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Emission from GRBs and their afterglows : Indian observations

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Abstract. The study of Gamma-ray bursts, electromagnetically the most luminous events in the Universe though only for a few seconds, was revolutionized in 1997 when the Italian-Dutch X-ray satellite BeppoSAX started providing the positions of some events with an accuracy of a few arcminutes within a few hours after the burst. Indian contributions in this area are summarized. While mainly ISRO contributed to studies of GRB emission, a number of research organizations contributed to the optical observations of GRB afterglows. So far successful optical observations have been obtained for five afterglows namely GRB 990123, GRB 991208, GRB 991216, GRB 000301C and GRB000926. The light curves, spectral energy distributions and energetics of these are discussed in the light of recent fireball plus blast wave theoretical models of GRBs. Their early-time flux decay constant is ~ 1.1 which become ~ 2.4 at later times. All are having relatively flat spectral index with its value ranges from 0.73 to 0.95. Observations of these afterglows support the model of non-isotropic synchrotron emission from the centre 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.

Key words : Gamma-ray bursts, synchrotron emissions, follow-up observations, GRB afterglows

1. Introduction

It is a happy occasion to address this august audience during the 20th meeting of the Astronomical Society of India and National Symposium on *Multi-wavelength astronomy*, organized by the Department of Physics, D.D.U. Gorakhpur University, Gorakhpur. The discovery and multi-wavelength observations of Gamma-ray burst (GRB) afterglows in 1997 has started a new era in GRB physics. It may therefore be timely here to highlight the recent results on this topic with special emphasis on contributions made from India.

GRBs are short and intense transient flashes of cosmic high energy (~ 10 KeV–10 GeV) photons. Most of the energy is released in the 0.1 – 1 MeV range. They are unpredictable in both time and location. The duration of the bursts ranges from about few msec to ~ 1000 sec. The situation of GRB and its afterglows can be compared with the supernova event (Bhattacharya 2000), though the time scales are shorter for GRB. The emission from GRBs and their afterglows though similar in nature to the emission from supernovae, is more energetic, as they release ~ 10^{51} – 10^{54} ergs or more in a few seconds. Following the naming sequence, nova and supernova, it is therefore appropriate to call GRBs as hypernova. The afterglow of a GRB appears after the GRB event but almost at the same location. It is generally, observed first in X-rays which then provides refined coordinates of the GRB event for the follow-up space and ground based observations at longer wavelengths. The afterglow emissions, unlike GRB emissions, are long lived. Hence, duration of their follow-up observations ranges from days to months to years depending upon the wavelength.

The origin of GRBs is a mystery even after about 34 years of their accidental discovery on July 2, 1967 by the Vela satellites (Klebesadel et al. 1973). Since then, several dedicated satellites have been launched to observe the GRB bursts. Interest focused on where they came from and what they were, but was hampered by lack of sufficient data to even locate them. The Burst and Transient Source Experiment (BATSE, the detector on the Compton Gamma-Ray Observatory launched in 1991) alone detected over 2700 bursts. The GRBs are generally multi-peaked which follow a sharp rise and exponential decay profile. Even though, there is no

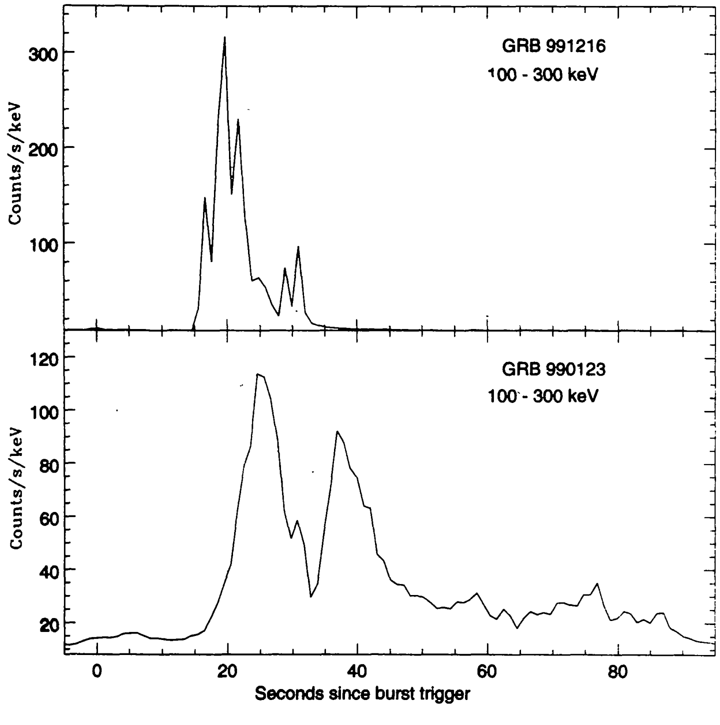

Figure 1. The BATSE light curves of GRB 990123 and GRB991216 in 100-300 keV energy band. Times are relative to the BATSE trigger time of UT 09:46:56 on January 23, 1999 for GRB 990123 and of UT 16:07:01 on December 16, 1999 for GRB 991216. Note the multi-peaked nature of the events.

typical GRB temporal-profile, Fig. 1 shows the BATSE light curves of GRB 990123 and GRB 991216 in 100 – 300 KeV energy band and they can be considered as representative of light curves of GRBs. Distribution of the duration (measured by the time interval containing 90% of the photon counts) indicate two distinct groups of GRBs: short (< 1 s with mean ~ 0.3s) with harder γ-ray spectrum and more variability; and long (> 1 s with mean ~ 25s) with softer spectrum and smoother burst (cf. Bhat 1999; Fishman 1999 and references therein). The data also showed isotropic sky distribution of the GRBs, indicating their cosmological origin.

