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Optical observations of GRB afterglows from India

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Abstract. Optical observations of GRB afterglows provide information about GRB distances as well as their isotropic/non-isotropic nature of emission. More than 30 GRB fields have been probed by us during 1999 to 2003, out of which optical observations were obtained successfully for 14 GRB afterglows. Important results derived from their light curves, spectral energy distributions and energetics are summarized. In general, early time flux decay constant (~ 1.1) becomes steeper (~ 2.4) at later times. Most of them are having relatively flat spectral index with values ranging from 0.7 to 1.0. Observations of these afterglows support the model of non-isotropic synchrotron emission from the center of the GRBs which reduces the budget of isotropic energy emission from $\geq 10^{53}$ ergs to $< 10^{52}$ ergs, a value which is compatible with the current popular model of the origin of GRBs. Recent optical and radio observations of GRB030329 clearly indicates the association of Supernova with the GRB event.

Keywords : Gamma-ray bursts, GRB afterglows, flux decay, spectral index

1. Introduction

Gamma Ray Bursts (GRBs), discovered in the late sixties by the Vela satellites, are electromagnetically the most luminous objects for a few seconds in the Universe releasing $\sim 10^{52}$ ergs or more energy of high energy cosmic photons. An estimate of the total amount of energy released in the GRB event is essential for understanding the origin of GRBs. Accurate (within few arcminutes) localization of the GRBs by BeppoSAX provided the first detection of multi wavelength afterglow sources in 1997 (see van Paradijis et al. 2000, Sagar 2002 for a review). Since then about 100 GRB afterglow sources have been detected at X-ray, optical, near-IR or radio wavelengths. These multi wavelength

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observations have provided significant insight about the progenitors of GRBs. The current and upcoming missions (HETE-2, INTEGRAL, SWIFT) will collect and build up on the BeppoSAX legacy by increasing the number of accurate and timely localization of GRBs and improving the statistics of afterglow detected sources. In particular, the real time dissemination of GRB error boxes will open to investigation the so far unexplored early portion of the afterglow light curves.

The physics of the radio through X-ray continuum afterglow emission are now believed to be rather well understood in terms of the external synchrotron shock model (for a recent review see Meszaros 2002, Dermer 2002). However, inspite of these significant advances, the ultimate source of GRBs is still a matter of vital debate. This is mainly due to the fact that the continuum GRB afterglows are the "smoking gun" of the GRB explosion, revealing only very little information about the progenitor. However, even without a direct observation of the central engines of GRBs, it might be possible to infer their nature indirectly if detailed probes of the structure and composition of their immediate vicinity can be found.

The hypothesis that supernovae are the progenitors of gamma ray bursts dates back to the epoch of first GRB discovery and has received support in recent years from the detection of supernova features in the optical afterglows of GRBs (Resmi et al., 2005 and references therein). These are re-brightenings at rest-frame intervals of 10-15 days after the GRB, circumburst media with wind characteristics, iron emission lines, association of GRBs with star-forming regions. The most tempting hint of association between GRBs and SNe is obviously the similarity of the intrinsic energy of these phenomena, when collimation and beaming are taken into account in GRBs (Frail et al., 2001).

2. Importance of Indian location for GRB afterglow observations

It is well known that GRB events are unpredictable both in time and location. But due to their transient nature early and dense temporal coverage of the light curves of GRB afterglows are extremely important for probing constraints on the current theoretical models of GRBs. We therefore started optical observations of GRB afterglows at ARIES since January 1999 under a long term research programme in collaboration with astronomers from all over the globe. The collaborators in this programme are the teams led by Prof. D. Bhattacharya from Raman Research Institute, Bangalore; Dr. G. C. Anupama from Indian Institute of Astrophysics, Bangalore; Prof. A. P. Rao from NCRA, TIFR, Pune and Prof. A. J. Castro-Tirado from Instituto de Astrfisics de Andalucia, Spain. The geographical location of India coupled with the availability of reasonably good astronomical sites (cf. Sagar 2000) having moderate size optical telescopes equipped with modern CCD astronomical detectors is valuable to make a unique contribution towards the optical observations of GRB afterglows. The longitude of India locates it in the middle of about 180 degree wide longitude band having modern astronomical facilities between

