

Multiwavelength observations of GRB afterglows

Alberto J. Castro-Tirado

Instituto de Astrofísica de Andalucía (IAA-CSIC), Glorieta de las Astronomía s/n, E-18080
Granada, Spain
email: ajct@iaa.es

Abstract. Multiwavelength observations of gamma-ray burst afterglows are presented, in particular those in the optical and millimetre wavelengths. I will focus on the observations mostly carried out at Spanish ground-based observatories (mainly the 10.4m GTC) and at the Plateau de Bure Interferometer in the French Alps. The importance of global networks of robotic telescopes (like BOOTES, established worldwide) for early time observations in order to put constraints on the physical mechanisms of the GRB early time emission phase is also discussed. The overall observational efforts provide additional clues for a better understanding of the reverse and forward shock. Finally I will report on the *Lomonosov*/UFFO-p capabilities taking into account its launch in 2012.

Keywords. gamma-rays: bursts, accretion disks, acceleration of particles, black hole physics

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 leading to the first X-ray afterglow discovery (Costa *et al.* 1997), now we know that Gamma-Ray Bursts (GRBs) originate at cosmological distances with energy releases of 10^{51} – 10^{53} ergs. The multiwavelength emission that follows the gamma-ray emission (the “afterglow”) satisfies the predictions of the “standard” relativistic fireball model. See Castro-Tirado (2001) for a review of the field prior to the year 2000.

Since the launch of the *Swift* mission in 2004, more than 500 GRBs have been detected, with 85% of them being recorded in follow-up X-ray observations, 60% with optical detection and nearly 200 redshifts have been measured since 1997 (including 41 prior to *Swift*). *Fermi* was launched in 2008, to record the higher energy (MeV) population.

For the record, it is worth mention that a likely X-ray afterglow was pinpointed 5 yr before the *BeppoSAX* detection of GRB 970228. Such was the case for GRB 920723B (Castro-Tirado 1994), and the word “afterglow” was indeed used by Terekhov *et al.* (1993). Moreover, the first optical afterglow was already serendipitously imaged in 1992 for GRB 920925c (Hurley *et al.* 2000) being reported 15 yr later (Denisenko & Terekhov 2007).

2. Afterglow science in long-duration GRBs

Since the initial works by Paczynski (1986) and Goodman (1986), the physics of relativistic ejections by a compact source was further developed. The standard model was developed by Meszaros & Rees (1997) and also by Paczynski & Rhoads (1993). Hereafter, we will consider a few selected results on both the reverse and forward shock emission.

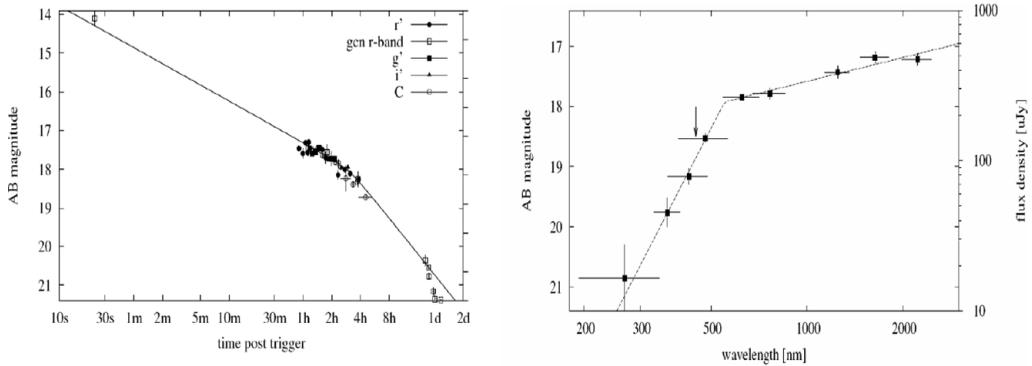


Figure 1. Left panel: The overall lightcurve of the GRB 080603B afterglow including BOOTES data. Right panel: The spectral energy distribution of the optical afterglow in the rest frame. The small arrow marks the Ly- α position for $z = 2.69$. From Jelinek *et al.* (2012).

