Gamma-ray bursts, evolution of massive stars and star formation at high redshifts
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GRBs in the last decade: prompt emission, forward and reverse shocks and the SN connection

A. J. Castro-Tirado*
Instituto de Astrofiísica de Andalucía (IAA-CSIC), Granada, Spain

Abstract. I show some of the advances in the gamma-ray burst field over the last decade, focusing on the prompt emission and reverse/forward shock components as well as the supernova relation for the long-duration GRBs, including the possible progenitors.

Keywords : gamma-ray bursts: afterglows – telescopes : optical

1. Introduction

Since their discovery in gamma-rays in 1967 and the detection of the first counterparts at other wavelengths in 1997 thanks to the *BeppoSax* improvement on the localization accuracy, now we know that Gamma-Ray Bursts (GRBs hereafter) originate at cosmological distances with energy releases of 10^{51}–10^{53} ergs. The multi-wavelength emission that follows the gamma-ray emission (the "afterglow") satisfies the predictions of the "standard" relativistic fireball model. See Castro-Tirado et al. (2001) for a review of the field prior to the year 2000.

Since the launch of the *Swift* mission in 2004, more than 800 GRBs have been detected, with ~80% of them being recorded in follow-up X-ray observations, ~50% with optical detection and more than 200 redshifts have been measured since 1997 (including 41 prior to *Swift*). *Fermi* was launched in 2008, to record the higher energy (MeV) population.

2. Prompt emission, reverse and forward shocks

We know that GRBs arise at cosmological distances (with mean redshift $z \sim 2.5$ and redshifts in the range ~0.01 to 9 or more), with huge isotropic equivalent radiated

*email: `ajct@iaa.es`

energy, and small timescales (in the range few ms to 10^2s), thus implying a small emitting region (< ct). The spectrum is non-thermal and relativistic outflows (bulk Lorentz factor $\Gamma > 100$) are involved.

A frequent assumption is that short and long GRBs (with the short ones representing 1/3 of the overall GRB population) are due to different progenitors leading to the same succession of events: formation of a compact object and ejection of a relativistic outflow. Differences in the two classes of bursts (prompt/afterglow) are then due to different initial conditions.

Since the initial works by Paczynski (1986) and Goodman (1986), the physics of relativistic ejections by a compact source is not well understood. The fireball model is a good starting point but the real jet evolution could be rather different, especially if the magnetic field plays a dominant role in the acceleration mechanism. Basic ingredients are the energy (E_0) injected in matter (M_0) very close to the central engine (R_0), the adiabatic expansion and hydrodynamical acceleration. If $E_0 >> M_0 c^2$, relativistic motion is produced. Additional ingredients for a more complex modeling should be the presence of magnetic fields, a gradual energy injection, complex composition (neutrons, protons, etc.), dense external medium, collimation, etc.

The standard model was developed by Meszaros & Rees (1997) and also by Paczynski & Rhoads (1993).

2.1 Prompt gamma-ray emission

Regarding the prompt emission, shortest (10^{-3} s) variability has been observed with rarely ms-long structures and more common low-level 10^2 Hz flickering (Walker et al. 2000) but short timescale variability is difficult to explain with the external shock. The prompt emission must have an internal origin, being produced from dissipative processes within the relativistic outflow itself. The possible energy reservoirs and extraction mechanisms are: i) Thermal energy / photospheric emission; ii) Kinetic energy/internal shocks + shock acceleration of particles; iii) Magnetic energy/Magnetic dissipation (e.g. reconnection).

The central engine is expected to be highly variable on different timescales, therefore the ejected mass flux and energy flux should also vary on similar timescales: different regions in the outflow have initially different Lorentz factors. This leads to the formation of shock waves (internal shocks, Rees & Meszaros 1994).

Radiative processes are explained with synchrotron emission although an inverse Compton contribution has been revealed sometimes. The model can explain several observed features like variability in light-curves, spectral evolution and the GRB diversity (X-ray flashes, X-ray rich bursts, etc.).

