An insight into the progenitors of gamma ray bursts from the optical afterglow observations

Kuntal Misra and Ram Sagar*

We have probed more than 50 gamma ray bursts (GRBs) fields since January 1999 and obtained successful optical afterglow observations for 27 of them. Upper limits were reported for the rest of the cases. Optical observations of GRB afterglows provide information about GRB distances, nature of emission, surroundings, their environments and progenitors. The presence of supernova signature in long-duration GRB afterglows has further strengthened the fact that the collapse of a massive star gives rise to a long-duration GRBs. However, the observed properties of short-duration GRBs are in agreement with the NS–NS or NS–BH coalescence model.

Keywords: Coalescence model, gamma ray burst, optical afterglow, progenitors.

GAMMA ray bursts (GRBs), with their brilliance, have mystified and fascinated astronomers since their discovery. Like other spectacular discoveries such as the cosmic microwave background, GRBs were discovered by accident. The American Vela satellites, which were meant to monitor the 'outer space treaty', detected in July 1967 serendipitously an intense flash of gamma rays of unknown origin. It was in 1973 that the first detected GRB was announced to the scientific community[1]. This caused furious research activity amongst scientists and different theoretical models were proposed.

GRBs are brief intense flashes of radiation in the γ-ray band (10 keV–10 GeV), lasting for a few milliseconds to a few hundred seconds. GRBs shine hundreds of times brighter than a typical supernova and about a million trillion times as bright as the sun, making them briefly the brightest source of cosmic gamma-ray photons in the observable universe. In fact, they constitute the brightest bursts of electromagnetic radiation in the universe. They occur at an average rate of one per day throughout the universe and their radiation completely floods the almost dark γ-ray sky. One such flash contains about 10^{50}–10^{51} ergs of energy.

After the US Vela satellites, many other missions localized a large number of GRBs, but there was no direct clue to their origin until the launch of Burst And Transient Source Experiment (BATSE) on-board the Compton Gamma Ray Observatory (CGRO) in 1991. BATSE detected an inhomogeneous, but highly isotropic distribution of burst sources, which strongly suggested their cosmological origin[2]. The bursts have complicated and irregular time profiles, which vary drastically from one burst to another. GRB light curves exhibit a tremendous variety ranging from single, featureless spikes to a completely erratic sequence of pulses. Several time profiles of long GRBs are shown in Figure 1. The typical variation takes place on a timescale of less than a millisecond, suggesting a compact system as a progenitor of the GRB. The convention of naming GRBs is yymmdd, e.g. the GRB 980329 occurred on 29 March 1998.

The duration distribution of GRBs is bi-modal, clearly dividing the burst into two categories. According to the BATSE classification scheme, the bursts are termed as long and short based on the T_{90} duration[3]. Here T_{90} is the time needed to accumulate 90% of the counts in the 50–300 keV band of BATSE. For long bursts $T_{90} > 2$ s and for short bursts $T_{90} < 2$ s. Apart from the duration, they also differ in their spectra. Bursts of the short category exhibit harder spectra than bursts of the long category. The hardness is measured using the ratio of photon counts in a high and a low energy channel. Figure 2 shows the bi-modal distribution of bursts[4]. As the properties of the two classes of GRBs differ, it may indicate that the progenitors giving rise to these two classes of events are different.

A GRB exhibits two distinct phases of evolution: the burst and the afterglow. The burst lasts only for a few seconds and appears in the γ-ray band alone, whereas the afterglow is a multi-wavelength phenomenon ranging from X-ray, optical to radio bands, and lasting for about a few days to a few years. The ultra-relativistic energy flow during the burst emitted in the form of γ-rays is converted to radiation. This conversion of energy occurs due to some internal process, such as internal shocks and collisions within the flow[5,6]. But not all the energy of the relativistic shell can be converted to radiation by internal shocks. The remaining kinetic energy dissipates via external

Kuntal Misra is in the Inter University Centre for Astronomy and Astrophysics, Post Bag 4, Ganeshkhind, Pune 411 007, India and Ram Sagar is in the Aryabhatta Research Institute of Observational Sciences, Manora Peak, Nainital 263 129, India.
*For correspondence. (e-mail: kuntal@iucaa.ernet.in)

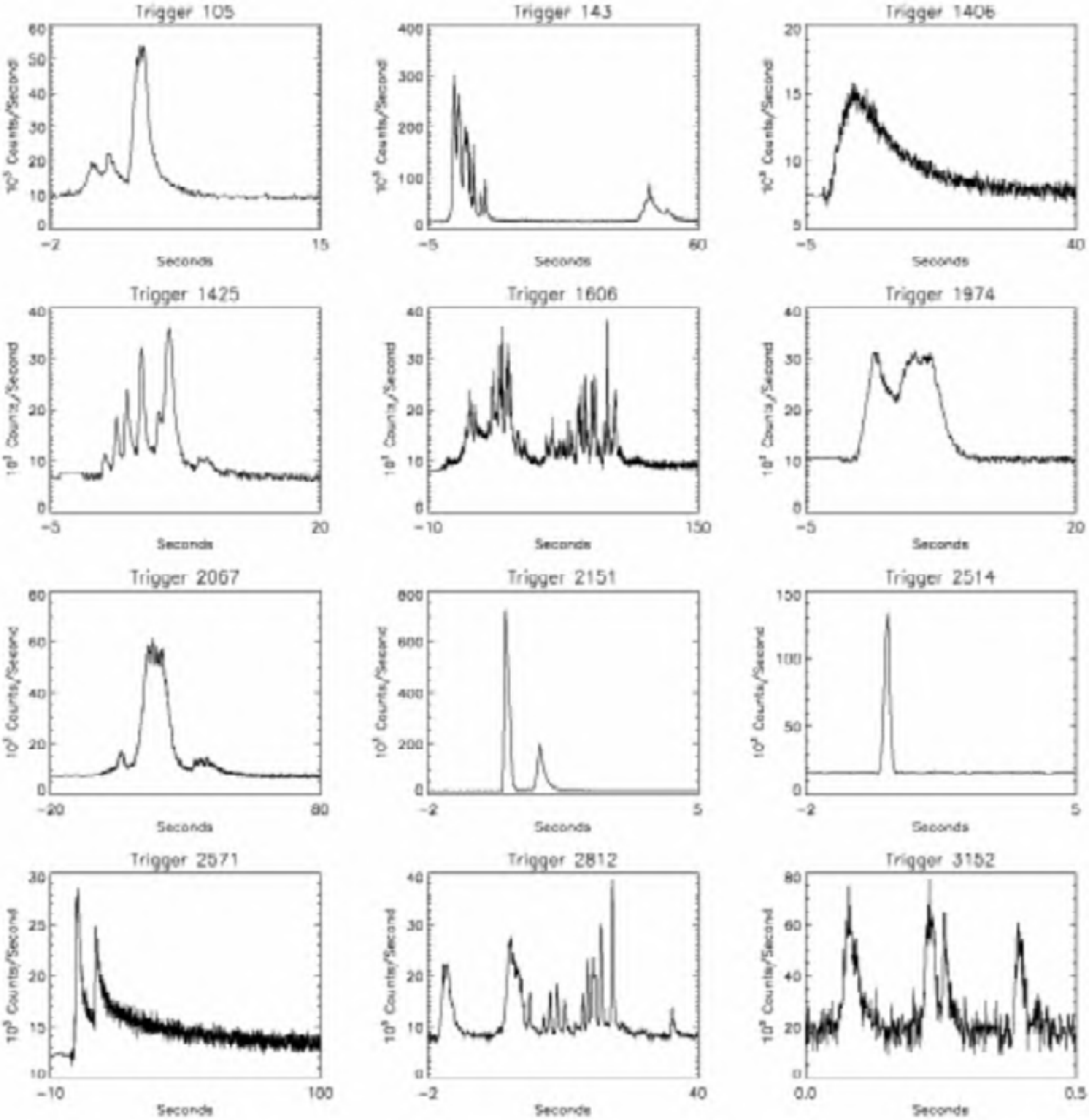

Figure 1. A gallery of BATSE GRB light curves. The light curves display a large diversity with some being spiky and chaotic in nature, some showing a FRED-like profile and some being smooth. Credit: NASA–BATSE Team.