A generic scheme of a cosmological GRB model has emerged in the last few years (see Piran 1999 for a review). According to this, the observed γ-rays are emitted when an ultra-relativistic energy flow is converted into radiation. The current model for GRBs and their afterglows is the fireball plus blast wave (Fig. 2). The GRBs are thought to arise when a massive explosion, known as a fireball, releases a large (~ M_0c^2) amount of kinetic energy into a volume of ≤ 1 light ms across. When this ultra-relativistic (Lorentz factor $\Gamma \geq 300$) outflow of particles interacts with surrounding material, both forward and reverse shocks are formed. The GRB itself is thought to owe its multi-peaked light curve (see Fig. 1) to a series of internal shocks within a relativistic flow while the afterglows are due to the external (forward) shocks driven in the interstellar medium surrounding the burster. As the external shock interacts with increasing amount of swept-up material, it becomes less relativistic, and produces a slowly fading afterglow first in X-ray, then ultra-violet, optical, infrared, millimeter and radio radiation. The afterglow emissions are most likely synchrotron radiation (Sari et al. 1998; Piran 1999 and references therein). The occurrence of GRB, based on the simplest model, is one burst per million years per galaxy. The events are therefore extremely rare in a galaxy.

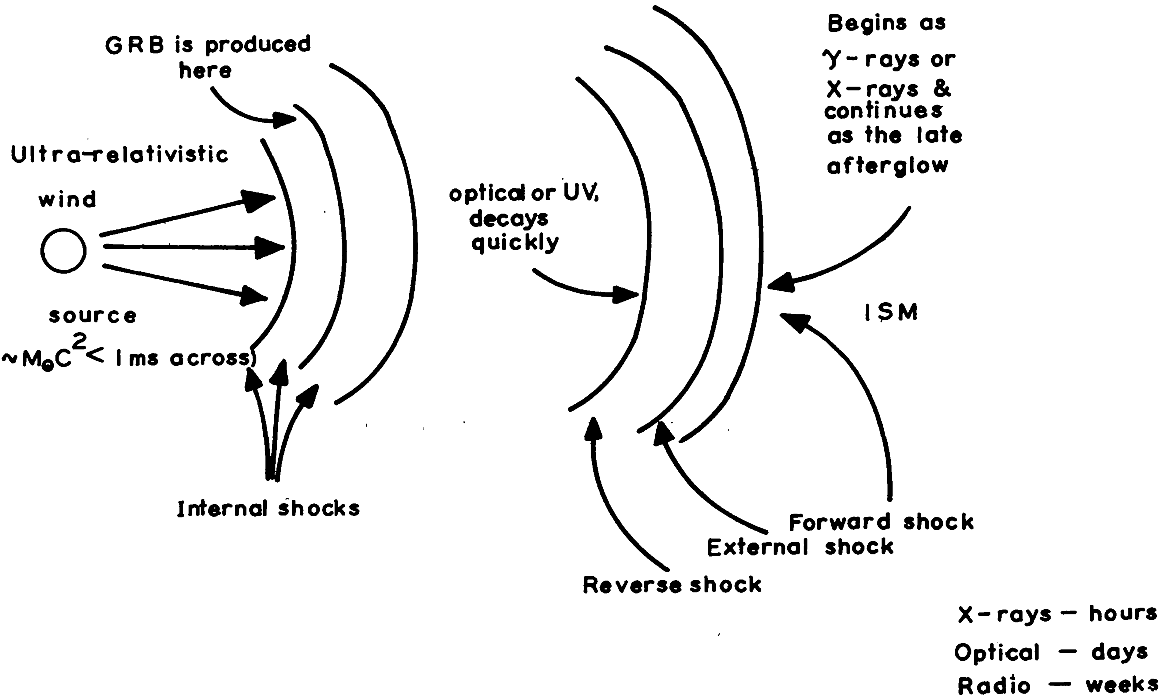

Figure 2. Schematic overview of the fireball plus relativistic blast wave model.

After launching of many space-borne instruments, and in particular, the Italian-Dutch X-ray satellite BeppoSAX in mid-1996, it became possible to obtain position of GRB with an accuracy better than 3-5 arc minutes within hours of occurrence and also carry out multi-wavelength observations of GRB afterglows. This led to the discovery of GRB afterglows in 1997 at X-ray wavelength by Costa et al. (1997); at optical by van Paradijs et al. (1997) and at radio wavelengths by Frail et al. (1997). In the same year, first redshift measurements of a GRB afterglow at millimeter wavelengths was discovered by Bremer et al. (1998). First Indian observations of a GRB afterglow were obtained in 1999 at optical wavelengths from Nainital (cf. Sagar 1999). Such multi-wavelength observations have contributed significantly to our understanding of origin of GRB sources. They indicate that some, and most likely all GRBs are cosmological. This immediately implies that GRB sources are much more luminous than previously thought. For a few seconds, in fact, they become electromagnetically so luminous that they out-shine the rest of the combined Universe.