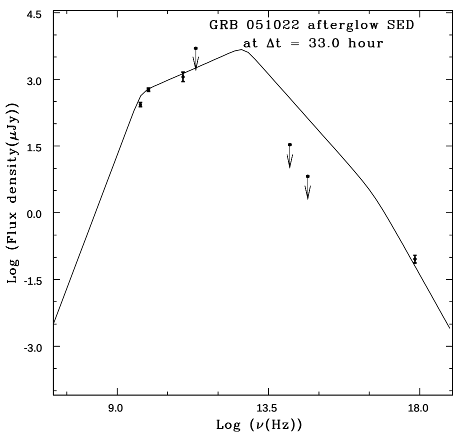

Figure 1. The spectral energy distribution of the dark GRB 051022 afterglow at T_0 + 33 hr, following the standard model (Sari, Piran & Narayanan 1998). We consider $p = 2.6$, assuming the slow-cooling regime. The initial parameters given at T_0 + 0.06 days are $\nu_a = 5.1 \times 10^9$ Hz, $\nu_m = 6.5 \times 10^{14}$ Hz, $\nu_c = 2.1 \times 10^{17}$ Hz and $F_{\nu,max} = 5.5$ mJy. Adapted from (Castro-Tirado et al. 2007).

Amongst the recent results by the Large Area Telescope (LAT) on-board *Fermi* in the gamma-ray range are the following ones:

- A detection rate of ∼ 10 LAT GRBs yr^{-1}. Most GRBs do not require an extra component in addition to a band spectrum.
- Prompt spectrum: 8 of the 10 LAT GRBs are consistent with a single dominant component, but 3 out of the 4 brightest LAT GRBs clearly show a distinct high-energy spectral component.
- Many LAT GRBs show later onset and longer duration of the high-energy emission, relative to low energies.
- Short and long GRBs seem to have similar high-energy properties: delayed onset, longer duration, distinct HE spectral component, high $\Gamma_{\min}$ (∼ 10^3).

2.2 Prompt optical emission

Following the first event (GRB 990123) detected by ROTSE (Akerlof et al. 1999), the main observational results obtained so far are:

- Now, almost routine observations with robotic telescopes worldwide (ROTSE, TAROT, BOOTES, etc.

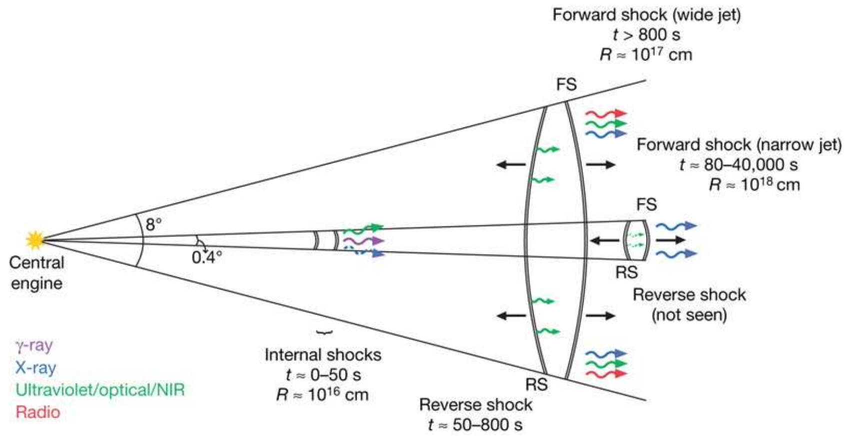

Figure 2. The modeling of the brightest optical afterglow ever seen (reaching 5th mag for about 40 s). The prompt gamma-ray emission is due to the internal shocks in the narrow jet, and the afterglow is a result of the forward and reverse shocks from both the narrow and wide jets. The reverse shock from the narrow jet is too faint to detect in comparison with the bright wide-jet reverse shock and the prompt emission. If X-ray observations had begun earlier, we would have detected X-ray emission during the prompt burst. These expected (but unobserved) emission sources are indicated by the dashed photon lines (from (Racusin et al. 2008)).