shocks that produce an 'afterglow' seen in different wavelengths. Afterglows, being long-lasting phenomena, are an important tool to study these multi-wavelength, energetic cosmic explosions. Until the discovery of afterglows, little was known about the origin and nature of GRBs. The afterglow flux evolves as a power law in time represented as $f_\nu \propto \nu^\beta t^\alpha$, where t is the time since burst, α is the temporal flux decay index, β is the spectral index, and ν the frequency of observation.

It is now known that the progenitors giving rise to the long- and short-duration bursts are different. The collapse of a massive star is responsible for a long-duration GRB, whereas coalescing of compact objects such as NS–NS or NS–BH is believed to be the progenitors of short-duration GRBs. Figure 3 displays the progenitor scenario for long- and short-duration GRBs. Further details on the progenitors of long and short bursts will be discussed later in this article.

Until BeppoSAX, the precise localization of these events was not possible. Timely and accurate (within a few arcminutes) localization of the GRBs by BeppoSAX provided the first detection of multi-wavelength afterglow sources in 1997 (refs 7, 8). With this it was confirmed that GRBs are of cosmological origin and result from the death of massive stars. While all GRBs of the long–soft variety may be accompanied by supernovae, not all supernovae, or even all sub-types of core collapse supernovae, make GRBs. The GRBs may only come from the most rapidly rotating and most massive stars, possibly favoured in regions of low metallicity. Ordinary supernovae, on the other hand, which comprise about 99% of massive star deaths, may come from stars where rotation plays a smaller role or none at all. Indeed, the SN–GRB connection is forcing a re-evaluation of the role of rotation in the death of massive stars. The continued observations of both GRBs and the supernovae that accompany them should yield additional diagnostics that will help us gain deeper insight into both phenomena, and specially the 'central engine' that drives all these explosions.

Until the launch of Swift (http://swift.gsfc.nasa.gov/docs/swift/swiftsc.html) satellite in November 2004, afterglows were known only for long-duration GRBs. But there was a major breakthrough after Swift, when afterglows of short-duration GRBs were discovered and followed in the X-ray, optical and radio wavelengths. Now, around 325 X-ray, 220 optical and 55 radio afterglows of both long and short GRBs, have been detected and observed using satellites and ground-based observatories (these are the number of afterglows detected till 31 December 2007, obtained from http://www.mpe.mpg.de/jcg/grb.html). The current and upcoming missions (HETE-2, INTEGRAL, SWIFT and Fermi (formerly known as GLAST)) will collect and build up on the BeppoSAX legacy by increasing the number of accurate and timely localizations of GRBs and improving the statistics of afterglow-detected sources.

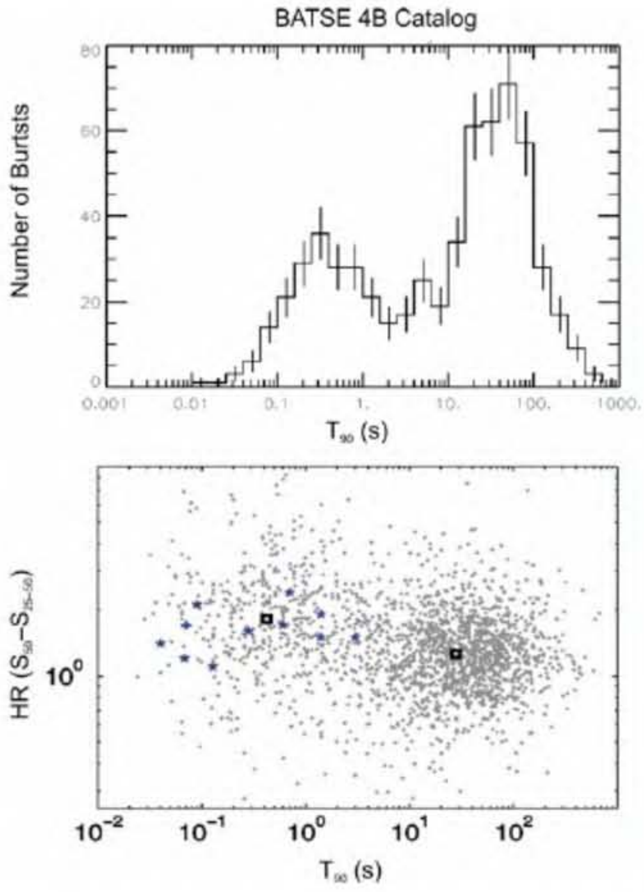

Figure 2. (Upper panel) Duration of BATSE GRBs showing two groups. Credit: NASA–BATSE Team. (Lower panel) Hardness ratio of GRBs with available data from the BATSE catalogue (dots). Short, hard bursts detected by Swift (stars) and HETE-2 (plus) are marked in the bottom figure[4].

Geographical location of India for GRB afterglow observations

Early and deep observations of GRB afterglows and supernovae provide one of the most interesting and scientific results in astronomy. Because of their transient nature and relatively fast flux decay, quick follow-up observations of such objects are required. Robotic telescopes have opened a new window to study the early afterglow emission within few seconds of the burst. The launch of Swift has also made the GRB study prolific over the last three years

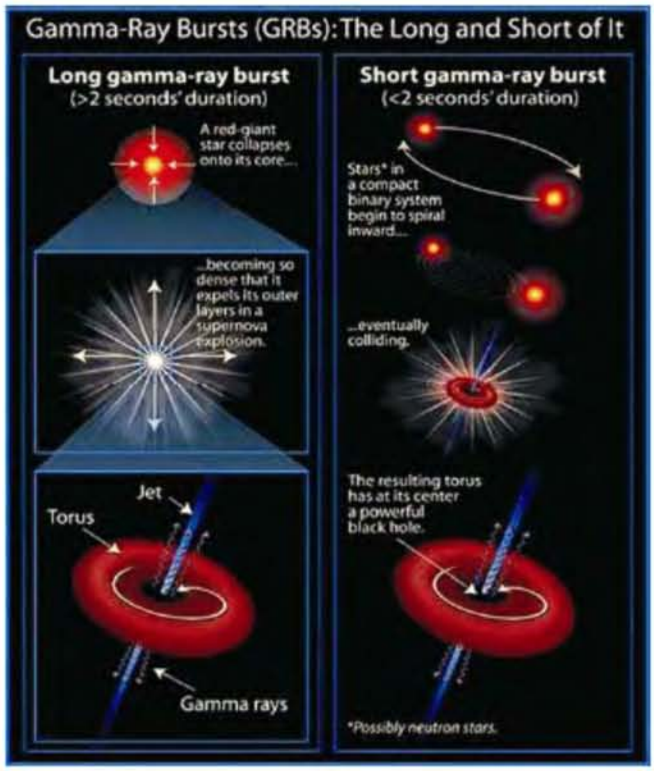

Figure 3. Progenitors of long- and short-duration GRBs. Credit: hubblesite.org.

