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Gamma-ray bursts at near-IR/optical/X-ray wavelengths

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Abstract. GRBs remained a puzzle for many high-energy astrophysicists since their discovery in 1967, but with the advent of X-ray satellites like *BSAX*, *RXTE* and those of the Third Interplanetary Network, it has been possible since 1997 to discover the first optical/IR counterparts just within a few hours of occurrence. This has greatly improved our understanding of these sources and the physical properties of the afterglows, revealing the existence of beaming and the different emitting regions but has also posed many new questions. The launch of *Swift* in Nov 2004 has opened a new era in GRB research thanks to the detection of a considerable number of events, together with other satellites like *HETE-2* and *INTEGRAL*. The classical, long duration GRBs,have been observed to originate at cosmological distances in a range of redshifts with $0.105 \leq z \leq 4.50$ implying energy releases of $\sim 10^{51}$ ergs. The results on GRB 021004 and GRB 030329 confirm that the central engines that power these extraordinary events are due to be collapse of massive stars rather than the merging of compact objects as previously also suggested. Short GRBs still remain a mystery in spite of the recent detection of the first X-ray afterglow for one such event.

Key words. Gamma ray: bursts – Stars: evolution – Galaxy: abundances – Cosmology: observations

1. Introduction

In 1967-73, the four *VELA* spacecraft (named after the spanish verb *velar*, to keep watch), that where originally designed for verifying whether the former Soviet Union abided by the Limited Nuclear Test Ban Treaty of 1963, observed 16 peculiarly strong events (Klebesadel et al. 1973; Bonnell and Klebesadel 1996). On the basis of arrival time differences, it was determined that they were related neither to the Earth nor to the Sun, but they were of cosmic origin. Therefore they were named cosmic Gamma-Ray Bursts (GRBs hereafter). Nearly 4000 events have been detected to date.

2. Observational facts and implications

2.1. GRBs in the gamma-ray domain

GRBs appear as brief flashes of cosmic high energy photons, carrying the bulk of their energy above ≈ 0.1 MeV (Fig. 1). The KONUS instrument on *Venera 11* and *12* gave the first indication that GRB sources were isotropically distributed in the sky (Mazets et al. 1981; Atteia et al. 1987). Based on a much larger

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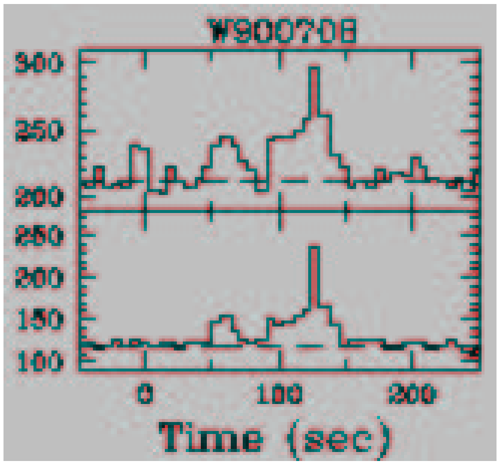

Fig. 1. One of the typical long-duration GRBs detected by WATCH on *GRANAT*, lasting for about 150-s in the 8-20 keV range (above) and in the 20-60 keV range (below). From Lund et al. (1982).

sample, this result was nicely confirmed by BATSE on board the *CGRO* satellite (Meegan et al. 1982). In general, there was no evidence of periodicity in the time histories of GRBs. However there was indication of a bimodal distribution of burst durations, with ~25% of bursts having durations around 0.2 s (the short/hard GRB class) and ~75% with durations around 30 s (the long/soft GRB class). A deficiency of weak events was noticed in the log *N*-log *S* diagram, as the GRB distribution deviates from the -3/2 slope of the straight line expected for an homogeneous distribution of sources assuming an Euclidean geometry. However, the GRB distance scale had to remain unknown for 30 years. A comprehensive review of these observational characteristics can be seen in (Fishman and Meegan 1995).