The rapid localization of GRBs has brought a new dimension to GRB research. In fact, GRB research has now moved its focus from statistical studies of GRB properties and celestial distribution (cf. Bhat 1999), to the study of origin of emission from GRB and their afterglows. GRB research has now entered the afterglow era. As multi-wavelength observations are of crucial importance for understanding and constraining the active emission mechanisms of GRBs as well as for the study of the nature, structure and composition of their surroundings, a number of Indian research institutions are participating in their observations as an intergral part of international observing campaigns. A brief account of Indian contributions with special emphasis on the optical observations of the GRB afterglows is presented below.

2. Indian Observations of GRBs and their afterglows

Indian contributions made towards the observations of emissions from GRBs and their afterglows are described in the sub-sections to follow.

2.1 Observations of GRB emissions

In order to observe the emission from mysterious GRBs, the scientists at the Indian Space Research Organisation Satellite Centre have successfully flown experiments on the Indian Stretched Rohini Series Satellites (SROSS-C) during 1992 May-July and also on another Indian Scientific satellite SROSS-C2 on 1994 May 4. (cf. Kasturirangan 1999). The first experiment was designed to monitor GRBs in 20 keV-3 MeV energy range with an aim to determine high (~ 2 ms) time resolution light curve, to search for periodicities in the GRB emission, etc. The observations were carried out for a period of about 55 days and a few GRB events were observed successfully. The light curve of the GRB 920612 indicates that it is an event of 2.5 sec duration with fluence of ~ 5×10^{-6} erg/cm^2, while GRB 920629 light curve showed strong oscillations with a period of about 237 ms. The GRB detector on SROSS-C2 has detected so far over 50 GRB events with fluence > 5×10^{-6} erg/cm^2 in 20 keV-3 MeV energy band. The experimental details and main scientific results derived from these observations have been described earlier by Kasturirangan et al. (1997) and Kasturirangan (1999) and recently by Sinha et al. (2001). In brief, classification based on morphological similarities of their light curves, distribution of GRB durations derived from SROSS C-2 observations indicates bimodality in agreement with pre-BATSE results. An evidence for quasi-periodic oscillations at a 100 ms level is seen in at least three bursts namely GRB 940203, GRB 941210 and GRB 950512. Even today, SROSS-C2 is an integral member of the Interplanetary Network (IPN) of ten spacecrafts monitoring GRBs and has been playing a small but a definite role of recording and confirming GRB events. The observational properties of the small sample of SROSS-C2 GRBs reflect and conform with the observations made by other spacecrafts, e.g., isotropy, and bimodal duration distribution - with short events being harder - and presence of quasi-periodic millisecond oscillations. The SROSS C-2 is expected to provide useful data for another year or so (Sinha et al. 2001).

2.2 Optical observations of GRB afterglows

In order to establish identity and meaning in astrophysical terms and also to arrive at more definitive and clearer conclusions, optical observations of GRB afterglows are indispensable. It is because of this reason distances and other important parameters of GRBs could be estimated only recently when optical observations started routinely providing redshift and light curves of their afterglows, though the phenomena was discovered in late sixties.

It is well known that the GRB event is unpredictable in both time and location. At the same time, due to its transient nature, early and dense temporal coverage of the light curves of the GRB afterglows are extremely important for providing constraints on the current theoretical models. In this context, the availability of reasonably good astronomical sites (cf. Sagar et al. 2000a, b) having moderate size optical telescopes equipped with modern CCD astronomical detectors in India and its geographical location are valuable (cf. Sagar 2000), as they can make 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

Table 1. GRB fields imaged from Nainital. Location of the imaged regions and photometric passbands of the observations along with the detection of GRB afterglows are also given.

GRB event	α_{20000}	δ_{2000}	Filters	Afterglow observed
GRB 990123	$15^h25^m29^s$	$+ 44^\circ 45'$	*B,V,R*	Yes
GRB 991208	15 33 55	+ 46 26	*I*	Yes
GRB 991216	05 19 31	+ 11 11	*R*	Yes
GRB 991217	23 03 08	+ 00 14	*R*	No
GRB 000115	08 03 30	− 17 13	*R*	No
GRB 000301C	16 20 21	+ 29 25	*V,R,I*	Yes
GRB 000408	09 10 32	+ 66 34	*R*	No
GRB 000424	06 58 52	+ 49 53	*R*	No
GRB 000519	23 04 25	+ 01 10	*R*	No
GRB 000615	15 32 34	+ 73 48	*R*	No
GRB 000926	17 04 10	+ 51 47	*R*	Yes
GRB 001019	17 11 44	+ 35 20	*R*	No
GRB 001105	13 01 54	+ 35 29	*R*	No
GRB 001212	06 49 35	+ 36 23	*R*	No

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 GRB 000301C have been carried out from India (cf. Sagar et al. 2000d, Masetti et al. 2000b, Bhargavi & Cowsik 2001). In India, there are four one metre class (two 1.2-m located at Japal-Rangapur near Hyderabad and Gurushikhar near Mount Abu; two 1-m located at Kavalur and Nainital) and two 2 metre class (2.34-m Vainu Bappu Telescope at Kavalur and 2-m of Indian Astronomical Observatory at Hanle in the high-altitude cold desert of south-eastern Ladakh which saw its first light at the midnight hours between 26 and 27 September 2000) optical telescopes. Another 2-m telescope of Inter University Centre of Astronomy and Astrophysics is expected to become operational soon at Giravali near Pune. The locations of these telescopes are shown in Fig. 3.