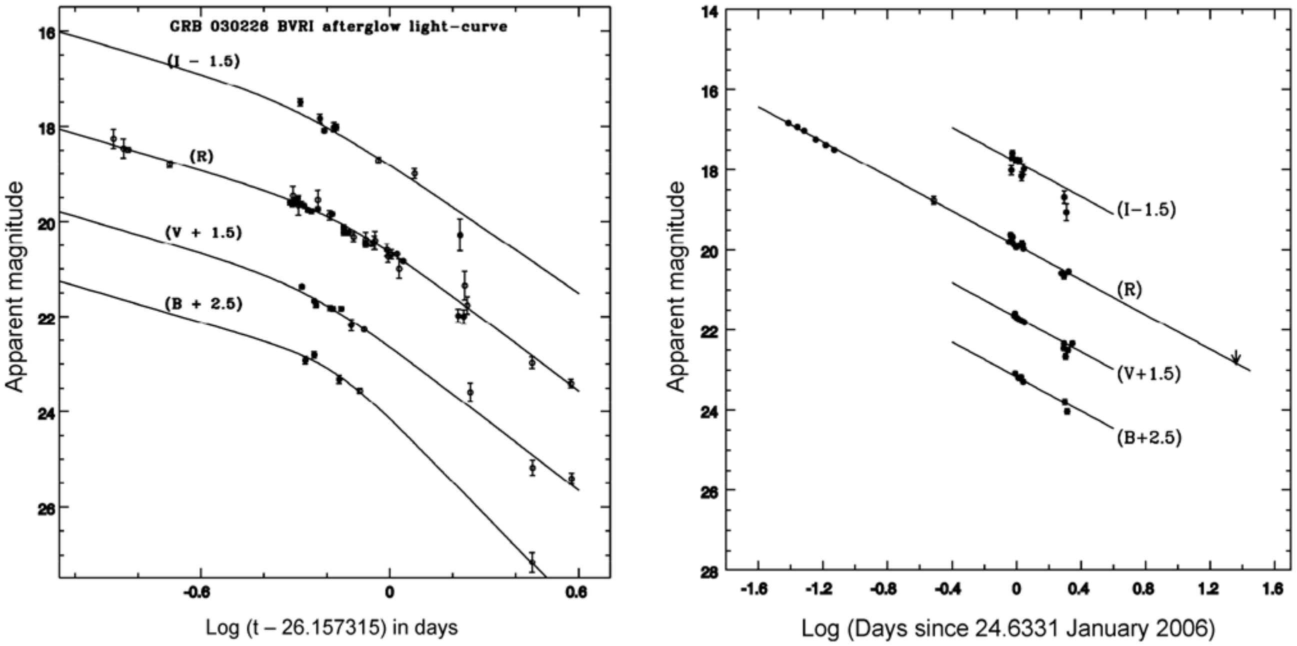

Figure 4. (Left) GRB 030226: Case of an achromatic jet break (from Pandey *et al.*[58]). (Right) GRB 060124: No break in the optical (from Misra *et al.*[19]). The light curves in different bands are offset by a number as indicated to avoid overlap of the data. The solid line indicates the least square best-fitted value of the temporal index. For GRB 060124, the upper limit derived using the observations at a later epoch is also shown.

and has allowed the study of early GRB afterglows in a time domain (less than a few minutes) previously unexplored. This brings in new surprises and challenges to understand the nature of the most violent and mysterious explosions in the universe.

India lies in the middle of the 180° wide longitude belt between Canary Islands (~20°W) and Eastern Australia (~160°E), thus filling in important temporal gaps in the observations of transient events[9,10].

We therefore carried out optical observations of GRB afterglows at the Aryabhatta Research Institute of Observational Sciences (ARIES), Nainital during January 1999–December 2007 under a long-term research programme in collaboration with astronomers from all over the globe. The primary optical dataset of GRB afterglows was acquired from the 1.04 m Sampurnanand Telescope (ST) at ARIES, and the 2.01 m Himalayan Chandra Telescope (HCT) at Indian Astronomical Observatory (IAO), Hanle. The optical data in combination with data at other wavelengths (radio and X-ray) help us to understand the multi-wavelength characteristics of these objects.

Optical observations and light curves

Since January 1999 to December 2007, we have probed more than 50 GRB fields and obtained successful optical observations of 27 GRB afterglows. Upper limits were reported for the rest of the cases. Broadband optical photometric observations of these GRB afterglows have been successfully carried out with the ST and HCT. Observations were mostly taken in *R* photometric passband as the quantum efficiency of CCD peaks in the passband. Whenever possible, observations were also taken in *U*, *B*, *V* and *I* passbands. In some of the cases optical afterglow observations were also acquired using HCT. The optical afterglows observed during 1999–2007 by our group are listed in Table 1.

Several image-processing softwares such as IRAF (Image Reduction and Analysis Facility distributed by the National Optical Astronomy Observatories), MIDAS (Munich Image and Data Analysis System, designed and developed by the European Southern Observatory (ESO) in Munich, Germany) and DAOPHOT (Dominion Astrophysical Observatory Photometry) have been developed by different observatories to carry out different tasks. These softwares were used for data reduction[11–13].

Our optical data are combined with other optical data available in the literature and also published data in other wavelengths, so as to get an insight into the multiwavelength characteristics of the afterglow evolution. Optical afterglow light curve of a GRB provides a wealth of information about the break in the light curve, variability in the light curve, late time supernova bumps and late time flattening due to the underlying host galaxy.