Canary Islands ($20°W$) and Eastern Australia ($157°E$). Because of this the observations which are not possible in Canary Islands or Australia (during day light hours), can be obtained from India. As an example, earliest optical observations of GRB000301C have been carried out from India (cf. Sagar et al., 2000b, Masetti et al., 2000, Bhargavi and Cowsik 2000). Also, optical observations taken from India have filled valuable temporal gaps in a number of GRB afterglow observations.

3. Optical observations and light curves

Broad band optical photometric observations of 14 GRB afterglows (GRB 990123, GRB 991208, GRB 991216, GRB 000301C, GRB 000926, GRB 010222, GRB 011211, GRB 020405, GRB 021004, GRB 021211, GRB 030226, GRB 030227, GRB 030328 and GRB 030329/SN 2003dh) have been successfully carried out at ARIES with the modern CCD detector mounted at the f/13 Cassegrain focus of 104-cm Sampurnanand Telescope. 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. Table 1 gives a list of GRB afterglows observed by our group. Photometry was done using standard packages IRAF, MIDAS and DAOPHOT. Further details of the instruments and data reductions are given by Sagar (2002) and recently by Pandey (2005)

We have combined our data with the published ones to define the light curves of the very fast evolving GRB afterglows. Optical afterglow light curve of a GRB provides valuable 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. Figure 1 shows the optical flux decay of GRB 010222 and GRB 030226 afterglows in the B, V, R and I passbands. Figure 2 displays those of GRB 000301C and GRB 021004 afterglows whereas figure 3 shows the light curve of GRB 030329 afterglow. The data are borrowed from the references listed in Table 1. The X-axis is log $(t - t_0)$ where t is the time of observation and t_0 is the time of GRB trigger. t_0 is 2001 Feb 22.308 UT for GRB 010222; 2003 Feb 26.1573 UT for GRB 030226; 2000 March 1.411 UT for GRB 000301C; 2002 October 4.5043 for GRB 021004 and 2003 March 29.4842 UT for GRB 030329. All times are measured in unit of days. The optical emission from all GRB afterglows is overall fading. However, the pattern of their flux decays differs. The light curves steepen after a period of few days. This can be attributed to the lateral expansion of ejected material, which was initially confined to a small cone. Overall the flux decay, as expected in GRB OTs having jet-like relativistic ejecta (Sari, Piran and Halpern 1999; Rhoads 1999), seems to be described by a broken power-law of the form $F(t) = F_0[\frac{2}{(t/t_b)^{\alpha_1 s} + (t/t_b)^{\alpha_2 s}}]^{1/s} + F_g$, where F_g is the constant flux from the underlying host galaxy or other non-varying contaminants, α_1 and α_2 are asymptotic power-law slopes at early and late times with $\alpha_1 < \alpha_2$. The parameter $s(> 0)$ controls the sharpness of the break, a larger s implying a sharper break. F_0 is the flux of afterglow at the cross-over time t_b. Further details about

Table 1. List of Optical afterglows observed from India. Results are published in the References given in the last column. Numbers are (1) Sagar et al., (1999); (2) Nilakshi et al., (1999); (3) Galama et al., (1999); (4) Castro-Tirado et al., (1999); (5) Sagar et al., (2000a); (6) Castro-Tirado et al., (2001); (7) Sagar et al., (2000b); (8) Masetti et al., (2000); (9) Sagar et al., (2001a); (10) Sagar et al., (2001b); (11) Bhattacharya (2001); (12) Jacobsson et al., (2003); (13) Masetti et al., (2003); (14) Pandey et al., (2003a); (15) Pandey et al., (2003b); (16) Pandey et al., (2004); (17) Castro-Tirado et al., (2003); (18) Pandey (2005); (19) Resmi et al., (2005).