2.1. The reverse shock emission

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 a uniform shell, the reverse shock is short-lived.

An important assumption is that the reverse shock microphysics parameters are equivalent to the internal shock microphysics parameters and different (in both cases) to 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 (Zhang, Kobayashi & Meszaros 2003, Gomboc *et al.* 2009).

For instance, for the case of GRB 060117 (Jelinek *et al.* 2006) and GRB 090902B (Pandey *et al.* 2010), a bright afterglow and a decay slope are suggestive of a reverse shock origin.

2.2. The forward shock emission

The afterglow is usually interpreted as the signature of the deceleration of the relativistic outflow by the external medium. The forward shock can be modelled under the frame of the standard fireball model, by means of the synchrotron spectrum moving towards longer wavelengths as function of time.

In the case of GRB 060117 (Jelinek *et al.* 2006), the peak time of the rising optical afterglow lightcurves could be used for determining the initial Lorentz factor following Molinari *et al.* (2007). The rising lightcurves ($F \propto t^\alpha$) are also important to understand the onset of the afterglow (Sari *et al.* 1999): $\alpha \sim 2$ ($\nu_c < \nu_{\text{optical}}$) or $\alpha \sim 3$ ($\nu_c < \nu_{\text{optical}}$) in the case of ISM or $\alpha \sim 0.5$ for a WIND density profile. It allows also off-axis and structured jet models to be constrained (Panaitescu *et al.* 1998).

Prior to *Swift*, there were very promising results (multiwavelength fits) but even then problems were noticed, like the jet breaks, first detected in GRB 990123 (Castro-Tirado *et al.* 1999, Kulkarni *et al.* 1999; see Fig. 1).

After the initial *Swift* results, the picture has turned out to be more complicated: the canonical *Swift* X-ray afterglow lightcurve 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).

In many occasions, energy injections have to be taken into account to properly fit $F(\lambda, t)$. Thus, GRB 021004 ($z = 2.33$) was modelled by multiple energy injections (de

Rebrightenings have been observed for many long-duration GRBs at epochs consistent with a rising light curve from a SN exploding within 1 day of the GRB time, a few of them being confirmed by spectroscopy and changes of colours around $\sim 15 (1+z)$ days after the GRB trigger. Thus, SNe/GRB should be reachable with the Spanish 10.4m GTC up to $z \sim 1$. In fact, GTC has allowed detection of the underlying SNe for both GRB 091127 (SN 2009nz) at $z = 0.490$ (Vergani *et al.* 2011a; see also Cobb *et al.* 2010, Berger *et al.* 2011) and GRB 111211A (de Ugarte Postigo *et al.* 2012).

2.4. Spectroscopic observations of GRB afterglows

Besides helping to determine the distance scale, spectroscopic observations of nearby events ($z < 0.3$) may reveal on a few cases unequivocal SN signatures similar to those of SN 1998bw, which coupled to the lightcurve monitoring will help to estimate the energy output, ^{56}Ni mass and remnant mass of the associated SN.

Besides this, optical (and near-IR) spectroscopy is most essential for understanding the GRB environment (abundances, metallicities, etc). As an example, in GRB 021004 ($z = 2.33$), high resolution spectroscopy revealed several high velocity systems in the range 200-3000 km/s (Starling *et al.* 2005, Castro-Tirado *et al.* 2010, Vergani *et al.* 2011b). In GRB 021004, the high velocity systems were naturally explained by multiple shells formed by stellar winds of a WR progenitor after passing through a LBV phase after reaching the Eddington limit. A $\sim 60 M_{\odot}$ ZAMS progenitor is suggested following the accepted evolutionary track: O - LBV - WR - SN (Castro-Tirado *et al.* 2010).

