope, the radioactive decay thereof being thought to power the early SN light curves. The spectra and light curve of SN 1998bw was modeled by the explosion of a bare C+O of a very massive star that has lost its hydrogen and helium envelopes with a kinetic energy more than ten times typical SNe energies (Iwamoto et al. 1998), and they called SN 1998bw a hypernova.

Since then several other SNe were classified as SN 1998bw-like hypernovae by their spectral features and light curves: SN 1997ef, SN 2002ap, SN 2003dh/GRB030329, SN 2003lw/031203. Recently, SN 1997dq was dubbed a hypernova by its similarity with SN 1997ef (Mazzali et al. 2004).

Extensive numerical modeling of light curves and spectra of hypernovae (see Nomoto et al. 2004 for a recent review) confirmed the need of atypically high for core-collapse SNe mass of nickel ($\sim 0.1 - 0.5M_{\odot}$) to be present in the ejecta in order to explain the observed hypernova properties. The rapid rise in of the observed light curves of the "canonical" SN 1998bw requires a substantial amount of ^{56}Ni to be present near the surface. This strongly indicates the important role of mixing during the explosion as nickel is synthesized in deep layers during a spherical explosion. This fact can serve as an additional evidence for non-spherical type Ic explosions. Generally, the asphericity appears to be a ubiquitous feature of core-collapse supernovae. For example, spectropolarimetry of SN spectra (Leonard and Filippenko 2004) indicates the increasing polarization degree for type Ib/c SNe compared to classical type II core-collapse SNe with rich hydrogen envelope (SN IIp), in which asymmetry appears to be dumped by the addition of envelope material.

Spectral modeling suggests (Nomoto et al. 2004) that the broad-band

spectral features generally seen in early and maximum light of hypernovae signal very rapid photospheric expansion. For example, Nomoto notes the very unusual for other SNe fact that OI ($\lambda = 7774\text{\AA}$) and CaII IR (at $\lambda \sim 8000\text{\AA}$) absorption lines merge into a single broad absorption in early spectra of SN 1998bw, which indicates a very large velocity of the ejecta (the line separation ~ 30000 km/s).

In general, varying (a) the progenitor C+O core mass from 2 to ~ 14 solar masses, choosing (2) the appropriate mass cut (corresponding to the mass of the compact remnant, a neutron star or black hole $M_c = 1.2 - 4M_\odot$), and (3) mass of ^{56}Ni isotope ($\sim 0.1 - 0.5M_\odot$) and its mixing allow Nomoto et al. (2004) to obtain the observed spectra and light curves of hypernovae.

This analysis suggests a possible classification scheme of supernova explosions. In this scheme, core collapse in stars with initial main sequence masses $M_{ms} < 25 - 30M_\odot$ leads to the formation of neutron stars, while more massive stars end up with the formation of black holes. Whether or not the collapse of such massive stars is associated with powerful hypernovae ("Hypernova branch") or faint supernovae ("Faint SN branch") can depend on additional ("hidden") physical parameters, such as the presupernova rotation, magnetic fields. (Ergma and van den Heuvel 1998), or the GRB progenitor being a massive binary system component (Tututkov and Cherepashchuk 2003). The need for other parameters determining the outcome of the core collapse also follows from the observed continuous distribution of C+O cores of massive stars before the collapse and strong discontinuity between masses of compact remnants (the mass gap between neutron stars and black holes) (Cherepashchuk 2001). The mass of ^{56}Ni synthesized in core collapse also appears to correlate with M_{ms} . In ordinary SNe (like 1987a, 1993j, 1994i), $M_{Ni} = 0.08 \pm 0.03M_\odot$, but for hypernovae this mass increases up to $\sim 0.5M_\odot$ for the most energetic events.

Another important consequence of hypernovae can be different explosive nucleosynthesis products. Here the most pronounced features are larger abundances (relative to the solar one) of Zn, Co, V and smaller abundance of Mn, Cr, the enhanced ratios of α -elements, and large ratio of Si, S relative to oxygen (see Nomoto et al. 2003 for more detail).