We show here representative light curves of a set of GRB afterglows observed by our group. The optical emission from all GRB afterglows is overall fading. However, the pattern of their flux decays differs. Figure 4 shows the optical flux decay of GRB 030226 and GRB 060124 afterglow in the *B*, *V*, *R* and *I* passbands. GRB 030226 shows the presence of an achromatic break, which is attributed

Table 1. Basic properties of the 27 GRB afterglows observed by our group. Representation of the different columns is as follows: Column 1, Burst name; Column 2, Name of the mission which localized the burst; Columns 3 and 4, Coordinates of the burst in J2000; Column 5, Burst trigger time expressed in days (T_0); Column 6, Duration of the burst in seconds (T_{90}); Column 7, γ-fluence in erg cm^{-2} within the specified energy channel; Columns 8 and 9, Detected Radio and X-ray transient; Column 10, Redshift; Column 11, Reference of our group

Optical afterglow	Localization mission	α_{2000} (in h : m : s)	δ_{2000} (in deg :′:″)	Burst trigger time (T_0) UT (days)	Duration T_{90}(s)	γ-fluence erg cm^{-2}/ range (keV)	Radio transient	X-ray transient	Red-shift (z)	Reference
GRB 990123	BeppoSAX	15:25:30.34	+44:45:59.10	Jan 23.4078	100	3.5×10^{-4}/40–700	Yes	Yes	1.61	9, 14, 48, 49
GRB 991208	Uly/Konus	16:33:53.52	+46:27:21.00	Dec 08.1922	60	1.0×10^{-4}/25–100	Yes	No	0.707	50, 51
GRB 991216	BAT/PCA	05:09:31.30	+11:17:07.26	Dec 16.6715	50	2.0×10^{-4}/20–100	Yes	Yes	1.02	50
GRB 000301C	AMS/Uly	16:20:18.60	+29:26:36.00	Mar 01.4108	10		Yes	No	2.04	10, 52
GRB 000926	Uly/Konus	17:04:09.00	+51:47:10.00	Sep 26.9927	25	2.2×10^{-5}/25–100	Yes	Yes	2.066	53
GRB 010222	BeppoSAX	14:52:12.55	+43:01:06.20	Feb 22.3079			Yes	Yes	1.478	32, 54
GRB 011211	BeppoSAX	11:15:17.98	–21:56:56.20	Dec 11.7981	270	5.0×10^{-6}/40–700	No	Yes	2.142	55
GRB 020405	Uly/MO/SAX	13:58:03.12	–31:22:21.90	Apr 05.0287	40	3.0×10^{-5}/25–100	Yes	No	0.695	56
GRB 021004	HETE-2	00:26:54.68	+18:55:41.60	Oct 04.5043	100	1.8×10^{-6}/50–300	Yes	Yes	2.335	20
GRB 021211	HETE-2	08:08:59.88	+06:43:37.88	Dec 11.4712	5.7	1.0×10^{-6}/8–40	No	No	1.01	57
GRB 030226	HETE-2	11:33:04.93	+25:53:55.30	Feb 26.1573	100	5.7×10^{-6}/30–400	No	Yes	1.98	58
GRB 030227	INTEGRAL	04:57:33.00	+20:29:09.00	Feb 27.3625	20		No	Yes		59
GRB 030328	HETE-2	12:10:48.40	-09:20:51.30	Mar 28.4728	100	3.0×10^{-5}/30–400	No	Yes	1.52	12
GRB 030329	HETE-2	10:44:49.96	+21:31:17.44	Mar 29.4841	35	1.6×10^{-4}/15–5000	Yes	Yes	0.168	60
GRB 041006	HETE-2	00:54:50.23	+01:14:04.90	Oct 06.5126		7×10^{-6}/30–400	Yes	Yes	0.716	30
GRB 041219A	INTEGRAL	00:24:27.68	+62:50:33.50	Dec 19.0715	520	1×10^{-4}/15–200	Yes	Yes		61
GRB 050319A	Swift	10:16:50.76	+43:32:59.90	Mar 19.3967	15	8×10^{-7}/15–350	No	Yes	3.240	36
GRB 050401	Swift	16:31:28.82	+02:11:14.83	Apr 01.5973	38	1.4×10^{-5}/15–350	Yes	Yes	2.90	62
GRB 050408	HETE-2	12:02:17.31	+10:51:09.40	Apr 08.6835	15	1.9×10^{-6}/30–400	No	Yes	1.236	63
GRB 050525A	Swift	18:32:32.57	+26:20:22.50	May 25.0020	10	1.2×10^{-5}/20–200	Yes	Yes	0.606	
GRB 051109A	Swift	22:01:15.31	+40:49:23.31	Nov 09.0502	25	2.1×10^{-6}/15–150	Yes	Yes	2.346	64
GRB 060124	Swift/ HETE-2/ Konus-Wind	05:08:25.50	+69:44:26.00	Jan 24.6631	710	7×10^{-6}/15–150	No	Yes	2.297	19
GRB 060210	Swift	03:50:57.37	+27:01:34.40	Feb 10.2075	5	7.7×10^{-6}/15–150	No	Yes	3.91	65
XRF 060218	Swift	03:21:39.68	+16:52:01.82	Feb 18.1489		6.8×10^{-6}/15–150	Yes	Yes	0.0331	66
GRB 061126	Swift	05:46:24.43	+64:12:38.78	Nov 26.3666	40	7.2×10^{-6}/15–150	No	Yes		67
GRB 070125	IPN	07:51:17.77	+31:09:04.11	Jan 25.3060	70	1.74×10^{-4}/20–10000	Yes	Yes	1.547	68
GRB 071010A	Swift	19:12:14.62	-32:24:07.16	Oct 10.1536	30	2.00×10^{-6}/15–150	No	Yes	0.98	69

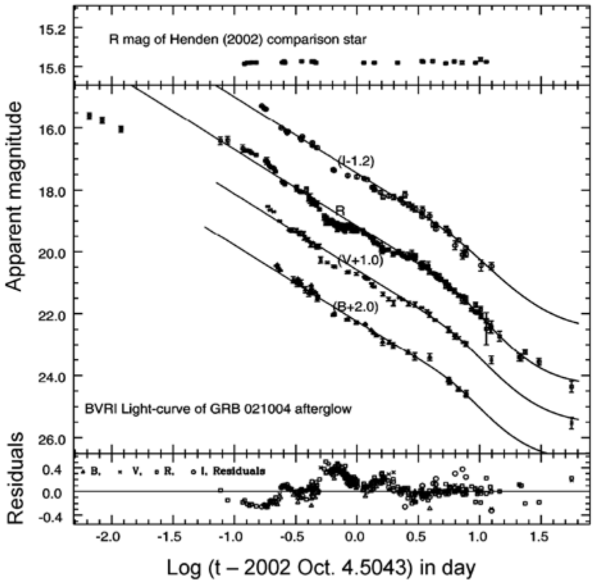

Figure 5. GRB 021004: Case of a superimposed variability (from Pandey *et al.*[20]). Marked vertical offsets have been applied to avoid overlapping of datapoints of different passbands. In GRB 021004 light curve, for comparison, *R* magnitude of comparison star[70] is also plotted in the upper panel. The *BVRI* band residuals in the sense observed minus power law fitted magnitudes are displayed in the lower panel.

to the lateral expansion of the ejected material, that was initially confined to a small cone. It is interesting to note that the optical light curves of GRB 060124 are well characterized by a single power-law without any steepening observed in the light curves. However, the X-ray light curve of GRB 060124 shows a mild steepening which is attributed to the presence of an injection break at high energies. In Figure 5 we observe that the afterglow of GRB 021004 displays superimposed variability, which is evident from the optical light curves. Figure 6 shows the light curve of GRB 030329 which is well-modelled using a double-jet model. This also showed the emergence of an associated supernova, SN 2003dh, seen as a rebrightening in the afterglow light curve. GRB 041006 (Figure 7) is modelled in terms of a hard electron energy index and showed signatures of an associated supernova evident from the afterglow light curves. Figure 8 displays the multi-wavelength light curves of GRB 050319, in which a clear signature of a wind-to-constant density medium transition is seen.