We have also used the 10.4m GTC (+OSIRIS) to determine redshifts for a handful of events (GRB 100316A, 110503, 110801A, 110918A and 120326A; Sánchez-Ramírez *et al.* 2012, Tello-Salas *et al.* 2012) and confirmed many others (like GRB 100816A, 110422A, 110918A and 120327A; see Fig. 2).

2.5. Polarimetric observations of GRB afterglows and hypernovae

Optical light of the afterglows should be polarized because the magnetic field of the ISM, and also the central source, are amplified in the shocked front, so the electrons emit polarized synchrotron light. The ejecta concentrates the radiation in a beam of width $\theta \sim 1/\Gamma(t)$, where $\Gamma(t)$ is the Lorentz factor. The observer line of sight must be within the beam (otherwise the GRB would be undetectable) but in general not perfectly aligned with the jet. This breaks the source-observer axi-symmetry, avoiding the cancellation of electric vectors created in different emitting regions (Lazzati *et al.* 2004).

Observations performed so far show varying levels of polarized emission in the jet and the geometry. Polarized optical emission has been claimed for a few classical GRBs, usually $P = 1-2\%$ (Gorosabel *et al.* 2004) and rarely up to 10% (Steele *et al.* 2009). $P \sim 1.5\%$ was measured for SN 2003dh / GRB 030329 (Greiner *et al.* 2003).

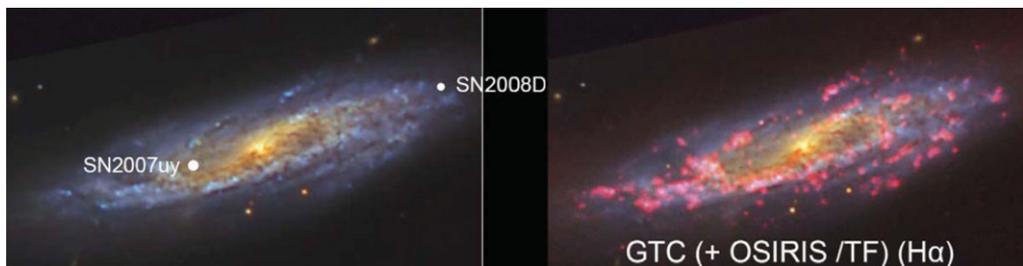


Figure 3. Left panel: NGC 2770 in broad-band optical filters showing the location of SN2007uy and SN 2008D. Right panel: The same field imaged in H- α thanks to the OSIRIS tunable filters in the GTC. From Gorosabel *et al.* (2011).

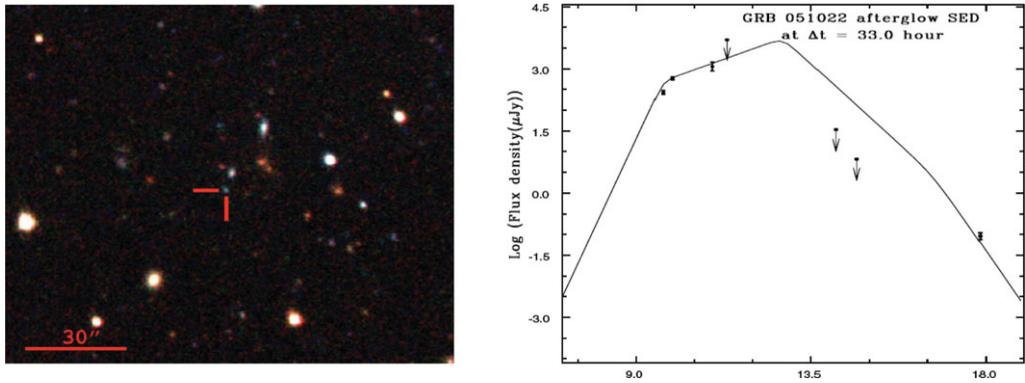


Figure 4. Left panel: the GRB 051022 mm afterglow was coincident with a blue galaxy at redshift $z = 0.809$. Right panel: the SED of the dark GRB 051022 afterglow. From Castro-Tirado *et al.* (2010).