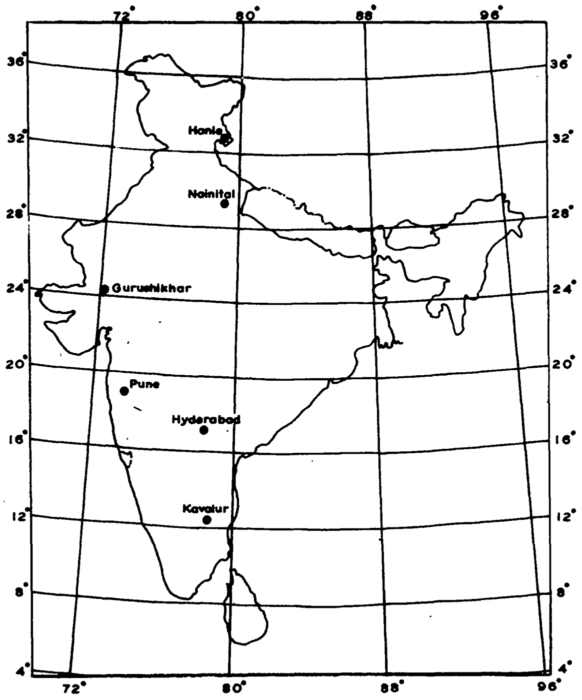

Figure 3. Location of 1-metre and larger size optical/near-IR telescopes in India.

They are almost evenly distributed from north to south in the country. On the whole, India has good number of small and moderate size optical telescopes equipped with modern CCD detector for providing valuable optical measurements of GRB afterglows.

3. Optical observations from Nainital

Since the optical transient of a long duration GRB has generally apparent R magnitude between 18 to 22, if it is detected within a few days or so after the burst, the 1-m class optical telescopes equipped with CCD detector are capable of observing them. From the discussions in above sections, it is also clear that the optical observations of the GRB afterglows can contribute significantly to an emerging front line research area of GRBs. They help in determining the degree of collimation of the initial emission through detailed study of the GRB afterglow light curve. We therefore started optical observations at Nainital in January 1999 under a long term research programme in collaboration with astronomers from all over the globe including India. Modern CCD detector mounted at the f/13 Cassegrain focus of 104-cm Sampurnanand telescope is being used for carrying out broad band photometric observations. Observational details of the GRB fields imaged till end of 2000 from Nainital are given in Table 1. The observations with relatively good signal to noise ratio can be obtained best in R band since the quantum efficiency of the CCD detector in use is maximum around peak wavelength of R. Because of this as well as the fact that the brightnesses of the GRB afterglows are generally close to the detection limit of 1-m size telescope ($R \sim 22$ mag), most of the observations were taken in R passband. Whenever time and observing conditions allowed, observations were also taken in B, V and I broad bands. Out of the 14 GRB fields observed from Nainital, optical photometric data were obtained successfully only for 5 GRB afterglows namely GRB 990123, GRB 991208, GRB 991216, GRB 000301C and GRB 000926 (see Table 1) including the first Indian observations of a GRB afterglow (cf. Sagar 1999).

3.1 Calibration of optical photometric observations

Because of its importance, the optical follow-up observations are carried out even during non-photometric sky conditions. For reliable determination of the photometric magnitudes, from such observations, photometric standards in the GRB field are desired as they are generally not available before hand. We therefore provide local photometric standards in the fields of GRB 990123 (Nilakshi et al. 1999); GRB 991208 (Sagar et al. 2000c) and GRB 000926 (Sagar et al. 2001) while Henden et al. (2000) and Henden (2000) provide such standards in the field of GRB 991216 and GRB 000301C respectively. Thus, we have used secured photometric calibrations in our data analysis. In order to avoid errors arising due to different photometric calibrations, we have used only those published measurements whose magnitudes could be determined relative to local standards. Further details of observations, data reductions and parameter determinations of the GRB afterglows observed from Nainital are published by Sagar et al. (1999, 2000c, 2000d, 2001); by Galama et al. (1999), Castro-Tirado et al. (1999, 2001) and Masetti et al. (2000b). The results of these observations are also presented as a poster paper in this meeting (see Pandey et al. 2001). The flux decay and spectral energy distribution of the afterglows and energetics of the GRBs are presented and discussed below in the light of recent fireball plus blast wave theoretical models of GRBs.