GRB	α_{2000}	δ_{2000}	Filters	Localizations by	Reference
GRB 990123	$15^h25^m29^s$	$+44°45'$	B, V, R	BeppoSAX/WFC	1,2,3,4
GRB 991208	16 33 55	+46 26	I	Uly/Konus/NEAR	5, 6
GRB 991216	05 19 31	+11 11	R	BAT/PCA	5
GRB 000301C	16 20 21	+29 25	V, R, I	ASM/Uly	7, 8
GRB 000926	17 04 10	+51 47	R	Uly/Konus,NEAR	9
GRB 010222	14 52 13	+43 01	VRI	BeppoSAX/WFC	10,11
GRB 011211	11 15 22	−21 56	R	BeppoSAX	12
GRB 020405	13 58 03	−31 22	I	Uly/MO/BeppoSAX	13
GRB 021004	00 26 56	+18 56	$BVRI$	HETE	14
GRB 021211	08 09 00	+06 44	$BVRI$	HETE	15
GRB 030226	11 33 05	+25 54	$UBVRI$	HETE	16
GRB 030227	04 57 33	+20 29	R	INTEGRAL	17
GRB 030328	12 10 48	−09 21	$BVRI$	HETE	18
GRB 030329/ SN 2003dh	10 44 49	+21 29	$UBVRI$	HETE	19

the GRB afterglows discussed here can be seen in the references listed in Table 1. The parameters of the GRB afterglows are listed in Table 2.

4. Discussions and Conclusions

During 5 years of our optical observations from 1999 to 2003, successful optical observations have been obtained for 14 (GRB 990123, GRB 991208, GRB 991216, GRB 000301C, GRB 000926, GRB 010222, GRB 011211, GRB 020405, GRB 021004, GRB 021211, GRB 030226, GRB 030227, GRB 030328 and GRB 030329/SN 2003dh) GRB afterglows. In the case of GRB 000301C, earliest optical observations have been carried out by us. Important temporal gaps in the light curves of a number of GRB afterglows have been filled by our observations due to geographical location of India. The overall flux decays observed in the light curves of all GRB afterglows discussed here are well understood in terms of a jet model. In the case of GRB 030329, even presence of double jets have been proposed (see Resmi et al., 2005 and references therein). However, there are certain peculiarities in most of the GRB afterglows and they are briefly outlined here.

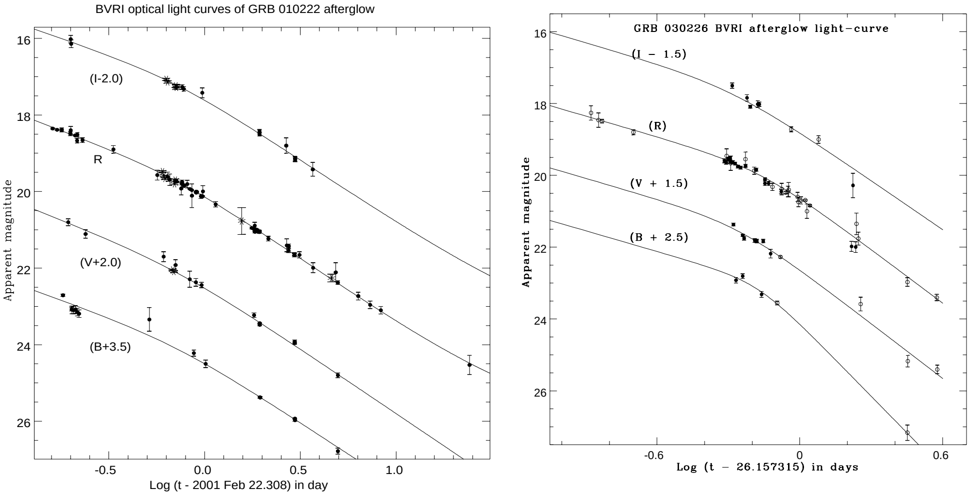

Figure 1. Optical light curves of GRB 010222 and GRB 030226 afterglows in *BVRI* passbands. Marked vertical offsets are applied to avoid overlapping of data points of different passbands. The solid curves are the least square best fitted relations for the parameters listed in Table 2.