Discussion and conclusions

In about a decade of optical observations of GRB afterglows carried out in India, successful optical observations have been obtained for 27 long-duration GRB afterglows till 2007 by our group. Our observations have filled in many temporal gaps in the afterglow light curves due to the geographical location and in a few cases, we have even reported the earliest optical observations (e.g. GRB 000301C, GRB 020405 and GRB 060124). We discuss the important observational results of long-duration GRB afterglows and towards the end we highlight the revolution in the study of short-duration GRBs in the Swift era.

Long-soft burst population

Some of the important features seen in the long-duration GRB afterglow light curves are briefly outlined here.

1. Achromatic breaks in afterglow light curves – Jet break: The jet model accounts fairly well for most of the well-observed pre-Swift GRB afterglow light curve breaks, e.g. GRB 990123 (refs 14–16), GRB 990510 (ref. 17), GRB 99121617 (ref. 18), and GRB 000301C (ref. 10). GRB 051109A, in the Swift era is one of the most well-observed bursts, whose X-ray and optical afterglow light curves show the presence of a break. A plausible explanation of the achromatic steepening observed in the X-ray and optical light curve at ~0.6 days is due to a jet-break with a flat-spectrum electron distribution ($p < 2$). Presence of double jets has been proposed in a few cases (e.g. GRB 030329 and GRB 050401).

2. Frequency-dependent chromatic breaks in afterglow light curves: In the Swift era, signature of achromatic jet-break is missing in many of the GRB afterglow light curves. The growing trend in the Swift era is that some breaks which we see in the broadband afterglow light curves may not be achromatic, i.e. there could be a break in the X-ray light curve which is not apparent in the optical light curves. These breaks are attributed to an entirely different cause. GRB 060124 is one such case in which we do not see achromatic breaks in X-rays and optical[19]. The steepening observed in the X-ray light curve might be due to the steepening of the energy spectrum of the injected electrons beyond a certain high energy limit.

3. Fluctuations in the optical light curves: The optical and X-ray light curves of GRB 060124 show a remarkable flickering at late times[19]. Achromatic flickering in optical bands has been seen in a few other GRB afterglows such as GRB 000301C (ref. 10), GRB 021004 (refs 20–22), GRB 021211 (ref. 23), GRB 050319 (ref. 24) and GRB 051028 (ref. 25). While some of the reported flickering could arise from variable observing conditions[24], most of the observed flickering appears to be real. Short timescale variability could, in many cases, be attributed to density variations in the external medium[26]. However, in some cases late injection of energy from the central engine provides a better explanation[23,27]. Gravitational microlensing has been proposed as the cause of achromatic variability in GRB 000301C[28], but this interpretation remains ambiguous. In the case of GRB 060124, the flickering is observed in all the optical bands as well as in X-rays. Timescales of this variability are short compared to the elapsed time since burst, and there is

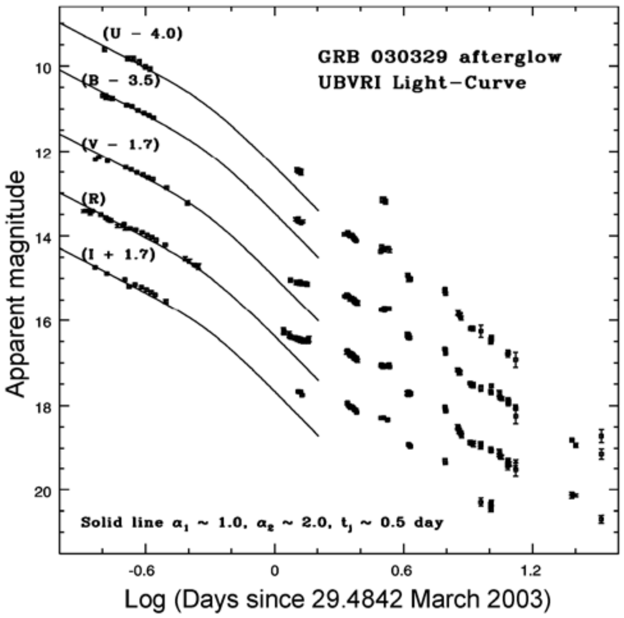

Figure 6. GRB 030329: Case of a double jet model and supernova emergence (from Resmi *et al.*[61]). Marked vertical offsets have been applied to avoid overlapping of datapoints of different passbands. Using the data for <1.5 days broken power law is overplotted using $\alpha_1 \sim 1.0$ $\alpha_2 \sim 2.0$ and $t_j = 0.5$ days. Data > 1.5 days may not have been fitted by the same power law, and are flattened due to the presence of a second wider jet[61,71].

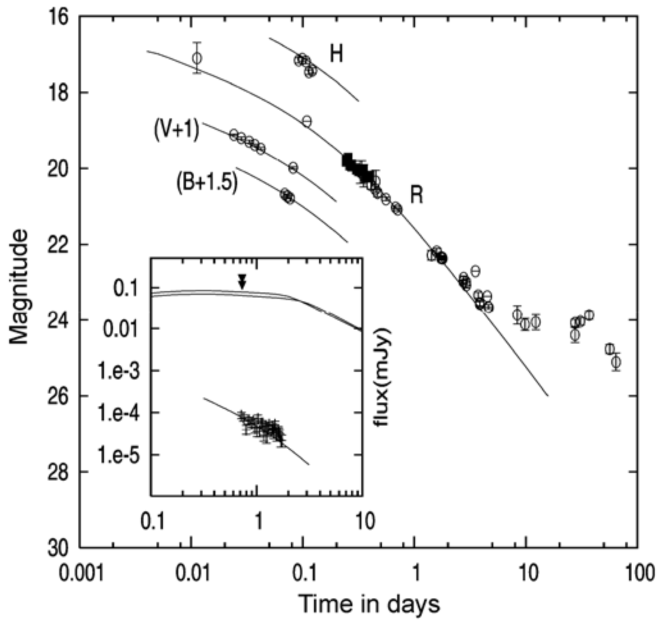

Figure 7. GRB 041006: Case of a hard electron energy spectrum and supernova bump at late times (from Misra *et al.*[30]). GRB 041006 afterglow observations in different bands along with the model. Filled circles represent our data and open circles represent data from the literature. Light curve in different bands is shifted as indicated. (Inset) X-ray observations and radio upper limits along with the model.

no evidence seen of persistent increase in the light curve level following the flicker episodes. This is akin to the variability expected due to inhomogeneities in the density of the circumburst material.

4. Hard electron energy index in GRB afterglows: The overall behaviour of the afterglow of GRB 051109A is well modelled by having the cooling break (ν_c) below optical and X-rays for the entire range of observations and attributing the break at ~0.5 days to the sideways expansion of the jet and $p = 1.4$, which is well below 2. Such an evolution is also seen in the afterglow light curve of GRB 010222 having a pre- and post-break decay index of ~0.7 and ~1.4 respectively, with a break time of ~0.7 days and $p \sim 1.4$ (ref. 21). Afterglows exhibiting $p < 2$ are not rare[29,30,31]. For such a flat spectral distribution, the upper cut-off γ_u of the electron energy distribution becomes important in the estimation of the total energy content. But the decay laws corresponding to $p > 2$ would apply also in this case if $\gamma_u \propto \gamma$, the bulk Lorentz factor of the shock[32].