4. Optical light curves in *R* photometric passband

Except for GRB 990123 and GRB 000301C, only a few optical data points could be obtained from Nainital for the GRB afterglows. In order to define the light curves properly of the very fast evolving (exponential flux decay constants range from ~ 1 to ~ 2.5) GRB afterglows, even such data points are needed since generally there exist no other simultaneous optical observations due to our geographical location as discussed in the last section. However, precisely for the same reason, and also to derive accurate parameters of the GRBs, our observations are used in combination with the data published in the literature after calibrating them accurately as discussed in the last section. Fig. 4 shows, as a sample, the optical flux decays of GRB 991208,

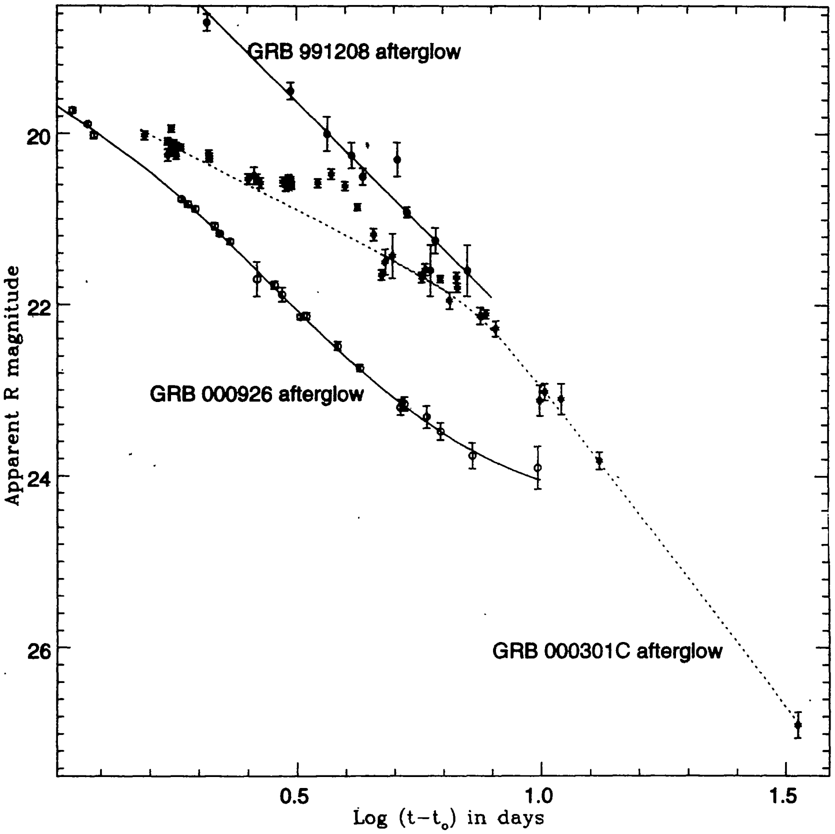

Figure 4. Light curves of GRB 991208 (•), GrB 000301C (∗) and GRB 000926 (o) afterglows in optical R passband. In the case of GRB 991208, solid line represents the least square linear fit to the data points, while the continuous dotted and solid curves represent the least square non-linear fit to the observed data of GRB 000301C and GRB 000926 respectively for a jet model with the value of sharpness parameter as 5 in both cases (see text). In the case of GRB 000301C, observed short term variability has been excluded, while in the case of GRB 000926, the constant flux from the underlying host galaxy has been included in the model fitting (see text).

GRB 0000301C and GRB 000926 afterglows in R passband since it contains the densely observed data which are borrowed from Sagar et al. (2000c), Sagar et al. (2000d) and Sagar et al. (2001) respectively. The X-axis is log $(t–t_0)$ where t is the time of observation and t_0 is the time of GRB trigger which is 1999 December 8.192 UT for GRB 991208; 2000 March 1.411 UT for GRB 000301C and 2000 September 26.9927 UT for GRB 000926. All times are measured in unit of day. The optical emission from all GRB afterglows is overall fading. However, there are differences in the pattern of flux decay. The light curve of GRB 991208 afterglow is well characterized by a single power law $F(t) \propto (t - t_0)^{-\alpha}$, where $F(t)$ is the flux of the afterglow at time t and α is the decay constant. In the case of GRB 000301C, short term variability above the overall flux decay has been observed ~ 4 days after the burst (cf. Berger et al. 2000; Sager et al. 2000d). Though the cause of the variability is not well understood, gravitational micro-lensing event has been proposed as a possible cause for this by Garnavich et al. (2000). The light curves of both GRB 000301C and GRB 000926 afterglows 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. The light curves of GRB 000926 flattens after ~ 6 days after the burst which is due to the contribution of host galaxy (cf. Sagar et al. 2001; Price et al. 2001). Unlike GRB 991208, the optical light curves of both GRB 000301C and GRB 000926 (Fig. 4) cannot be fitted by a single power-law. Overall the flux decay seems to be described by a broken power-law as expected in GRB afterglows having jet-like relativistic ejecta (Sari et al. 1999; Rhoads 1999). Broken power-law in these light curves can be empirically fitted by functions of the form (see Sagar et al. 2000d for details)

$$F(t) = 2F_0/[(t/t_b)^{\alpha_1 s} + (t/t_b)^{\alpha_2 s}]^{1/s} + F_g,$$

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; E_{52} is energy in units of 10^{52} ergs; θ is opening angle of the jet while α_1^p and α_2^p are the values predicted by the adiabatic jet synchrotron model from the observed value of β (see text.)