1. **Flux decays differ from one wavelength to other.** In the case of GRB 000926, a much steeper late decay of X-ray flux with $\alpha > 4$ and the flat spectral index (~ 0.8) is not consistent with the simple jet model which predicts similar late flux decay in both optical and X-ray regions. Similarly, the flux decays of GRB 991216 afterglow are also different at X-ray, optical and radio wavelengths.

2. **Sharpness of the breaks in the optical light curves.** Another area of possible disagreement with the standard fireball model is the sharpness of the break in the light curves (see Sagar 2002 for details). While the expected sharpness of the transition could depend on the density profile of the ambient medium (Kumar and Panaitescu 2000), the very sharp transitions seen in GRB 000301C, GRB 000926 and few others would be difficult to quantitatively explain in the standard fireball model. This is an area that deserves a detailed theoretical study.

3. **Fluctuations in the optical light curves.** The peculiarity in the light curves of GRB 000301C, GRB 011211, GRB 021004 and a few other afterglows seems to be not due to synchrotron emission of the fireball. They have been considered as manifestation of the variable external density of the medium or variation in the energy of the blast wave with time. In case of GRB 000301C, even presence of microlensing has been proposed as an explanation for the peculiarities.

4. **Location of cooling frequency in the case of GRB 010222.** A comparison of observed flux decay and spectral index parameters with the model indicates that the cooling frequency, ν_c, in the case of GRB 010222 afterglow, is below optical but above the peak frequency after the break in the optical light curve as $\beta \sim$

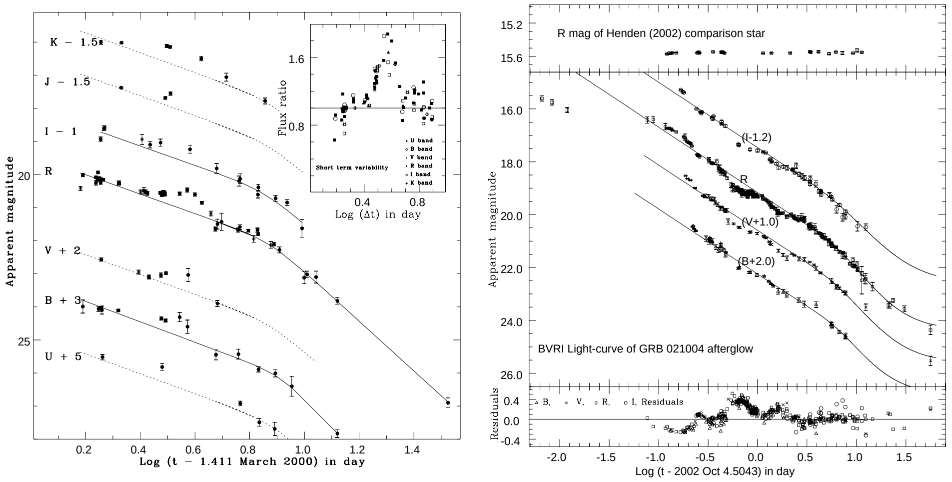

Figure 2. Optical light curves of GRB 000301C and GRB 021004 afterglows. Marked vertical offsets have been applied to avoid overlapping of data points of different passbands. In GRB 000301C light curve, the solid line represents the least square non-linear fit to the densely observed data for a jet model while dotted lines are the jet model curves for $\alpha_1 = 1.2$ and $\alpha_2 = 3.0$. Short term variability observed in different passbands is shown in the upper right corner box. In GRB 021004 light curve, for comparison, R magnitude of Henden (2002) comparison star 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.

