

The Short Gamma-Ray Burst Revolution

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Swift, a dedicated gamma-ray burst (GRB) satellite with ultrarapid slewing capability, and a suite of ground-based (ESO) telescopes have recently achieved a major breakthrough: detecting the first afterglows of short-duration GRBs. The faintness of these afterglows and the diversity of old and young host galaxies lend support to the emerging ‘standard model’, in which they are created during the merging of two compact objects. However,

the afterglow light-curve properties and possible high-redshift origin of some short bursts suggests that more than one progenitor type may be involved.

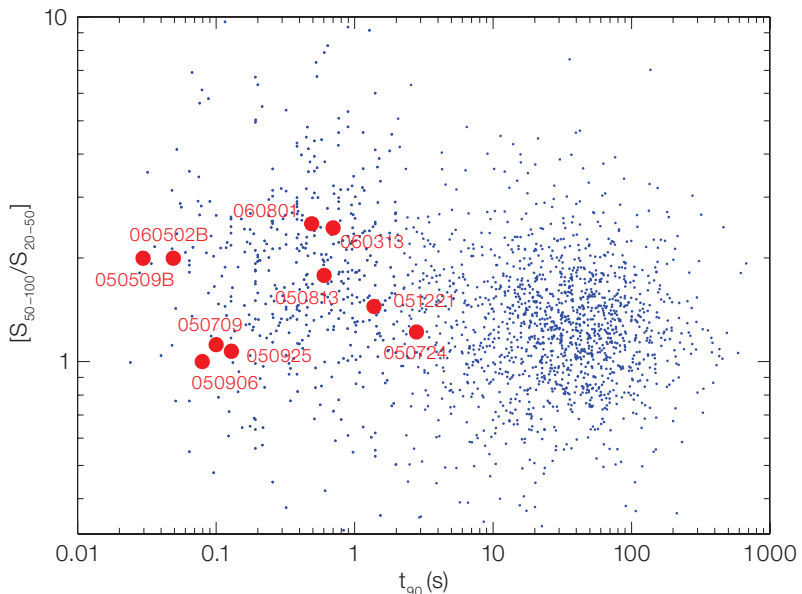
A decade ago studies of gamma-ray bursts (GRBs) were revolutionised by the discovery of long-lived afterglow emission at X-ray, optical and radio wavelengths. The afterglows provided precise positions on the sky, which in turn led to the discovery that GRBs originate at cosmological distances, and are thus the most luminous events known in the Universe. These afterglows also provided essential information for our understanding of what creates these extraordinary explosions. Observations from the VLT finally showed them to be associated with the final, catastrophic collapse of massive stars (Hjorth et al. 2003).

But the picture was not yet complete. In particular, these results applied only to the bursts with durations of > 2 s, while the burst duration distribution was clearly bimodal (Kouveliotou et al. 1993) splitting into long and short GRBs, with the short bursts also exhibiting markedly harder gamma-ray spectra (see Figure 1). The short bursts proved even more elusive than their long-duration cousins, and despite significant effort no afterglows could be found, maintaining our ignorance of their distance scales, energies and, of course, physical origin.

Afterglows – found!

Finally, in May 2005 *Swift* discovered the first X-ray afterglow to a short GRB. This was made possible because of the rapid ability of *Swift* to slew across the sky, pointing at the approximate location of the burst only a minute after it happened and pinpointing a very faint X-ray afterglow. The afterglow lies close to a massive elliptical galaxy in a cluster of galaxies at $z = 0.225$ (Gehrels et al. 2005; Pedersen et al. 2005; Figure 2). Many extremely deep observations, including those at the VLT, failed to locate either a fading optical afterglow, or a rising supernova component at later times (Hjorth et al. 2005a). The lack of an accompanying supernova (Figure 3), and the purported elliptical host galaxy (Figure 2), strongly suggest that the progenitors for these short bursts are different from those of long bursts. In particular, any radioactive material produced in the explosion must be far less.