Parameter	GRB 990123	GRB 991208	GRB 991216	GRB 000301C	GRB 000926
α_1	1.1 ± 0.1		1.2 ± 0.04	1.2 ± 0.14	1.4 ± 0.1
α_2	1.65 ± 0.06	2.2 ± 0.1	1.5 ± 0.1	3.0 ± 0.5	2.6 ± 0.1
t_b (days)	2.04 ± 0.46	~ 2	~ 2	7.5 ± 0.6	1.7 ± 0.1
β at (Δt days)	0.75 ± 0.1(0.8)	0.75 ± 0.1 (8.5)	0.74 ± 0.1 (1.6)	0.73 ± 0.1 (4.8)	0.95 ± 0.1 (2.3)
Redshift	1.6	0.07055	1.02	2.0335	2.0369
Distance (Gpc)	11	4.2	6.2	16.6	16.6
E_{52} (isotropic)	338	13	67	34	25
θ (deg)	5.0	8.7	6.0	8.6	8.0
E_{52} (non-isotropic)	1.1	0.13	0.3	0.4	0.2
α_1^p (jet model)	1.13 ± 0.15	1.13 ± 0.15	1.11 ± 0.15	1.1 ± 0.15	1.43 ± 0.15
α_2^p (jet model)	2.5 ± 0.2	2.5 ± 0.2	2.5 ± 0.2	2.5 ± 0.2	2.9 ± 0.3

where F_g is the constant flux from the underlying host galaxy, 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. With $s = 1$, this function becomes the same as that used by Stanek et al. (1999) to fit the optical light curve of GRB 990510 afterglow. F_0 is the flux of afterglow at the cross-over time t_b. The function describes a light curve falling as $t^{-\alpha_1}$ $t < < t_b$ and $t^{-\alpha_2}$ at $t > > t_b$. In jet models, an achromatic break in the light curve is expected when the jet makes the transition to sideways expansion after the relativistic Lorentz factor drops below the inverse of the opening angle of the initial beam. Slightly later, the jet begins a lateral expansion which causes a further steepening of the light curve.

The early and late time flux decay constants for the GRB events observed from Nainital are listed in Table 2. The break in the optical light curve of GRB 990123 afterglow has been noticed first by both Castro-Tirado et al. (1999) and Kulkarni et al. (1999) and discussed recently by Holland et al. (2000); while in case of GRB 991216 it has been studied by Halpern et al. (2000) and Sagar et al. (2000c). Ther is no break observed in the light curve of GRB 991208 but the flux decay is fast with $\alpha = 2.2 \pm 0.1$ (Sagar et al. 2000c). It is thus similar to the flux decays observed in GRB 980326 and GRB 980519 with $\alpha = 2.1 \pm 0.13$ (Groot et al. 1998) and 2.05 ± 0.4 (Halpern et al. 1999) respectively. In constrast, the first two and up to now the longest and best observed light curves from GRB 970228 and GRB 970508 show a single power law decay with $\alpha = 1.2$ with no indication for a beaming break. Bursts like GRB 991208; GRB 980519 and GRB 980326 are thus different in the sense that they are rapidly fading afterglows. Most probably, it is due to beaming which steepened the flux decay even before the start of their optical observations (cf. Sagar et al. 2000c). From the point of view of the flux decay, therefore, there are mainly three types of GRB afterglows:-

1. Shallow flux decay with $\alpha \sim 1.2$ like GRB 970228 and GRB 970508. These are probably spherical or at least have large opening angle.

2. Fast flux decay with $\alpha \sim 2.2$ like GRB 980326, GRB 980519 and GRB 991208. These are most probably with narrow jets in which break in the light curve occurred very early even before the first optical observations.

3. Afterglows like GRB 990123, GRB 990510, GRB 991216, GRB 000301C and GRB 000926 where breaks in the light curves are clearly observed. In these cases, early time flux decay constant is shallow while late time flux decay is fast. These are the best candidates for the presence of jets in the GRB emissions.

5. Spectral indices

The spectra of the GRB 000301C and GRB 000926 afterglows ~ 4.8 and 2.3 days after the burst are shown in Fig. 5 as a sample. The corresponding data are borrowed from Sagar et al.