2.1.1. Solving the distance scale

After the discovery of the first X-ray and optical afterglows (OA) for GRB 970228 detected by *BeppoSAX* (Costa et al. 1997; van Paradijs et al. 1997), the second OA associated to a GRB was detected within the GRB 970508 error box (Bond 1997; Pedersen et al. 1998). The GRB 970508 OA light curve reached a peak in two days (R = 19.7, (Djorgovski et al. 1997)) and was followed by a power-law decay $F \propto t^{-1.2}$ (Castro-Tirado et al. 1998). Optical spectroscopy obtained during the maximum allowed a direct determination of a lower limit for the redshift of GRB 970805 ($z \geq 0.835$), implying an isotropic energy release $E \geq 7 \times 10^{51}$ erg (Metzger et al. 1997). It was the first proof that GRB sources lie at cosmological distances. The flattening of the decay in late August 1997 (Pedersen et al. 1998; Sokolov et al. 1998) revealed the contribution of a constant brightness source -the host galaxy- that was revealed in late-time imaging obtained in 1998 (Bloom et al. 1998; Castro-Tirado et al. 1998; Zharikov et al. 1998). The maximum observed 1-day after the burst has not been detected in other GRBs so far and it was interpreted by a delayed energy injection or by an axially symmetric jet surrounded by a less energetic outflow (Panaitescu et al. 1998). The luminosity of the galaxy is well below the knee of the galaxy luminosity function, $L \approx 0.12\ L^{*}$, and the detection of deep Mg I absorption (during the bursting episode) and strong [O II] 3727 Å emission (the latter mainly arising in H II regions within the host galaxy) confirmed $z = 0.835$ and suggested that the host could be a normal dwarf galaxy (Pian et al. 1998), with a star formation rate (SFR) of $\sim 1.0\ M_{\odot}$ year^{-1} (Bloom et al. 1998). Prompt observations at cm and mm wavelengths led to the detection of the counterpart at these wavelengths (Frail et al. 1997; Pooley et al. 1997; Bremer et al. 1998). The fluctuations could be the result of strong scattering by the irregularities in the ionized Galactic interstellar gas, with the damping of the fluctuations with time indicating that the source expanded to a significantly larger size. However VLBI observations did not resolve the object (Taylor et al. 1997). A Fe Kα line redshifted at $z = 0.835$ in the X-ray afterglow spectrum (Piro et al. 1999) was attributed to a thick torus of material surrouding the central engine (Meszaros et al. 1998).

The *INTEGRAL* (Winkler et al. 2003) and *Swift* satellites (Gehrels et al. 2004) offer unique capabilities for the detection of GRBs thanks to their high sensitivity and imaging capabilities at γ-ray energies and X-ray/optical. Thus, the number of optical afterglows discovered since 1997 has increased to more than 70. About 40 host galaxies for classical, long duration GRBs, have been detected so far, in the range $0.105 \le z \le 4.50$ (if ESO 184-G82 is excluded). None of the hosts are brigther than the knee of the luminosity function L^* at their redshift, but the GRB hosts are noticeable bluer than typical galaxies of similar magnitude (Sokolov et al. 2001; Christensen et al. 2004). One interesting remark is that the mean redshift before the *INTEGRAL* and *Swift* era was 1.0, whereas the same value when considering events detected by any of the two satellite has increased to 2.1 (see also (Berger et al. 2005)).

2.1.2. The existence of collimated emission

GRB 990123 (Fig 2) was the first event for which contemporaneous optical emission was found simultaneous to the gamma-ray burst, reaching V ~ 9 (Akerloff et al. 1999). This optical flash did not track the gamma-rays and did not fit the extrapolation of the *BeppoSAX* and BATSE spectra towards longer wavelengths. This optical emission was interpreted as the signature of a reverse shock moving into the ejecta (Sari et al. 1999). A brief radiotransient was also detected (Frail et al. 1999) coincident with the optical counterpart (Odewahn et al. 1999) and spectroscopy indicated $z = 1.599$ (Andersen et al. 1999). A break observed in the light curve ~ 1.5 days after the high energy event suggested the presence of a beamed outflow (Castro-Tirado et al. 1999; Kulkarni et al. 1999; Fruchter et al. 1999), thus reducing the energy release by $\sim 10^2$. A weak magnetic field in the forward shock region could account for the observed multiwavelength spectrum in contrast to the high-field magnetic field for GRB 970508 and it seems that the emission from the three regions was first seen in this event (Galama et al. 1999): the internal, reverse and forward shocks.

Further support for a jet-like outflow came from GRB 990510, the first burst for which polarized optical emission was detected ($\Pi = 1.7 \pm 0.2$ %; Covino et al. 1999; Wijers et al. 1999). This confirmed the synchrotron origin of the blast wave itself and represented another case for a jet-like outflow (Stanek et al. 1999), as has been later seen in other events.