The optical light of hypernovae can also be polarized as in the case of normal supernovae: Thomson scattering in the expanding stellar atmosphere. If the expansion is perfectly spherical, the polarization coming from different stellar parts would be canceled so no net polarization would be detected, as in normal SNe. However, in hypernovae, the expansion is likely to be ellipsoidal, so the symmetry around the line of sight is broken, producing non-zero polarization.

For SN 2006aj (type Ic) / XRF 060218A there was evidence for aspherical expansion with $P = 4\%$ decreasing to 1.4% plus a 100° rotation in the position angle (Gorosabel *et al.* 2006). For SN 2008D / XRT 080109 in NGC 2270 there was evidence for aspherical expansion with $P = 1\%$ (Gorosabel *et al.* 2010). Neither SN 2008D nor XRT 080109 are associated with any given giant H-II region in NGC 2770 (Fig. 3).

2.6. Afterglows at mm wavelengths

Millimetre observations are not affected by high- z or extinction and usually can lead to sampling the synchrotron peak in the spectrum as well as detecting the tail of the prompt emission and the forward shock. Since the first mm afterglow ever detected by us (Bremer *et al.* 1998), the number of follow-ups amounted to 60, with 54 events being observed at 3mm and 20 of them being detected so far. Redshifts for the GRB afterglows lie in the range $z = 0.03$ - 9.2 , with measured flux densities (at 3 mm) varying between 0.25 and 60 mJy (but usually < 1.5 mJy) with the first observations taking place around 1-2 days after the GRB. We have detected 2 (out of 3) GRBs at $z > 6$: GRB 050904 ($z = 6.3$) and GRB 090423 ($z = 8.3$). On the lower redshift end, we have detected the low- z , faint GRB 080109 / SN 2008D ($z = 0.0065$). Amongst the long-duration class, we have detected two “dark” GRBs: one associated with a $z = 0.809$ galaxy (GRB 051022, Fig. 4) and another one (GRB 090404) whose host galaxy is not properly identified. Altogether, this implies a $\sim 42\%$ success rate (for this non-blind sample). A more in-depth analysis is presented in Castro-Tirado *et al.* (2012a).

3. Automated and Robotic Telescopes and their usage for GRB follow-ups

The (B)urst (O)bserver and (O)ptical (T)ransient (E)xploring (S)ystem (BOOTES), is a set of instruments that was conceived in 1995 and nowadays comprises four astronomical



Figure 5. Left panel: an image obtained by the CASANDRA-3 all-sky camera showing the silhouette of the 0.6m diameter YA telescope against the Milky Way at the BOOTES-3 robotic astronomical station in Blenheim (New Zealand). Right panel: the enclosure of 0.6m diameter MET telescope at the BOOTES-4 robotic astronomical station in Lijiang (China).

stations in Spain (two), New Zealand and China (Fig. 5). The main scientific goal is the follow-up of GRBs by means of fast ultralight weight 60cm diameter telescopes (Castro-Tirado *et al.* 2012b).

BOOTES-1 follow-ups have been partially summarized by Jelinek *et al.* (2011). The BOOTES network has allowed the discovery of a handful of optical afterglows (GRB 080330, GRB 080603B, GRB 080605, GRB 080606, GRB 101112A), observing many other at early times. BOOTES-2 and BOOTES-3, with larger diameter telescopes, have also contributed to some detailed studies on the forward shock evolution, as in the case of GRB 080603B, GRB 080605 and GRB 080606 (Jelinek *et al.* 2012) including the discovery of the optical afterglows of GRB 091029 and GRB 091208B. On the aggregate, BOOTES-1 have followed ~ 40 events, detecting 10 afterglows, BOOTES-2/TELMA have followed up 9 events, detecting 3 afterglows, whereas BOOTES-3/YA have followed up 17 events, detecting 5 afterglows. BOOTES-4/MET has just followed up two GRBs, as it was officially opened in Mar 2012.