5. Hypernova signatures in the late rebrightening of GRB afterglow: There is observational evidence of associated supernova features in a few GRB afterglows. In addition, a few afterglows show rebrightening or flattening in their light curves within a few days to weeks after the GRB event, which is commonly interpreted as the emergence of a supernova component. An effective way to probe the nature of such bumps is through spectroscopic observations. For example, spectroscopic observations in confirmed cases of GRB–SN associations have established such supernovae to be of a special class of SN Ic called 'hypernovae'.

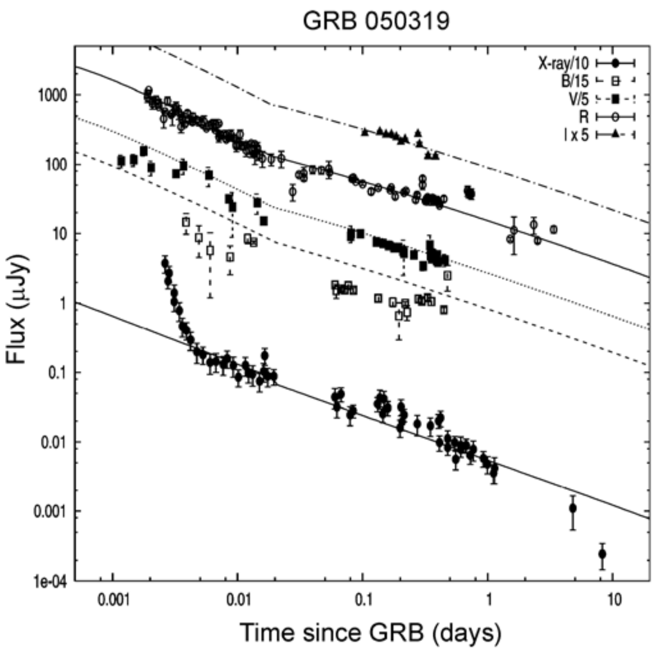

Figure 8. GRB 050319: Case of wind-to-ISM transition (from Kamble *et al.*[36]). The solid line represents a model in which the expanding fireball encounters the transition in density profile from the wind to constant density medium at 0.02 days.

The association of GRBs with massive stars has been established with the detection of a total of four GRBs (GRB 980425/SN 1998bw, GRB 031203/SN 2003lw, GRB 030329/SN 2003dh and XRF 060218/SN 2006aj), with direct photometric and spectroscopic connections to supernova events. The optical light curves of GRB 020405, GRB 030329, GRB 041006, GRB 050525A, XRF 060218 and a few others clearly indicate the presence of an associated supernova seen as late-time rebrightening.

A number of scenarios were proposed as progenitors of GRBs. Amongst them the collapsar model is now accepted to be the most favoured one responsible for the origin of long-duration GRBs. Quasars or the nuclei of galaxies as the progenitors of GRBs are ruled on the basis that some GRBs are found offset from the centre of their host galaxy. We will focus here on the collapsar scenario for long-duration GRBs. When a massive star collapses, it is expected to have its environment modified by stellar wind. The effect of such a circumstellar wind medium is expected to be seen in the evolution of a GRB afterglow, but so far this has not been conclusively found. The evolution of GRB afterglow light curves is significantly different in wind-like and constant-density profiles[33,34]. Attempts to look for the signatures of such a wind-modified circumburst density profile in the light curves of GRB afterglows have not been conclusive so far. The early X-ray afterglow light curve of GRB 050904 (ref. 35) suggests a wind-like density profile of the circumburst medium, while the late optical afterglow was consistent with evolution in a constant-density medium. The transition between these two types of density profiles would have taken place somewhere in between, which was not directly observed in the light curve. A signature of the transition from wind to constant-density medium of the circumburst medium is visible in the afterglow of GRB 050319 (ref. 36). The break seen in the optical light curve at 0.02 days could be explained as being due to the transition from wind to constant-density medium of the circumburst medium[36], which could be the first ever detection of such a transition at any given frequency band. Detection of such a transition could also serve as a confirmation of the massive star collapse scenario for GRB progenitors, independent of supernova signatures.

Evidence of X-ray emission line features has been marginally reported in a few cases, e.g. GRB 970508 (ref. 37), GRB 970828 (ref. 38), GRB 991216 (ref. 39), GRB 000214 (ref. 40), GRB 011211 (ref. 41). Chandra observations have revealed progenitor of GRB 991216 to be a massive star system that ejected, before the burst, ~0.01 $M_\odot$ of iron at a velocity ~0.1c (ref. 39). Chandra observations of GRB 000926 imply that the GRB exploded in a reasonably dense ($n \sim 30$ cm^{-3}) medium, consistent with a diffuse interstellar cloud environment[42].

Short hard burst population

The detection of short-duration GRBs dates back to the Vela satellites[43]. However, it was only in 1993 that short bursts ($T_{90} < 2$ s) were recognized as a separate class of objects with a harder spectrum.

A wave of significant advance took place in the field of GRBs with the launch of the Swift satellite. The accurate localization of bursts within a few seconds helped reveal the unexplored afterglow behaviour between minutes and hours, enabling the study of the transition from the prompt emission to the long-term afterglow. Swift achieved the long-awaited discovery of the afterglows of 'short' GRBs. This breakthrough occurred during May 2005, when Swift and HETE-2 succeeded in localizing several SHBs, leading to afterglow detections and to the determination of their redshifts. Following these discoveries, the study of short hard bursts (SHBs) progressed rapidly.

The progress in our understanding of SHBs since the launch of Swift has transformed the field from being speculative to a quantitative one. The observations have allowed us to determine some of the most important and basic properties of SHBs. Some of the conclusions based on the observations are:

1. SHBs occur at cosmological distances with a relatively wide spread in redshift and a median redshift of ~ 0.6.

2. The isotropic equivalent energy is typically two orders of magnitude lower than that of long GRBs, but has a wide distribution from 10^{48}–10^{52} erg.

3. The ejecta appears to be collimated, with opening angles larger than 5° for three SHBs (GRB 050709 (ref. 44), GRB 050724 (ref. 45) and GRB 051221A (ref. 46)), which is the median value for long GRBs. The beaming-corrected true energy release has a narrow distribution of ~10^{48}–10^{50} erg.

4. SHBs tend to occur in environments of lower density compared to those of long GRBs.

5. SHBs occur in both elliptical and star-forming galaxies, with many of them having a possible association with a cluster of galaxies (e.g. GRB 050509B, GRB 050813 and GRB 050911). Thus, the frequency of short GRBs in clusters of galaxies may reflect a possible association with globular clusters[47]. Out of a sample of Swift short GRBs, as many as five have been associated with early-type galaxies (e.g. GRB 050509B, GRB 050724, GRB 050813, GRB 050911 and GRB 060502B), while two are associated with late-type galaxies (e.g. GRB 050709 and GRB 051221A).