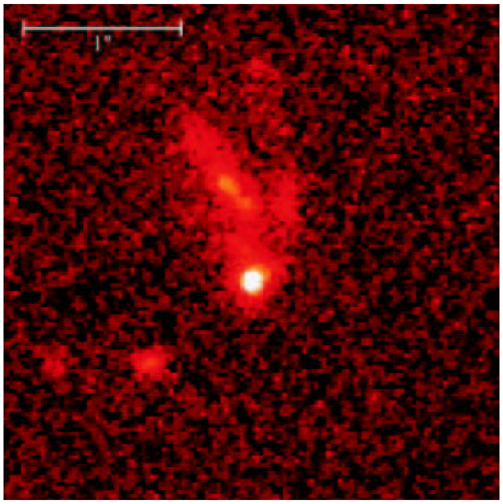

Fig. 2. The GRB 990123 optical afterglow superposed to the R = 24.5 galaxy system at z = 1.6, as observed by HST. From Fruchter et al. (1999).

2.1.3. Dark GRBs

Following the unsuccessful search for an OA for GRB 970111 (Castro-Tirado et al. 1997), intensive work was conducted for GRB 000210, a burst that was followed up by *CHANDRA*. The fact that no OA was detected despite of deep optical searches down to R ~ 23.5 implied to classify the event as a another "dark" GRB. A constant brightness optical counterpart ($R = 23.5$, Gorosabel et al. 2000) was coincident with the 1.6″ error box derived by *CHANDRA* (Garcia et al. 2000) implying that this was the likely host galaxy. A radiotransient was discovered with the VLA and from the X-ray spectrum, it was derived that either the gas is local to the GRB or that the gas is located in a dusty, gas-rich region of the galaxy (Piro et al. 2002), which is observed to harbour considering star formation (Gorosabel et al. 2003).

At least in another three cases (GRB 981226, GRB 990506 and GRB 001109), radiotransients were detected without accompanying optical/IR transients.The observed fraction of dark GRBs detected so far is ~ 40%. This could be due to intrinsic faintness because of a low density medium, high absorption in a dusty enviroment, or Lyman limit absorption in high redshift galaxies ($z > 7$). If GRBs are tightly related to star-formation, a substantial fraction of them should occur in highly obscured regions. For instance, most of star formation in the Hubble Deep Field is so enshrouded by dust that starlight from the galaxies detected by SCUBA is attenuated by a factor of $\sim 10^2$ (Hughes and Dunlop 1999).

2.1.4. The detection of X-ray lines

The GRB 011211 (at z = 2.14), displayed rapid variations in the R-band light curve approximately 0.5 days after the burst, suggesting that they were due to density fluctuations near the central engine on spatial scales of approximately 40-125 AU (Holland et al. 2002). The early afterglow spectrum was obtained by *XMM-Newton*, which observed 11 hours after the initial burst, and appeared to reveal decaying H-like K emission lines of Mg, Si, S, Ar and Ca, arising in enriched material with an outflow velocity of order ~ 0.1c (Reeves et al. 2002). This was attributed to matter ejected from a massive stellar progenitor occurring shortly before the burst itself. Thermal emission, from an optically thin plasma, is the most plausible model that could account for the soft X-ray emission. The X-ray spectrum of evolved with time over the first 12 ksec, suggesting that thermal emission dominated the early afterglow spectrum, whilst a power-law component dominated the latter stages. This implies that the progenitor of the GRB was a massive star and that the mass of the ejected material in GRB 011211 was estimated to be ~ 4-20 $M_\odot$ (Reeves et al. 2003).

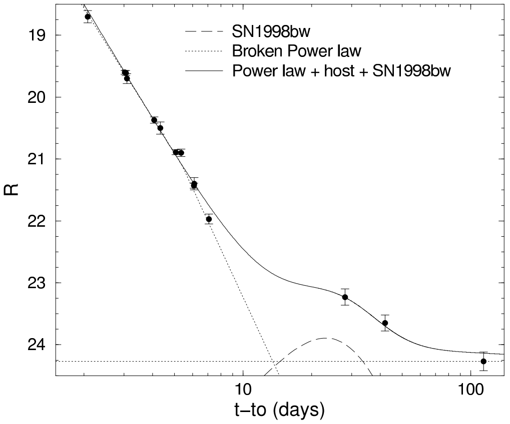

Fig. 3. The GRB 991208 R-band light curve (solid line) fitted with a SN1998 bw-like component at z = 0.706 (long dashed line) superposed to the broken power-law OA light curve displaying the second break at $t_{break} \sim 5\ d$ (with $\alpha_1 = -2.3$ and $\alpha_2 = -3.2$, short dotted lines) and the constant contribution of the host galaxy (R = 24.27 ±0.15, dotted line). From Castro-Tirado et al. (2001).