- GRB 080319B reaching 5.6 peak magnitude.
- Bright in the optical even at high redshift.
- Correlated/un-correlated behavior with gamma-rays (on a case by case basis).

With the advent of *Swift* it has became clear that ~ 50% GRBs are still dark (mostly dust, very few at high z), lack of optical flashes and the correlation between early optical versus X-ray evolution: a challenge for the fireball model.

2.3 Reverse shock

Due to the interaction with the surrounding medium, a reverse shock propagates within the ejecta. It is usually believed to contribute to the prompt emission (optical flash) and/or the early afterglow. For an uniform shell, the reverse shock is short-lived.

An important assumption is that the reverse shock micro-physics parameters are equivalent to the internal shock micro-physics parameters and different (in both cases) from the forward shock ones. If the outflow is variable, the reverse shock can be much more complicated than this simple picture and can even be long-lived. Thus, the strength of the reverse shock depends on magnetization content of the ejecta (see Zhang et al. (2003) and Gomboc et al. (2009)).

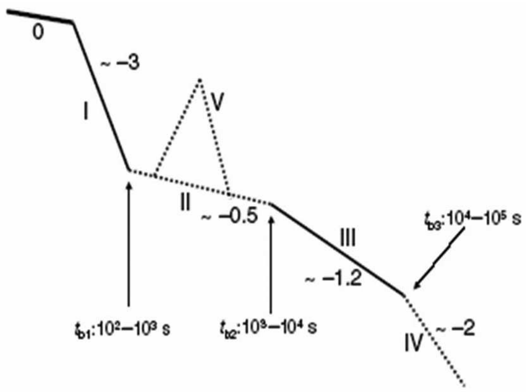

Figure 3. The canonical X-ray light curve. Adapted from Nousek et al. (2005).

For instance, in case of GRB 090902B, a bright afterglow and a steeper temporal decay slope are suggestive of a reverse shock origin. Absence of a jet break during the first 6 days implies a collimation-corrected -ray energy $E_{\gamma} > 2.2 \times 10^{52}$ erg, one of the highest ever seen in a long-duration gamma-ray burst (Pandey et al. 2010).

2.4 Forward shock

The afterglow is usually interpreted as the signature of the deceleration of the relativistic outflow by the external medium. Several aspects regarding the forward shock have been discussed previously: (i) Dynamics (Blandford & McKee 1982); (ii) Microphysics (ϵ_e, p, ϵ_B); (iii) Synchrotron radiation (Sari et al. 1998); (iv) the effect of a stellar wind (Chevalier & Li 2000); and (v) Spherical outflows and jets (Rhoads 1997).

Prior to *Swift*, there were very promising results (multi-wavelength fits) along with some problems, that had to be interpreted properly, like the jet breaks, first detected in GRB 990123 (Castro-Tirado et al. 1999; Kulkarni et al. 1999) and confirmed in many other cases (Sagar et al. 2001; Pandey et al. 2003).

After the initial *Swift* results, the picture has turned out to be more complicated: the canonical *Swift* X-ray afterglow light-curve presents five distinct regions (Nousek et al. 2005): (i) a steep decline; (ii) a shallow slope; (iii) the classical afterglow; (iv) a jet break/late plateau; and (v) flares (mostly in X-rays).

Moreover, several relations have been proposed taking into account observational facts: the E_p - E_{iso} (Amati) relation (Amati et al. 2002), the $E_{p,i}$ - E_{γ} (Ghirlanda) correlation (Ghirlanda et al. 2004), the Time lag vs. Peak Luminosity (anti)-correlation (Norris et al. 2000) and the Variability vs. Peak Luminosity relation (Reichart et al. 2001).

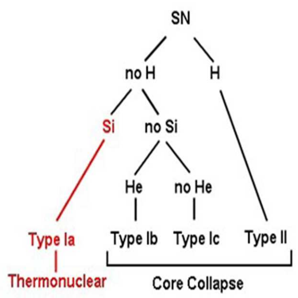

Figure 4. The classification of the different variety of SNe.