$\frac{\alpha_2}{2}$; $\alpha_1 \sim \frac{(3\alpha_2-2)}{4}$ and presence of excess emission around ν_c are observed (Sagar et al. 2001b). Such a low-value of ν_c so early (< 0.5 day) in the evolution of GRB 010222 afterglow may indicates the presence of a very strong post shock magnetic field. The value of p for GRB 010222 afterglow is $\sim 1.2 - 1.5$ which is much lower than the generally derived value of > 2. The GRB 010222 afterglow emission is thus unique. Bhattacharya (2001) has derived for the first time temporal behaviour of the light curve of such hard GRB afterglows and found that the expected behaviour will be the same as for $p > 2$ if the upper cutoff in the electron energy distribution evolves in direct proportional to the bulk of Lorentz factor of the blast wave.

5. **Presence of supernova signatures in the optical light curves.** First evidence for GRB Supernova signature was seen for GRB 980425/SN 1998bw (Galama et al., 1998) whereas first clear and unambiguous supernova signature was detected for GRB 030329/SN 2003dh (Stanek et al., 2003). The optical light curves of GRB 020405, GRB 030329 and few others clearly indicate that Supernova activities are associated with the GRB events.

Multi-wavelength observations of GRB afterglows and energetics in the presence of non-isotropic emission clearly indicate that collapsar model (e.g. merging remnants or explo-

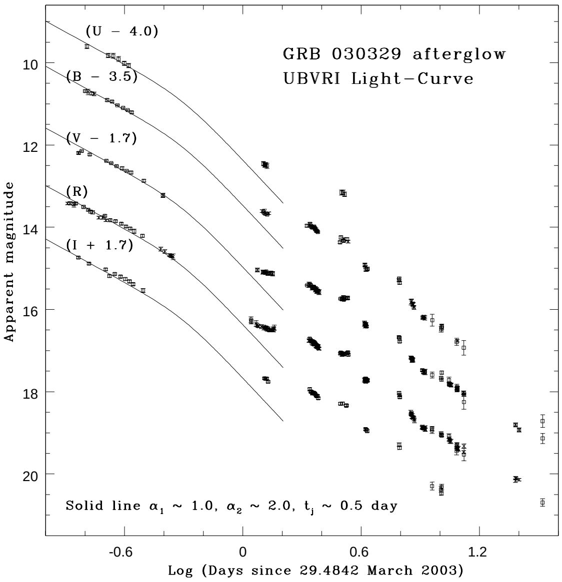

Figure 3. Optical light curve of GRB 030329. Marked vertical offsets have been applied to avoid overlapping of data points of different passbands. Using the data $\delta t < 1.5$ days broken power law is overplotted using $\alpha_1 \sim 1.0$ $\alpha_2 \sim 2.0$ *and* $t_j = 0.5$ *day*. Data > 1.5 day do not look like fitted by the same power law, flattened due to the presence of second wider jet (cf. Berger et al., 2003; Resmi et al., 2005)

sions of massive stars) can be responsible for the origin of long duration GRBs and not the quasars or the nuclei of galaxies as some GRBs are found offset by a median value of 3.1 kpc from the centre of their host galaxy. Marginal evidence for transient X-ray emission line features in GRB afterglows have been reported for five GRBs, GRB970508(Piro et al., 1999), GRB970828 (Yoshida et al., 2001), GRB991216 (Piro et al., 2000), GRB000214 (Antonelli et al., 2001), GRB011211 (Reeves et al., 2002). The line width and intensity of the two emission features discovered in the $X-$ray spectrum of the GRB 991216 (Piro et al., 2000) taken with the Chandra $X-$Ray Observatory imply that the GRB progenitor can be a massive star system that ejected, before the burst, $\sim 0.01 M\odot$ of iron at a velocity $\sim 0.1c$. The Chandra $X-$Ray Observatory observations reported by Harrison et al., (2001) for the GRB 000926 afterglow imply that the GRB exploded in a reasonably dense ($n \sim 30$ cm^{-3}) medium, consistent with a diffuse interstellar cloud environment. The presence of dust extinction amounting to $A_v \sim 1$ mag in the host galaxies of a number of GRB afterglows also broadly supports the proposal that GRBs could be associated with massive stars embedded in star-forming regions of the GRB host galaxies (see Sagar 2002 and references therein). However, there is no clue about the origin of short duration, hard GRBs. Also, follow-up observations within few minutes to few hours of the burst are generally not available even for long duration GRBs.