2.1.5. The GRB-SN connection

A peculiar Type Ic supernova (SN 1998bw) was found in the error box for the soft GRB 980425 by Galama et al. (1998). The SN was associated to the galaxy ESO 184-G82, an actively star forming SBc sub-luminous galaxy at z = 0.0085. The fact that the SN event occurred within ± 1 day of the GRB event, together with the relativistic expansion speed derived from the radio observation (Kulkarni et al. 1998) suggested a SN/GRB relationship for the first time. The total energy released would be 8×10^{47} erg which is about $\sim 10^5$ smaller than derived for ”classical” GRBs. Follow-up *HST* observations of ESO 184-G82 2.1 yr after the event, revealed an object consistent with being a point source within the astrometric uncertainty of 0.018″ of the SN position. The object is located inside a star- forming region and is at least one magnitude brighter than expected for the SN based on a simple radioactive decay model, implying either a significant flattening of the light curve or a contribution from an underlying star cluster (Fynbo et al. 2000).

Independently, Castro-Tirado and Gorosabel (1999) and Bloom et al. (1999)

also suggested the presence of an underlying SN in GRB 980326. Reichart (1999) also proposed that a type Ib/c supernova lay ”behind” another GRB (GRB 970228), overtaking the light curve two weeks after. This fact seems to be confirmed by following work (Galama et al. 2000). Further evidences have been found for another bursts (Castro-Tirado et al. 2001; Della Valle et al. 2003; Garnavich et al. 2003; Masetti et al. 2003; Greiner et al. 2003; de Ugarte Postigo et al. 2005; see also Fig. 3).

For GRB 021004, at least seven absorption line complexes spanning a velocity range of about 3000 km/s were found in the vicinity of the host galaxy, at z = 2.33. This observational evidence was interpreted as the presence of a multiple shell structure formed by the winds around the massive star progenitor, which it is thought to have been a Wolf-Rayet star (Schaefer et al. 2003; Mirabal et al. 2003; Castro-Tirado et al. 2005a).

GRB 030329 is, together with GRB 031203, one of the two nearest classical, long duration GRB detected so far, at $z = 0.1685$. Due to its proximity, spectroscopic campaigns started already 1 day after the event, which led to the detection of SN absorption features superposed on the power-law OA spectrum. These signatures increased with time and resembled remarkably the SN1998bw/GRB 980425 spectrum (Fig. 4). Thus, in spite of no optical bump being present in the optical/nIR light curve (Guziy et al. 2005), the underlying object was dubbed SN2003dh (type Ic) (Stanek et al. 2003) and from VLT spectroscopy, a photospheric expansion velocity of ~ 0.1c one week after the GRB was derived (Hjorth et al. 2003), comparable to the value found for SN1998bw. This event is therefore considered as the smoking gun that has allowed to definetively connect the collapse of massive stars with the long-duration GRBs, as was already proposed in 1974 (Colgate 1974) amongst the more than 100 theoretical models for explaining their origin.

It is possible than in these powerful supernovae, also dubbed “hypernovae” (Paczynski 1998), the explosions will be assymetric, where we are observing the GRB produced in a relativistic jet propagating along the rotation axis of the massive progenitor (Woosley 1993).

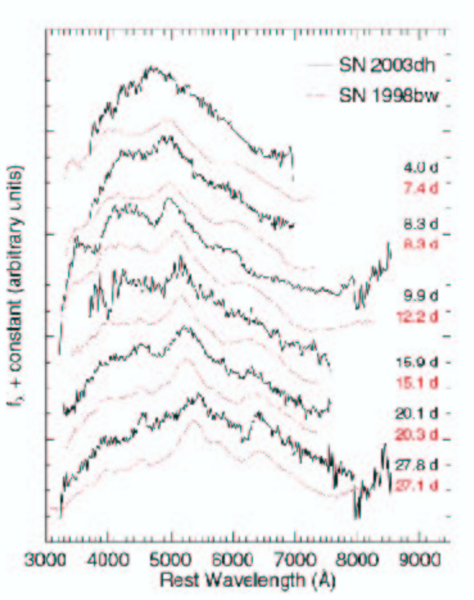

Fig. 4. Spectral evolution of the combined GRB 030329, the associated SN 2003dh and its host galaxy (no reddening correction applied). The lower spectra, dominated by SN 2003dh, reveals the typical broad-band SN signatures. To ease comparison, the spectrum of SN 1998bw at 33 days after the explosion is shown at the GRB 030329 redshift. From Hjorth et al. (2003).