4. UFFO-p onboard Lomonosov

GRB afterglows can also be monitored by doing the follow-up using the triggering satellite itself, besides sending the position to the Earth (*BeppoSAX* in 6-8 hr, *Swift* in 1 min). Early follow-up (within ~ 1 hr) is only available to *Swift* so far (sometimes even very early, with response times of ~ 1 min) due to the slewing time of the entire spacecraft. Is it possible to beat this 1 min barrier from space? Indeed, in UFFO-p (UFFO-pathfinder) the optical path moves, not the spacecraft itself. This is achieved thanks to a fast slewing motorized mirror (new concept) in the Slewing Mirror Telescope (SMT) instrument (a mirror of 10 cm diameter) and an intensified CCD at the Cassegrain focus to achieve less than 1 s optical response after X-ray trigger. The second instrument is the UFFO Burst Alert & Trigger telescope (UBAT) for detecting the GRB locations. The UBAT employs a coded-mask γ /X-ray camera with a wide field of field of ~ 1.8 sterad ($90^\circ \times 90^\circ$) and is comprised of three parts: a coded mask, a hopper, and a detector module. The UBAT DM consists of a LYSO scintillator crystal array sensitive to ~ 200 keV (effective area

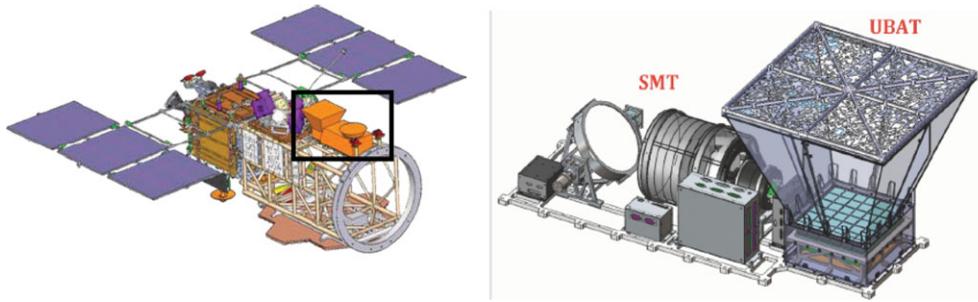


Figure 6. The integrated UFFO-pathfinder, to be launched aboard the *Lomonosov* spacecraft. The SMT enclosure is not shown in this drawing. Adapted from Chen *et al.* (2011).

of $\sim 190 \text{ cm}^2$), multi-anode photo multipliers, and analog and digital readout electronics (Park *et al.* 2009, Chen *et al.* 2011; see Fig. 6).

5. Summary

Afterglow emission can be detected in all the electromagnetic range, in all timescales from seconds to months (the later only in some cases). A variety of features can be studied by different techniques (photometry, spectroscopy, polarimetry) to gain insight into the underlying hypernovae and progenitors, environments, abundances, metallicities, host galaxies, etc. The overall observational efforts provide additional clues for a better understanding of the reverse and forward shock in the framework of the existing theoretical models, which should also accommodate the last observational results (not always easy).

In order to shed additional light in the field, technological developments are also required, e.g. new instrumentation at large facilities (like GTC) and at robotic telescope networks (like BOOTES). Future space missions, like *Lomonosov*/UFFO-p (to be launched in 2012) should be well suited for studying GRB emission at very early stages.

6. Acknowledgements

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Discussion

L. AMATTI: What about the UFFO Mission?

A. J. CASTRO-TIRADO: The UFFO-p is scheduled for launch this year, aboard the *Lomonosov* spacecraft, in a low-Earth orbit. See also the contribution by H. Lim *et al.* (in these proceedings).

B. ZHANG: Can you say a few words about using ALMA for studying GRB afterglows?

A. J. CASTRO-TIRADO: ALMA, thanks to its superb sensitivity, will opening a new era in the study of GRB afterglows detecting most of them if observed closed to the passage of the peak synchrotron emission. See also the contribution by A. de Ugarte Postigo *et al.* (in these proceedings).