Figure 1: The hardness-duration diagram for GRBs. The x-axis shows the duration over which 90 % of the observed total flux is detected, while the y-axis shows the ratio of fluxes in the 50–100 keV over the 20–50 keV bands, and is essentially a gamma-ray colour. Two groups (blue points) are seen, those with durations > 2 s and soft gamma-ray spectra and those with durations < 2 s and harder gamma-ray emission. These GRBs are taken from the BATSE catalogue. Also shown (in red) are the short bursts detected by *Swift* and *HETE-2* over the past 18 months.



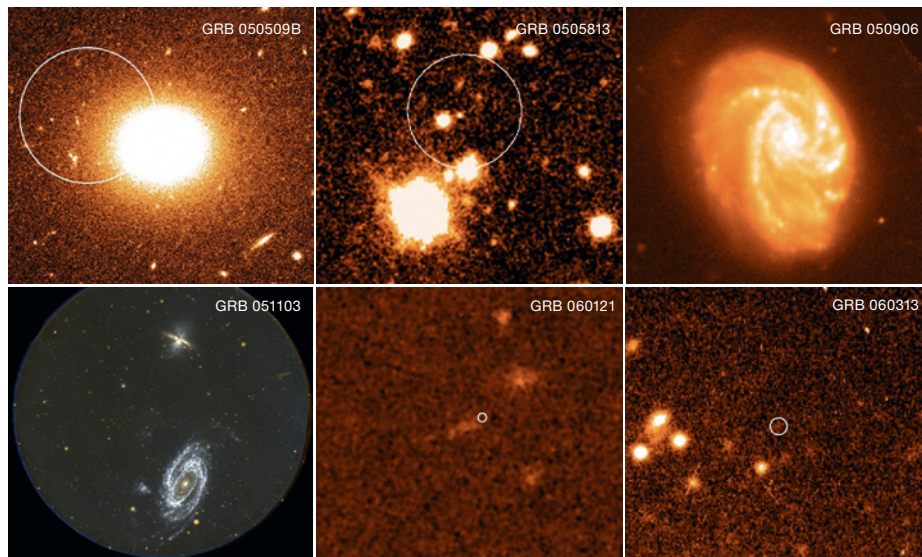


Figure 2: The diverse possible host galaxies of several short duration GRBs. GRB 050509B, the first localised short GRB, had no optical afterglow, no supernova (Figure 3) but was localised to an elliptical galaxy at $z = 0.225$ (image from VLT). GRB 050813 had no optical afterglow. In its error circle several galaxies at $z = 1.72$ were found (image from VLT). GRB 050906 had no afterglow either but inside the error circle (which is much larger than the image shown) the galaxy IC 328 ($z = 0.031$) was present (image from VLT). Inside the large IPN error box of GRB 051103 several galaxies from the nearby M81/M82 group were found (image from GALEX). GRB 060121 had a faint optical afterglow and was localised to a very faint galaxy (image from HST). GRB 060313 had a bright afterglow discovered at ESO and was localised to a very faint galaxy (image from VLT).

Optical emission from a short GRB was finally found for the HETE-2 GRB 050709 (Hjorth et al. 2005b) using the Danish 1.5-m telescope at La Silla. Gemini observations pinpointed the burst to a dwarf galaxy at $z = 0.16$. This emission is likely to be synchrotron emission, just as in long GRBs. Another short burst with an optical afterglow was GRB 051221 at $z = 0.54$. These results firmly place short GRBs at cosmological distances. However, the evidence so far indicates that they are at moderate redshifts, closer than the mean for the long GRBs which now lies at $z = 2.8$ (Jakobsson et al. 2006), a result which in itself relies significantly on ESO efforts.

Host galaxies

One of the striking differences between long and short GRBs is in the properties of their host galaxies. Long GRB hosts are mostly blue, sub-luminous and star-forming, and the GRBs preferentially occur in their brightest regions (Fruchter et al. 2006). In contrast, short GRB host galaxies seem to be a more varied class, and can be red, old and non-star-forming, with the GRBs originating at occasionally large radial separations from the host core. Any model for the origin of the short GRBs must naturally explain these observations; so far the prevailing choice is therefore compact objects – compact object mergers, e.g., neutron star – neutron star (NS-NS) or neutron

star – black hole (NS-BH). These systems merge following orbital decay due to emission of gravitational radiation. Based on observations of known systems in the Milky Way, it is clear that this can take billions of years. Also, on creation, a neutron star obtains a large ‘kick’ from the supernova, removing it from the region of star formation in which it was made, and, potentially pushing the binary far from its host galaxy at the time of the merger. This has made compact binary mergers the most popular model for short GRB origin, yet some observations continue to challenge this suggestion.