Table 2. Parameters of the GRB afterglows observed from Nainital. α_1 and α_2 are the early and late times optical flux decay constants; t_b is the cross-over time when α_1 changes to α_2; β is the spectral index in slow cooling regime generally between X-ray to optical regions at epoch δt; θ is opening angle of the jet; E_{52} is the energy in units of 10^{52} ergs.

GRB afterglow	Temporal Index α_1	Temporal Index α_2	Jet-break time t_b in days	Spectral Index β	δt in days	Redshift	θ (deg)	E_{52} (non-iso)
GRB 990123	1.1±0.1	1.65±0.06	2.04±0.46	-0.75±0.1	0.8	1.6	5.0	1.1
GRB 991208	–	2.2±0.1	~2	-0.75±0.1	8.5	0.706	8.7	0.13
GRB 991216	1.2±0.04	1.5±0.1	~2	-0.74±0.1	1.6	1.02	6.0	0.3
GRB 000301C	1.2±0.14	3.0±0.5	7.5±0.6	-0.73±0.1	4.8	2.03	8.6	0.4
GRB 000926	1.4±0.1	2.6±0.1	1.7±0.1	-0.95±0.1	2.3	2.04	8.0	0.2
GRB 010222	0.74±0.05	1.35±0.04	0.7±0.07	-0.83±0.13	0.77	1.48	2.70	0.176
GRB 011211	0.95±0.02	2.11±0.07	1.56±0.02	-0.56±0.19	0.57	2.14	3.4	0.012
GRB 020405	1.54±0.06	1.85±0.15	$10< t_b <20$	-0.9±0.3	–	0.69	15	0.75
GRB 021004	0.99±0.05	2.00±0.2	6.50±0.2	-0.63±0.20	1.37	2.33	7	0.035
GRB 021211	1.11±0.01	–	–	-0.66±0.34	0.13	1.01	–	–
GRB 030226	0.77±0.04	2.05±0.04	0.65±0.05	~-1	0.61	1.98	3.2	0.08
GRB 030227	1.10±0.14	–	~1.5	-1.25±0.14	0.87	–	–	–
GRB 030328[1]	1.0	–	0.8	-2.3	–	1.52	3.7	0.059
GRB 030329[2]	~ 1	~ 2	~ 0.5	–	–	0.17	~ 5	0.0071

[1] Values taken from Ghirlanda et al., 2004

[2] α_1, α_2, t_b derived for data < 1.5 day. θ *and* E_52 values taken from Ghirlanda et al., 2004

A large fraction of the GRB afterglow optical observations carried so far have used the 1-m class and the moderate size optical telescopes. This indicates that in future these telescopes, as large amount of observing time is available on them, will play an important role in understanding the origin of GRB afterglows. India, as it has good number of moderate size telescopes located at good photometric sites, can therefore contribute, mainly due to its advantage of geographical location, significantly in the follow-up observations of the GRB afterglows. The 1.2-m Mt. Abu optical/near-IR telescope equipped with good focal plane instruments will definitely play an important role in this context.

The multi-wavelength observations of recent GRB afterglows have thus started revealing features which require explanations other than generally accepted so far indicating that there may be yet new surprises in GRB afterglows.

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