4 Progenitors of GRBs

The GRB-SN connection leads to the almost generally accepted concept that massive stars that lost their envelopes are progenitors of long GRBs (this limitation is due to the fact that predominantly long GRBs with duration ≥ 2 s can be well localized on the sky and provide rapid alerts for follow-up multiwavelength observations). For short single-pulsed GRBs (a quarter of all bursts, see e.g. catalog by Stern et al. 2001) the binary NS+NS/NS+BH merging hypothesis (Blinnikov et al. 1984, Ruffert and Janka 1999, Janka et al. 1999) remains viable.

As we already noted, the emerging evidence is that there are intrinsically faint, single-pulsed, apparently spherically-symmetric GRBs (980425, 031203) associated with strong hypernovae. These hypernovae require maximal amount of nickel to be synthesized in explosion and large kinetic energies. On the other hand, another unequivocal hypernova SN 2003dh, associated with the "classical" GRB 030329, can be modeled with exceptionally high kinetic energy (4×10^{52} ergs) but smaller amount of nickel ($\sim 0.35M_{\odot}$) and smaller mass of the ejecta ($8-10M_{\odot}$) (Mazzali et al. 2003). These parameters were obtained assuming spherical symmetry, which is of course not the case for GRB 030329. But if this tendency is real and will be confirmed by later observations, we can return to our hypothesis (Postnov and Cherepashchuk 2001) that there should be distinct classes of GRBs according to what is the final outcome of collapse of the CO-core of a massive star. If the collapse ends up with the formation of a neutron star, intrinsically faint smooth GRB could be produced and heavy envelope is ejected in the associated SN Ib/c explosion. The GRB energy in this case can be essentially the rotation energy of the neutron star $\sim 10^{49} - 10^{50}$ ergs, as in the electromagnetic model by Usov (1992). If a BH is formed, a lighter envelope is ejected with accordingly smaller amount of nickel and possibly with higher kinetic energy, and more energetic, highly variable GRB with a "universal" jet structure (Postnov et al. 2001) appears fed by non-stationary accretion onto the BH.

The GRB energy dichotomy can be also interpreted in another, more exotic way requiring a new physics. For example, it was recently suggested (Gianfanga et al. 2004) that ultramassive axions in the mirror world with the Peccei-Quinn scale $f_a \sim 10^4 - 10^6$ GeV and mass $m_a \sim 1$ MeV can be produced in the gravitational collapse or merging of two compact stars. The axions tap most of the released energy and can decay ~ 1000 km away mostly into visible electron-positron pairs (with 100% conversion efficiency) thus creating

the initial GRB fireball. The estimates show that successful short GRBs can be obtained in compact binary coalescences, while long GRBs can be created in collapsars. In extended SNI progenitors, this energy may help the mantle ejection. In compact CO-progenitors for SN Ib/c axions decay inside the star, so depending on the stellar radius weaker or stronger GRBs associated with SNe type Ib/c explosions can be observed. In this picture again the collapse with the formation of a neutron star or BH may have different signatures.

5 Conclusions

There are several unequivocal associations of cosmic GRBs with peculiar very energetic type Ib/c SNe (hypernovae). The two closest GRBs discovered so far (989425 and 031203) proved to be intrinsically weak compared to the bulk of other GRBs with measured redshifts. They both show a single-peak smooth gamma-ray light curve with no signs of jet-induced breaks in the afterglows. In the third (most strong) case of the GRB-SN association, GRB 030329/SN 2003dh, the GRB light curve is two-peaked, the afterglows show evidence for jet. Modeling of the underlaid hypernovae light curve and spectra revealed the first two cases to require smaller kinetic energies but higher mass of the ejecta and the amount of the synthesized nickel than SN 2003dh. We propose that the tendency "weaker, more spherically symmetric GRB - stronger hypernova" is due to the formation of a NS in the case of weak GRBs and of a BH in the case of strong variable GRBs as the final outcome of the core collapse. In the NS case the GRB energy comes from the rotational energy of neutron star and is possibly mediated by the electromagnetic field. When BH is formed the GRB energy source is the gravitational energy released during non-stationary accretion onto the black hole or the black hole rotation.

We are sure that the increasing statistics of GRB/SNe in the nearest future obtained with new GRB-dedicated space missions like SWIFT will tell us much more on the nature of GRBs and their progenitors.

The author acknowledges the Organizing Committee of the QUARKS-2004 conference for financial support. The work was also supported by RFBR grants 02-02-16500, 03-02-17174 and 04-02-16720.

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