2.1.6. Short GRBs

The nature of short duration GRBs, a class that comprises about 25% of all events (Mazets et al. 1981; Kouveliotou et al. 1993), still remains a puzzle, as no counterparts have been discovered so far, in spite of intense efforts in order to detect the optical, infrared and radio counterparts to several short, hard bursts (Kehoe et al. 2001; Gorosabel et al. 2002; Hurley et al. 2002; Klotz et al. 2003). Although a possible optical transient related to GRB 000313 was proposed by Castro-Tirado et al. (2002), no firm conclusion was established.

The short/hard GRB 050509b was discovered by *Swift*/BAT detector on 9 May 2005.

The burst lasted for $\approx$ 30 ms. The prompt dissemination (13.7 s) of the GRB position enabled prompt responses of automated and robotic telescopes on ground, although no prompt afterglow emission was detected. By the time when *Swift* slewed and started data acquisition (about 60 s after the event onset), fading X-ray emission was detected by the *Swift*/XRT, what can be considered as the first clear detection of an afterglow in a short duration GRB (Kennea et al. 2005; Gehrels et al. 2005). This triggered a multiwavelength campaign at many observatories aimed at detecting the afterglow at other wavelenghts, as in the case of the long duration GRB class. No afterglow emission has been detected at longer wavelengths (from optical to radio), in spite of the first reported X–ray afterglow detection for one such even, confirming the elussiveness of the afterglow of the short duration events. This burst could be located in the cluster of galaxies NSC J123610+285901 at $z = 0.225$ or beyond (Fig. 5). In the former case, the potential host galaxy seems to be an extincted ($A_{\rm V} \sim 1.8$ mag) elliptical galaxy (consistent with its morphology) harbouring an evolved dominant stellar population (age $\sim$ 250 Myr) (Castro-Tirado et al. 2005b).

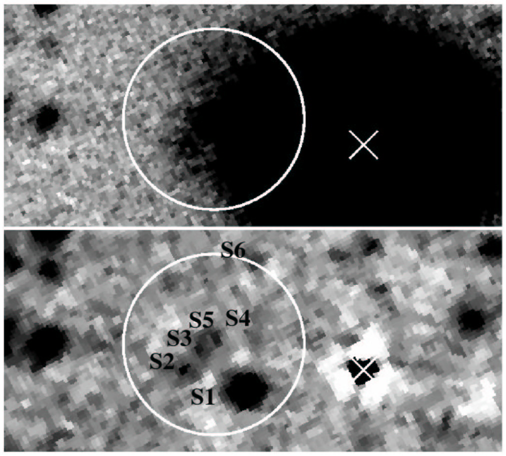

Fig. 5. The deep *R* band image of the GRB 050509b field taken at the 6.0BTA on 11 May 2005. The contribution of the elliptical galaxy, marked with a cross (*upper panel*) has been removed in order to better show the content of the *Swift*/XRT error box (*lower panel*). The six sources S1-S4 and S5-S6 within the *Swift*/XRT error box are indicated. The field is 45″ × 20″ with North up and East to the left. From Castro-Tirado et al. (2005b).

3. Conclusions

GRBs remained a puzzle for many high-energy astrophysicists since their discovery in 1967, but the *INTEGRAL* and *Swift* missions have given the astronomers the possibility of fully exploiting the capabilities of robotic and ground-based "classical" instrumentation aiming at promptly identifying counterparts at optical and near-IR wavelengths. For instance, GRB 050509b was the second short duration GRB which is detected by *Swift*/BAT after GRB 050202 (which happened close to the Sun and could not be properly followed-up), and the first localised with high accuracy by *Swift*/XRT. In spite of *CGRO*/BATSE detecting about 1/3 of events belonging to the short duration class, *Swift* has only detected 2 (out of $\sim$ 35 events), most likely due to its softer threshold energy. However, thanks to its extraordinary repointing capabilities, the accurate localisations for future events and the corresponding multiwavelength follow-up, will shed more light on the origin of the short-duration GRBs, besides of expanding our knowledge of the long-duration GRB class.

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