3. The supernova connection and progenitors

3.1 The supernova-long duration GRB link

It is admitted that for stars with masses M > 8 $M_\odot$, the collapse of their stellar nuclei at the end of their lives gives rise to the variety of observed supernovae (SNe hereafter).

Thus, the identified progenitors of type II SNe show M ∼ 10-15 $M_\odot$, with a possible upper limit at 16.5 $M_\odot$ (Smartt 2009). For the type Ib and type Ic it is believed that the progenitors are Wolf-Rayet stars having lost their H (for Ib) and He (for Ic) envelopes (stripped envelope supernovae). For the type Ibc, no progenitors have been identified, and theory suggests masses > 30 $M_\odot$ but depends on rotation, metallicity, mass loss, etc. Another possibility is lower mass stars in binary systems (Podsiadlowski et al. 1992).

In any case, the energetics is ∼ 10^{53} erg in neutrinos and ∼ 10^{51} erg in kinetic energy. Only a small fraction is radiated.

Remnants of type II SN are either a neutron star (NS) at low M values or a black hole (BH) at high M values. For the type Ib/c the remnants are either BH or NS depending on the mass.

A typical SN has a luminosity L = 10^{10} $L_\odot$, a temperature T ∼ 10^4 K, and keeps brightening for a few weeks. With R ∼ 10^{15} cm, and a velocity of a few × 10^3 km s^{-1} (highly supersonic), implies a kinetic energy 10^{51} erg. The radiated energy is 10^{49} erg which, if supplied by radioactive decay will imply a few 0.1 $M_\odot$ of ^{56}Ni.

Colgate (1968) predicted that supernovae should emit X- and γ-rays early on; with a shock erupting out of the star. After discovery of GRBs, this model remained one of the many models (more than one hundred) to which (Paczynski 1986) sug-

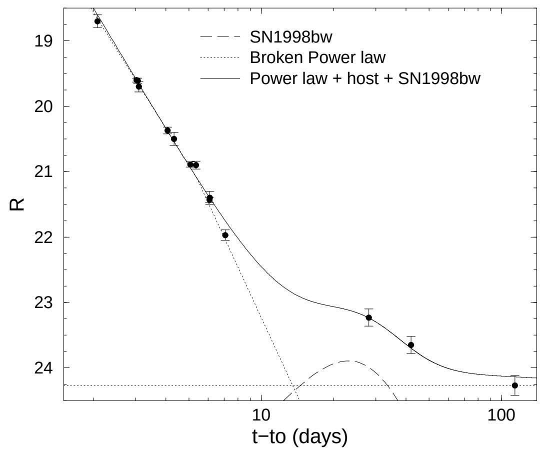

Figure 5. The GRB 991208 R-band light curve (solid line) fitted with a SN1998 bw-like component at $z = 0.706$ (long dashed line) superposed to the broken power-law OA light curve displaying the second break at $t_{break} \sim 5\ d$ (with $\alpha_1 = -2.3$ and $\alpha_2 = -3.2$, short dotted lines) and the constant contribution of the host galaxy (R = 24.27 ±0.15, dotted line), see also Sagar et al. (2000). The figure is adapted from Castro-Tirado et al. (2001).

gested SN-like phenomenon. The collapsar model was proposed soon after (Woosley 1993).

Thus, the collapsar is a massive star endowed with a lot of angular momentum. If the remnant is a black hole, the angular momentum leads to formation of an accretion disk and the energy is deposited along the polar axis, forming a jet. The remnant could also be a magnetar, a rapidly spinning neutron star with a very intense magnetic field (up to 10^{15} G).