It is evident from the observational properties that SHBs occur much closer than the long-soft bursts. The short duration of SHBs suggests that they are unlikely to originate from the collapse of massive stars, for which the natural timescale is significantly longer. Instead the main focus is on coalescing compact objects such as NS–NS or NS–BH as progenitors to SHBs. These observed properties of SHBs are in broad agreement with the NS–NS or NS–BH coalescence model. Other progenitor systems such as magnetars have also been proposed. However, magnetars may contribute to a local population of SHBs. To make any quantitative statements about the progenitors, precise knowledge about the distance, energy scale and environment is required. This understanding relies on arcsec localization and the identification of afterglows. Clearly, an increased sample of events will shed additional light on the progenitor population. With a much larger sample, the clear correlation between the burst and the host galaxy properties, evolution of these properties as a function of redshift and the association of SHBs with galaxy clusters may emerge in future studies.

Future scope

GRB afterglow science has completed a decade of intensive study, yet there are many unanswered questions in the GRB afterglow evolution. With the availability of large data, many unusual features are noticed in different GRB afterglows, which remain unexplained. Some of the open issues related to such kind of energetic cosmic explosions are mentioned here:

- GRB jet configuration raises a question whether GRBs are at all collimated: the presence of structured jets in some of the afterglows.
- Non-universal value of p for GRB afterglows: evolution of microphysics parameters with time.
- Study of dark GRBs: whether they constitute an altogether different class of events.
- Environments and surroundings of short–hard bursts and ultimately the nature of their central engine.

The launch of Swift has paved the way to address some of these issues, e.g. the accurate localization of bursts within a few seconds helps to reveal the unexplored afterglow behaviour between minutes and hours, enabling the study of the transition from the prompt emission to the long-term afterglow. Simultaneous optical and NIR follow-up observations in the early times using the ground-based robotic telescopes will shed further light on the mechanism responsible for early emission in GRBs. A large fraction of the GRB afterglow optical observations carried out so far has used the 1 m class and moderate-size optical telescopes. The availability of moderate-size optical telescopes, located at good photometric sites, equipped with modern-day CCD detectors and most importantly, the geographical location of India will play a significant role in the follow-up studies of GRB afterglows. The upcoming 1.3 m telescope of ARIES in Devsthal will further strengthen the prospects to study the 'transients of energetic cosmic explosions'.

In addition to the ground-based facilities, HST will continue to play an important role in identifying the underlying host galaxies and the signatures of associated supernovae. High-resolution spectroscopy of host galaxies and the redshift determination will be better served by the availability of large, ground-based telescopes of 4–10-m class. The upcoming extremely large telescopes (ELTs) in the world will be excellent to carry out high spatial resolution host galaxy studies. ELTs will push this kind of study to higher redshift-detected GRBs. The issue of generation of magnetic field in GRBs may be supplemented with the help of polarimetric studies of GRB afterglows using bigger optical telescopes.

1. Klebesadel, R. W., Strong, I. B. and Olson, R. A., Observations of gamma-ray bursts of cosmic origin. *ApJ*, 1973, **182**, L85.
2. Fishman, G. J. and Meegan, C. A., Gamma-ray bursts. *ARAA*, 1995, **33**, 415–458.
3. Kouveliotou, C. *et al.*, Identification of two classes of gamma-ray bursts. *ApJ*, 1993, **413**, L101–L104.
4. Nakar, E., Short-hard gamma-ray bursts. *PhR*, 2007, **442**, 166–236.
5. Narayan, R. *et al.*, Gamma-ray bursts as the death throes of massive binary stars. *ApJ*, 1992, **395**, L83–L86.
6. Rees, M. J. and Mészáros, P., Unsteady outflow models for cosmological gamma-ray bursts. *ApJ*, 1994, **430**, 93–96.
7. Costa, E. *et al.*, Discovery of an X-ray afterglow associated with the γ-ray burst of 28 February 1997. *Nature*, 1997, **387**, 783–785.
8. van Paradijs, J. *et al.*, Transient optical emission from the error box of the -ray burst of 28 February 1997. *Nature*, 1997, **386**, 686–689.
9. Sagar, R. *et al.*, Optical follow up of the GRB 990123 sources from UPSO, Naini Tal. *BASI*, 1999, **27**, 3–7.
10. Sagar, R. *et al.*, GRB 000301C with peculiar afterglow emission. *BASI*, 2000, **28**, 499–513.
11. Sagar, R., Observations of GRB afterglows from Nainital: Evidence in favour of jet model. *BASI*, 2002, **30**, 237–248.
12. Pandey, S. B., Optical studies of GRB related events, Ph D thesis, Kumaun University, 2005.
13. Misra, K., Multi-wavelength studies of energetic cosmic explosions, Ph D thesis, Kumaun University, 2008.
14. Castro-Tirado, A. J. *et al.*, Decay of the GRB 990123 optical afterglow: implications for the fireball model. *Science*, 1999, **283**, 2069–2073.
15. Kulkarni, S. R. *et al.*, The afterglow, redshift and extreme energetics of the γ-ray burst of 23 January 1999. *Nature*, 1999, **398**, 389–394.
16. Fruchter, A. S. *et al.*, Hubble space telescope and Palomar imaging of GRB 990123: Implications for the nature of gamma-ray bursts and their hosts. *ApJ*, 1999, **519**, L13–L16.
17. Harrison, F. A. *et al.*, Optical and radio observations of the afterglow from GRB 990510: Evidence for a Jet. *ApJ*, 1999, **523**, L121–L124.
18. Halpern, J. P. *et al.*, GRB 991216 joins the jet set: Discovery and monitoring of its optical afterglow. *ApJ*, 2000, **543**, 697–703.
19. Misra, K. *et al.*, Optical observations of GRB 060124 afterglow: a case for an injection break. *A&A*, 2007, **464**, 903–908.
20. Pandey, S. B. *et al.*, Optical observations of the bright long duration peculiar GRB 021004 afterglow. *BASI*, 2003, **31**, 19–36.
21. Bersier, D. *et al.*, The unusual optical afterglow of the gamma-ray burst GRB 021004: Color changes and short-timescale variability. *ApJ*, 2003, **584**, L43–L46.
22. Björnsson, G. *et al.*, Energy injection episodes in gamma-ray bursts: The light curves and polarization properties of GRB 021004. *ApJ*, 2004, **615**, L77–L80.
23. Li, W. D. *et al.*, The early light curve of the optical afterglow of GRB 021211. *ApJ*, 2003, **586**, 9–12.
24. Wozniak, P. *et al.*, RAPTOR observations of the early optical afterglow from GRB 050319. *ApJ*, 2005, **627**, L13–L16.
25. Castro-Tirado, A. J. *et al.*, GRB 051028: an intrinsically faint gamma-ray burst at high redshift? *A&A*, 2006, **459**, 763–767.
26. Wang, X. and Loeb, A., Variability of gamma-ray burst afterglows due to interstellar turbulence. *ApJ*, 2000, **535**, 788–797.
27. Zhang, B. and Mészáros, P., Gamma-ray bursts with continuous energy injection and their afterglow signature. *ApJ*, 2002, **566**, 712–722.
28. Garnavich, P. *et al.*, Resolving gamma-ray burst 000301C with a gravitational microlens. *ApJ*, 2000, **544**, L11–L15.
29. Panaitescu, A. and Kumar, P., Fundamental physical parameters of collimated gamma-ray burst afterglows. *ApJ*, 2001, **560**, L49–L53.
30. Misra, K. *et al.*, Optical observations and multiband modelling of the afterglow of GRB 041006: Evidence of a hard electron energy spectrum. *BASI*, 2005, **33**, 487–497.
31. Resmi, L., Multiband modelling and radio observations of gamma ray burst afterglows, Ph D thesis, Indian Institute of Science, 2006.
32. Bhattacharya, D., Flat spectrum gamma ray burst afterglows. *BASI*, 2001, **29**, 107–114.
33. Wijers, R. A. M. J. and Galama, T. J., Physical parameters of GRB 970508 and GRB 971214 from their afterglow synchrotron emission. *ApJ*, 1999, **523**, 177–186.
34. Chevalier, R. and Li, Z.-Y., Wind interaction models for gamma-ray burst afterglows: The case for two types of progenitors. *ApJ*, 2000, **536**, 195–212.
35. Gendre, B. *et al.*, The gamma-ray burst 050904: evidence for a termination shock? *A&A*, 2007, **462**, 565–573.
36. Kamble, A. P., Resmi, L. and Misra, K., Observations of the optical afterglow of GRB 050319: The wind-to-ISM transition in view. *ApJ*, 2007, **664**, L5–L8.
37. Piro, L. *et al.*, The X-ray afterglow of the gamma-ray burst of 8 May 1997: Spectral variability and possible evidence of an iron line. *ApJ*, 1999, **514**, L73–L77.
38. Yoshida, A. *et al.*, A Possible emission feature in an X-ray afterglow of GRB 970828 as a radiative recombination Edge. *ApJ*, 2001, **557**, 27–30.
39. Piro, L. *et al.*, Observation of X-ray lines from a gamma-ray burst (GRB991216): Evidence of moving ejecta from the progenitor. *Science*, 2000, **290**, 955–958.
40. Antonelli, L. A. *et al.*, Discovery of a redshifted iron K line in the X-ray afterglow of GRB 000214. *ApJ*, 2000, **545**, L39–L42.
41. Reeves, J. N. *et al.*, The signature of supernova ejecta in the X-ray afterglow of the γ-ray burst 011211. *Nature*, 2002, **416**, 512R–515R.
42. Harrison, F. A. *et al.*, Broadband observations of the afterglow of GRB 000926: Observing the effect of inverse Compton scattering. *ApJ*, 2001, **559**, 123–130.
43. Strong, I. B., Klebesdal, R. W. and Olson, R. A., A preliminary catalog of transient cosmic gamma-ray sources observed by the VELA satellites. *ApJ*, 1974, **188**, 1–3.
44. Fox, D. B. *et al.*, The afterglow of GRB 050709 and the nature of the short-hard-ray bursts. *Nature*, 2005, **437**, 845–850.
45. Berger, E. *et al.*, The afterglow and elliptical host galaxy of the short γ-ray burst GRB 050724. *Nature*, 2005, **438**, 988–990.
46. Soderberg, A. M. *et al.*, The afterglow, energetics, and host galaxy of the short-hard gamma-ray burst 051221a. *ApJ*, 2006, **650**, 261–271.
47. Grindlay, J., Portegies, Z. S. and McMillan, S., Short gamma-ray bursts from binary neutron star mergers in globular clusters. *Nature*, 2006, **2**, 116–119.