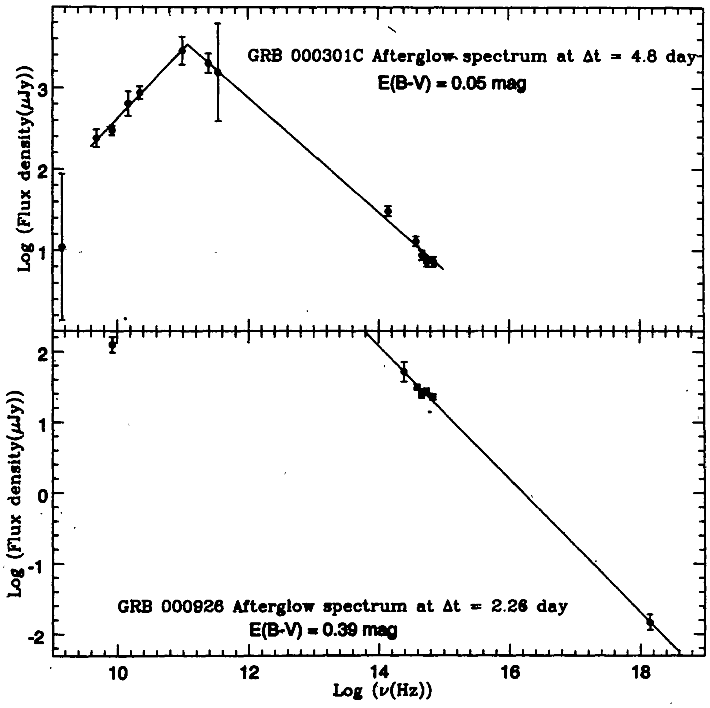

Figure 5. Spectral energy distribution of GRB 000301C and GRB 000926 afterglows after about 4.8 and 2.3 days respectively. In the case of GRB 000301C only galactic extinction amounting to $E(B - V) = 0.05$ mag while in the case of GRB 000926 both galactic and intrinsic extinction due to host galaxy amounting to $E(B - V) = 0.03$ and 0.36 mag respectively have been applied.

(2000d) and Sagar et al. (2001) respectively. It is observed that as the frequency decreases the flux increases. However, in the case of GRB 000301C, it turns over after millimeter wavelengths. The spectral energy distributions are generally well fit by the power-law $F(\nu,t) \propto \nu^{-\beta}$ for a range of frequencies that contain no spectral breaks. The value of β is 0.95 in X-ray to near-IR spectral region in the case GRB 000926 while it is 0.73 for GRB 000301C in the optical to millimeter region. Table 2 lists the values of β along with other parameters of the GRB afterglows observed from Nainital. This indicates that their β values, in the slow cooling phase, range from 0.7 to 0.95. The spectral energy distributions are thus relatively flat.

Fig. 5 indicates that the peak frequency appears to lie in the millimeter region for both GRB 000926 and GRB 000301C. This peak frequency is thus similar to that of GRB 970508 (cf. Galama et al. 1998) but different from that of GRB 990123 (Galama et al. 1999) where the peak is in radio region and that of GRB 971214 for which the peak is in optical/near-IR wave band (Ramaprakash et al. 1998). From this, one may infer that the synchrotron peak frequency may span a large range in GRB afterglows.

6. Comparison with the fireball model

The afterglow of a GRB is thought to be synchrotron radiation from a relativistic shock driven into the circum-burst environment (see Fig. 2). The decay slope is therefore dependent on the dynamics of the fireball, and the spectral slope on the importance of cooling, but within each regime α and β are functions only of p, the power-law exponent of the electron Lorentz factor. This provides a verifiable relation between the two observable quantities α and β, and a way to infer the fireball dynamics.

There is recent evidence that the fireball in at least some GRBs are not spherical but are collimated, like jets, into a small solid angle. In such cases, theoretical models predict a break and a marked steepening in the afterglow light curve (Mészáros & Rees 1999; Rhoads 1999; Sari et al. 1999, Huang et al. 2000; Wei & Lu 2001). The time of occurrence of this break in the afterglow light curve depends upon the opening angle of the collimated outflow. Observational evidence for a break was found first in the optical light curve of GRB 990123 afterglow (Castro-Tirado et al. 1999; Kulkarni et al. 1999) and later on in that of GRB 990510 (Stanek et al. 1999), GRB 990705 (Masetti et al. 2000a), GRB 991216 (Halpern et al. 2000; Sagar et al. 2000c); GRB 000301C (Breger et al. 2000; Sagar et al. 2000d) and GRB 000926 (Sagar et al. 2001; Price 2001) afterglows. At late times, when the evolution is dominated by the lateral spreading of the jet, the value of α is expected to approach the electron energy distribution index while the value of β is expected to be $\alpha/2$ if the cooling frequency is below the observing frequency and $(\alpha - 1)/2$ otherwise (Sari et al. 1999). The slope of the light curve before the break is then expected to be $3\beta/2$ (Sari et al. 1998). The values of early (α_1^p) and late (α_2^p) times flux decay constants can thus be predicted from observed values of β for the adiabatic jet synchrotron model. The values thus derived for the GRBs under discussions are listed in Table 2. A comparison of the predicted values with the corresponding observed values of flux decay constants (see Table 2) indicates that the afterglow emission from all of them except GRB 991208 is of jet type and not spherical, and that the cooling frequency is above the range of observed frequencies. In the case of GRB 991208, rapid decay with flat spectral energy distribution indicate that most probably break in the light curve occurred even before the first optical observations. We therefore conclude that effects of beaming are present in the light curves of all five GRB afterglows observed from Nainital.