The first hints of the long duration GRB / SN connection happened in 1998, when GRB 980425 took place in the same region of the sky (also coincident in time) with SN 1998bw. Later on, an underlying SN was proposed by Castro-Tirado & Gorosabel (1999) in GRB 980326 and modelled by Bloom et al. (1999). Indeed, the smoking gun took place in 2003, when a multi-wavelength campaign led to the detection of prominent broad emission lines similar to the ones seen in SN 1998bw / GRB 980425 (Stanek et al. 2003; Hjorth et al. 2003). The optical afterglow spectrum showed some evolution starting from the first night after the burst, and the beginning of spectral changes are seen as early as 10-12 hours after the GRB. The onset of the spectral changes for t < 1 day indicated that the contribution from Type Ic supernova (SN) into the OT optical flux can be detected earlier (Sokolov et al. 2003). Mazzali et al. (2003) used a hybrid model to match the spectrum near maximum light, resulting in $E_{kin} = 3.8 \times 10^{52}$ erg, $M_{ej} = 8\ M_{\odot}$. M (Ni) = 0.35 $M_{\odot}$ yielding a $M_{(ZAMS)} \sim$ 35-40 $M_{\odot}$.

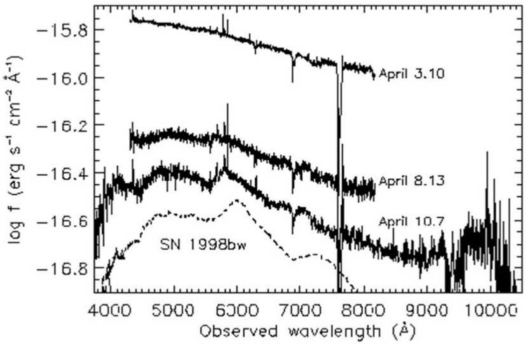

Figure 6. The GRB 030329/SN2003dh optical afterglow spectrum at different epochs, showing the evolution and the appearance of the bumps seen in GRB 980425/SN 1998bw. This figure is adapted from Hjorth et al. (2003).

In most cases, no spectroscopy is available and the light curve can be fit, initially using SN 1998bw as template to mimic the main bump (if present), but other high energetic SN light curves have been used, like SN 1997ef, SN 2002ap, etc. See also Zeh et al. (2004) and Ferrero et al. (2006). Finally, we want to point out that another 4 SNe/GRB have gotten spectral confirmation: GRB 031203/SN2003lw (Malesani et al. 2004), XRF 020903 (Soderberg et al. 2004), GRB 060218/SN 2006aj (Sollerman et al. 2006) and GRB 100316D/SN2010bh (Bufano et al. 2011).

In this respect, the possible existence of a continuum encompassing the diversity of explosive stellar deaths, ranging from ordinary supernovae (SNe; lacking any sign of a relativistic outflow) to relativistic hypernovae associated with energetic long duration gamma-ray bursts (GRBs), is under intense debate, with borderline systems like XRT 080109 shedding some light on this interesting astrophysical problem (Gorosabel et al. 2010).

However, there are some exceptions: no SNe was found to be associated to GRB 060505 and 060614 (Fynbo et al. 2006). The question is whether they are short GRBs (where no SNe is expected) or long GRBs (where a SN should have been seen). In any case, to overcome the problem, it has been proposed that it is actually possible to explode a star without making Ni ($< 1\% M_{\odot}$). So, it could be possible to make a GRB without making radioactive elements.

Another issue is whether there are SNe or mini-SNe in short GRBs? For instance, GRB 050509b was the first short GRB for which an X-ray afterglow was localized accurately by *Swift* Gehrels et al. (2005). If this burst happened at an elliptical galaxy at z = 0.225 (Castro-Tirado et al. 2005; Bloom et al. 2006), this will give support for binary mergers although no associated SNe were found (Hjorth et al. 2005a). First detections of optical and radio afterglows were achieved for two other short events: GRB 050709 and 050724 (Hjorth et al. 2005b; Berger et al. 2006) although the X-ray flaring seen in GRB 050724 (Barthelmy et al. 2005) leaves some open questions. Finally, could GRB 060121 (de Ugarte Postigo et al. 2006) represent a second population of short events at higher redshift ?