48. Nilakshi *et al.*, BVRI CCD photometric standards in the field of GRB 990123. *BASI*, 1999, **27**, 405–410.
49. Galama, T. J. *et al.*, The effect of magnetic fields on γ-ray bursts inferred from multi-wavelength observations of the burst of 23 January 1999. *Nature*, 1999, **398**, 394–399.
50. Sagar, R. *et al.*, Temporal behaviour of emissions from gamma-ray bursts and optical/near-IR afterglows of GRB 991208 and GRB 991216. *BASI*, 2000, **28**, 15–31.
51. Castro-Tirado, A. J. *et al.*, The extraordinarily bright optical afterglow of GRB 991208 and its host galaxy. *A&A*, 2001, **370**, 398–406.
52. Masetti, N. *et al.*, Unusually rapid variability of the GRB000301C optical afterglow. *A&A*, 2000, **359**, L23–L26.
53. Sagar, R. *et al.*, GRB 000926 and its optical afterglow: Another possible evidence for non-isotropic emission. *BASI*, 2001, **29**, 1–13.
54. Sagar, R. *et al.*, Optical and radio observations of the bright GRB 010222 afterglow: evidence for rapid synchrotron cooling? *BASI*, 2001, **29**, 91–106.
55. Jakobsson, P. *et al.*, The afterglow and the host galaxy of GRB 011211, *A&A*, 2003, **408**, 941–947.
56. Masetti, N. *et al.*, Optical and near-infrared observations of the GRB020405 afterglow. *A&A*, 2003, **404**, 465–481.
57. Pandey, S. B. *et al.*, The optical afterglow of the not so dark GRB 021211. *A&A*, 2003, **408**, L21–L24.
58. Pandey, S. B. *et al.*, Early optical and millimeter observations of GRB 030226 afterglow. *A&A*, 2004, **417**, 919–924.
59. Castro-Tirado, A. J. *et al.*, GRB 030227: The first multiwavelength afterglow of an INTEGRAL GRB. *A&A*, 2003, **411**, L315–L319.
60. Resmi, L. *et al.*, Radio, millimeter and optical monitoring of GRB 030329 afterglow: constraining the double jet model. *A&A*, 2005, **440**, 477–485.
61. Pandey, S. B. and Misra, K., GRB 041219 optical observations. *GCN Circular*, 2005, 2887.
62. Kamble, A. P. *et al.*, Optical observations of GRB 050401 afterglow: A case for double jet model. *MNRAS*, 2008, astro-ph/0806.4270.
63. Misra, K. and Pandey, S. B., GRB 050408 optical observations. *GCN Circular*, 2005, 3202.
64. Misra, K. *et al.*, GRB 051109A optical observations. *GCN Circular*, 2005, 4259.
65. Misra, K., GRB 060210: Optical observations. *GCN Circular*, 2006, 4742.
66. de Ugarte Postigo, A. *et al.*, GRB 060218: optical/nIR observations at La Palma. *GCN Circular*, 2006, 4790.
67. Gomboc, A. *et al.*, Multiwavelength analysis of the intriguing GRB 061126: The reverse shock scenario and magnetization. *ApJ*, 2008, **687**, 443–455.
68. Updike, A. C. *et al.*, The rapidly flaring afterglow of the very bright and energetic GRB 070125. *ApJ*, 2008, **685**, 361–375.
69. Covino, S. *et al.*, The complex light curve of the afterglow of GRB071010A. *MNRAS*, 2008, **388**, 347–356.
70. Henden, A., GRB021004, UBVRcIc field photometry update. *GCN Circular*, 2002, 1630.
71. Berger, E. *et al.*, A common origin for cosmic explosions inferred from calorimetry of GRB030329. *Nature*, 2003, **426**, 154–157.

ACKNOWLEDGEMENTS. We thank Prof. D. Bhattacharya, Dr G. C. Anupama, Prof. T. P. Prabhu, Prof. A. J. Castro-Tirado, Dr S. B. Pandey, Dr L. Resmi, Dr. Atish P. Kamble, Dr D. K. Sahu, Dr B. C. Bhatt and other collaborators in this research programme for useful discussions and valuable help.

Received 16 September 2008; accepted 21 November 2008