Light curves

So far, the optical afterglows of short GRBs have typically been fainter than for long GRBs (Figure 4). This has meant

that the afterglows have been less well sampled and few good spectral energy distributions have been secured. For this work 8-m telescopes are required, even at early times. By far the best early optical light curve for a short GRB comes from GRB 060313, with observations beginning on the ground (from the Danish 1.5-m telescope) only six minutes after the burst and continuing for several hours. At the VLT, following a Rapid Response Mode activation, a total of twenty seven 100-second observations were obtained. These high-S/N and high-cadence observations allowed rapid, small amplitude variability to be seen. This suggests that energy is being input into the afterglow out to late times post-burst. This is problematic for merger models, since the final coalescence should occur very rapidly, with little material remaining to fuel the burst afterwards. One possible

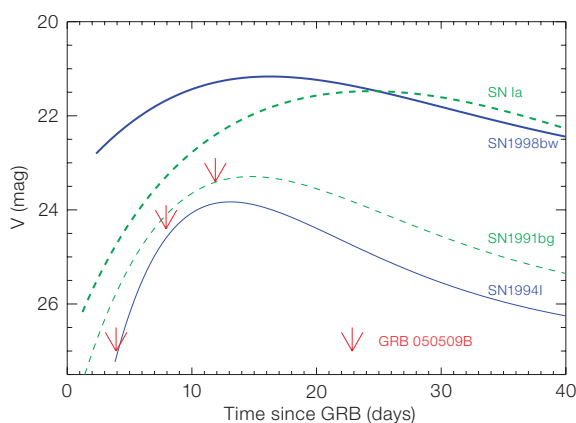


Figure 3: No supernova associated with short GRB 050509B. The upper limits (red arrows) on variable sources inside the GRB 050509B error circle (see Figure 2) compared to the light curves of different SNe redshifted to $z = 0.225$ (blue: Type Ia; green: Type Ia; thick curves: bright supernovae; thin curves: faint supernovae). The stringent upper limits obtained with the VLT rule out the presence of a super-nova accompanying the first localised short burst, GRB 050509B.

solution of this puzzle is that after the merger, a neutron star/magnetar rather than a black hole is formed.