3.2 The progenitors for the long-duration GRB class

In the light of all these observational evidences, it is timely to discuss about the nature of the central engine of long-duration GRBs. There are two main possible scenarios that can give rise to a GRB: i) Collapse of massive stars (Bodenheimer & Woosley 1983; Woosley 1993; Benz et al. 1998; Paczynski 1998), and ii) Coalescence of neutron stars in a binary system (Lattimer & Schramm 1974; Paczynski 1986; Eichler et al. 1989; Narayan et al. 1992; Mochkovith et al. 1993). Other models like a pulsar with a precessing jet (Fargion 1999) cannot be excluded.

How to produce a long-duration GRB from the massive star evolution theoretical modeling? we know that:

- Low mass stars ($M < 8\ M_{\odot}$) in close binary systems will undergo a thermonuclear explosion of a carbon-oxygen white dwarf, with no remnant (Type Ia SN) (Hoyle & Fowler 1960).
- Massive stars of $8\ M_{\odot} < M < 25\ M_{\odot}$ will lead to a core-collapse SN, and neutron star remnant (Type II, Ibc) (Zwicky & Baade 1934).
- Massive stars of $140\ M_{\odot} < M < 250\ M_{\odot}$ will lead to a pair-instability SN (Rakavy & Shaviv 1967).
- For stars of other masses: black-hole remnants, usually no SN explosion expected.

In all cases, the clue seems to be the rapid rotation, foreseen in both the collapsar (Woosley 1993; MacFadyen & Woosley 1999) and magnetar (Usov 1992) scenarios.

There are a number of necessary conditions for taking place a GRB. First, a high angular momentum in the core (to power relativistic jets) is needed, although this is difficult to achieve in most stars due to the core braking. Second, a removal of the H envelope (jet crossing time < 100s) is required. And third, a massive core is most essential to form a black hole (but not needed for the magnetar scenario).

And we should point out that:

- The observed SNe associated with GRBs are Type Ic, and GRB progenitors are rapidly rotating WR-type stars.
- Some special evolutionary paths may be needed to meet the angular momentum requirements.

- There are three different ways to make massive He starts (i.e. WR-type stars): i) mass loss by stellar winds from single stars (implying a strong spin-down); ii) binary interaction; and iii) chemically homogeneous evolution.

Amongst other long-duration GRB progenitors models, we can add the following four:

- Tidal spin-up of He stars in close binaries (Izzard & Tout 2003; Detmers et al. 2008).
- Case-C mass transfer in binary systems with a low-mass companion (Brown et al. 2000; Podsiadlowski et al. 2010).
- Mergers: He core + He core or He star + NS/BH (Fryer & Heger 2005).
- Chemically Homogeneous Evolution Scenario (CHES), through which the star is gradually transformed into a Wolf-Rayet star on the main sequence without mass loss and the core can retain a large amount of angular momentum thus constituting a GRB progenitor (Yoon & Langer 2005; Woosley & Heger 2006).

And one of the most relevant questions nowadays is whether the first stars (Pop III stars) could produce long GRBs?

4. Conclusions

I have shown some of the advances in the gamma-ray burst field over the last decade, focusing on the prompt emission and reverse/forward shock components as well as in the supernova relation for the long-duration GRBs, including the possible progenitors.

The field of Gamma-ray bursts is, still after several decades, an exciting and challenging one, which is strengthening our understanding about the Universe.

The research in GRBs has major impact not only on Stellar Astrophysics but also on Observational Cosmology, coupled with theoretical research in all these fields and the promising link to the gravity-wave Universe.

Multi-wavelength observations (photometry, spectroscopy, polarimetry) and other sources of information (neutrinos, gravitational waves) are most essential to better understand the GRB diversity and the contamination by other astrophysical objects (Castro-Tirado et al. 2008, 2011).

Technological developments are also required, at both ground-based facilities (instruments, robotic and rapid reacting systems) and in space (forthcoming space-born missions).

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