7. The energetics and origin

One of the most important clues to the origin of GRBs is the total amount of energy released in the event. Optical observations have helped to derive this important quantity in a number of cases by setting the distance scale through measurement of redshift, and by determining the degree of collimation of the initial emission through detailed study of the afterglow light curve. Clear evidence of the steepening of the light curve, signature of an originally collimated outflow expanding laterally, has been found within a few days of the GRB event in all GRB afterglows discussed here except for GRB 991208 where first observations could be taken only at about 2.1 days after the burst. The values of t_b indicate that steepening in the optical light curves due to beaming mostly occurs within 2 days after the burst. We therefore argue that observed steep decay in the optical light curve of GRB 991208 afterglow (see Fig. 4) may be due to beaming which occurred even before the start of its optical observations.

The anisotropy of the initial ejection needs to be incorporated into the derived energetics of the burst. The known redshifts for the GRB afterglows yield a minimum luminosity distance (see Table 2) for standard Friedmann cosmology with Hubble constant H_0 = 65 km/s/Mpc, cosmological density parameter $\Omega_0 = 0.2$ and cosmological constant $\Lambda_0 = 0$ (if $\Lambda_0 > 0$ then the inferred distance would increase). If the original emission were isotropic, the observed fluences between 25–100 keV yield the total γ–ray energy release which are always > 10^{53} erg. However, the t_b values estimated for them imply, using the expression in Sari et al. (1999), a jet opening angle (θ) of few degrees. This means that the actual energy released from the GRBs is reduced by a factor depending upon the value of θ relative to the isotropic value and becomes $\leq 10^{52}$ ergs (see Table 2).

Recent observations suggest that GRBs are associated with stellar deaths, and not with 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 (cf. Bloom et al. 2000). However, release of energies as large as ~ 10^{53} erg or more in radiation is extremely difficult to accommodate within the popular stellar death models (coalescence of neutron stars or the death of massive stars). However, evidence is now mounting in favour of non-isotropic emission. Thus, it is possible that all cases where the inferred isotropic equivalent energy is large, the emission actually is confined within narrow jets, with total energy much below the isotropic equivalent. The γ–ray energy released then becomes $\leq 10^{52}$ erg, a value within the reach of the currently popular models for the origin of GRBs (see Piran 1999 and references therein).

The intrinsic visual extinction ($A_V \sim 1.1$ mag) derived for the GRB 000926 afterglow (see Sagar et al. 2001) also carries a possible clue to the class of progenitor objects. Extinction of comparable magnitude have been noticed also in GRB 971214 ($A_V \sim 0.9$ mag, Ramaprakash et al. 1998 and references therein); GRB 980329 ($A_V \sim 1.2$ mag, Palazzi et al. 1998); GRB

980703 ($A_V \sim 0.8 - 1.2$ mag, Vreeswijk et al. 1999) and GRB 000418 ($A_V \sim 1.0$ mag, Klose et al. 2000). The presence of dust extinction in the host galaxies broadly supports the proposal that GRBs could be associated with massive stars embedded in star-forming regions of the GRB host galaxies (Paczyński 1998).

8. Conclusions

India has contributed in the observations of emissions from both GRBs and their afterglows. GRB emissions have been observed from 51 events so far. Indian Scientificc GRB experiment on SROSS-C2 is still working as a part of IPN. Out of 14 GRB fields imaged from Nainital, successful optical observations have been obtained for 5 GRB afterglows. In the case of GRB 000301C, earliest optical observations have been carried out from India. Light curves of these GRB afterglows are discussed in the context of the GRB origin. The steepening in the light curves occurred generally within 2 to 2.5 days after the burst, except for GRB 000301C. The overall flux decays observed in light curves of all GRB afterglows discussed here are well understood in terms of a jet model. However, in the case of GRB 000926, a much steeper late decay of X-ray flux with $\alpha = 4.3\pm1$ and ~ 5, while the spectral index is the same (~ 0.8), as reported by Piro & Antonelli (2000) and Garmire et al. (2000) respectively is not consistent with the simple jet model which predicts similar late flux decay in both optical and X-ray regions. Another area of possible disagreement with the standard fireball model is the sharpness of the break in the light curve. While the expected sharpness of the transition could depend on the density profile of the ambient medium (Kumar & Panaitescu 2000), the very sharp transitions seen in GRB 000301C and GRB 000926 would be difficult to quantitatively explain in the standard fireball model. This is an area that deserves a detailed theoretical study.

The peculiarity in the light curves of GRB 000301C seems to be due to superposition of a short term achromatic variability over a large frequency range on the overall steepening in the flux of the GRB 000301C. The late time flux decays at X-ray and optical wavelengths seem to be significantly different for GRB 000926 afterglow. Similarly, the flux decays of GRB 991216 afterglow (cf. Frail et al. 2000) are also different at X-ray, optical and radio wavelengths. 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.

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. Multi-wavelength follow-up observations of GRB afterglows obtained so far, though they are mostly after few hours of the burst, clearly indicate that long duration GRBs are produced from stellar-like systems e.g. merging remnants or explosions of massive stars. 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. The High Energy Transit Explorer launched last year is expected to make the desired observations possible as it will provide the accurate positions of both short and long durations GRBs within a few minutes of the burst. India can therefore contribute, mainly due to its advantage of geographical location, significantly in the follow-up observations of the GRB afterglows.

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