Near and far

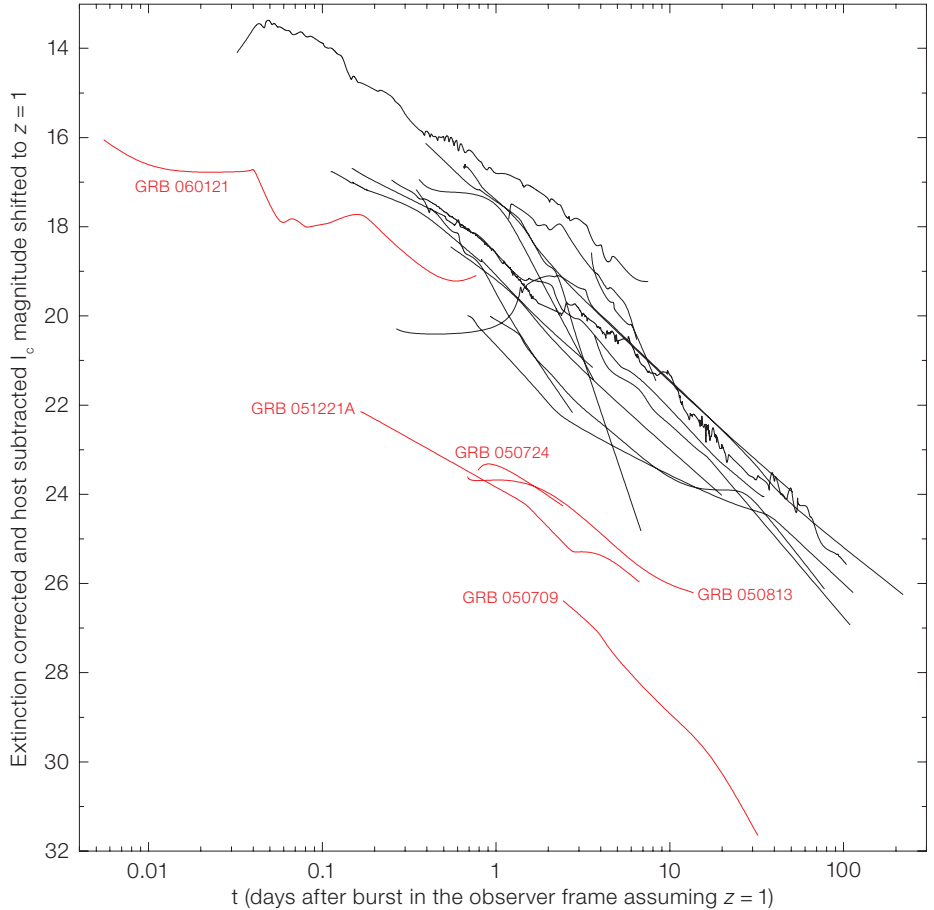
In parallel with these discoveries, other insights into the nature of short bursts were also emerging. At the end of 2004 the Galactic soft gamma repeater SGR 1806–20 underwent a giant flare, re-releasing over 10^{46} ergs of energy in 0.2 s. This event could have been seen from tens of megaparsecs away, and indicated that some short bursts may arise from similar flares (Hurley et al. 2005; Palmer et al. 2005). This being the case it might be expected that GRBs would correlate with large-scale structure in the local universe, and indeed our comparison of the locations of bursts seen by BATSE with the locations of local galaxies revealed that between 10–25 % of short bursts might originate from within 100 Mpc (Tanvir et al. 2005). This may be supported by the presence of the bright nearby galaxy IC 328 in the error box of the short GRB 050906 and the short GRB 051103 localised to the M81/M82 galaxy group (Figure 2).

But these nearby short GRBs only represent one extreme of the population. At the other end, the short GRB 060121 (Figures 2 and 4) was found to originate in a very faint and red host galaxy, which may have $z > 4.5$, and therefore a much larger energy budget than previously known short bursts. Similarly, GRB 060313 (Figure 2) also has a faint host, possibly indicative of a higher redshift.

Where next?

Recent progress in understanding short bursts has been both dramatic and yet the picture is far from complete. It would seem hard to explain the full range of behaviour of short bursts with a single progenitor model, and it is likely that more than one progenitor type (e.g. SGR flares, and compact binary mergers) is required. Even allowing for this, the luminosity function and distance range of the two (or more) systems must be extremely broad.

Figure 4: Illustrative light curves of long GRBs (black) and short GRBs (red). The light curves have been interpolated, corrected for extinction and shifted to a common redshift of $z = 1$. The afterglows of short GRBs are much fainter in the mean than those of long GRBs. The curve for GRB 050813 represents an upper limit. The redshift of GRB 060121 has been assumed to be $z = 4.6$.



Fortunately, ESO telescopes are likely to drive further progress. We expect that the continued build-up of light curves (through Rapid Response Mode and Target of Opportunity observations) and host galaxies (through our dedicated Large Programme to study galaxies of long and short GRBs) will allow stronger statements to be made about the progenitors of short GRBs. Detailed modelling of light curves and broadband spectra will allow us to constrain the emission mechanism and physical properties such as the density of the surrounding medium. A statistical study of the galaxies hosting short GRBs should also give clues about formation time scales and environments.

Absorption line spectroscopy, as is routinely obtained on long GRBs for measuring redshifts and probing the environment of the progenitors, has so far not been successful on short GRBs. For GRB 060313 we obtained a spectrum which unfortunately was too noisy to reveal any significant absorption lines.

Another interesting line of research may be to obtain polarimetric observations. In contrast to long GRB afterglows, the ordered, strong magnetic field of a neutron star may imply that NS-NS mergers create highly polarised afterglows.

Whatever else we learn, our experience of attempting to resolve the puzzle of GRBs tells us to expect many further surprises.

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