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Optical and radio observations of the bright GRB 010222 afterglow: evidence for rapid synchrotron cooling?

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Abstract. We report photometric observations of the optical afterglow of GRB 010222 in V, R and I passbands carried out between 22–27 February 2001 at Nainital. We determine the CCD Johnson BV and Cousins RI photometric magnitudes for 31 stars in the field of GRB 010222 and use them to calibrate our measurements as well as other published $BVRI$ photometric magnitudes of the GRB 010222 afterglow. We construct the light curve of the afterglow emission in B, V, R and I passbands, and from a broken power-law fit determine the early and late time power-law flux decay indices as 0.74±0.05 and 1.35±0.04 respectively. Steepening in the flux decay seems to have started around 0.7 day after the burst. Negligible Galactic extinction amounting $E(B-V) = 0.023$ mag is derived in the direction of the GRB. We derive the value of the spectral index in the X-ray to optical region to be 0.61±0.02 and 0.75±0.02 at $\Delta t = 0.35$ and 9.13 day. We attempted radio observations of the afterglow from RATAN-600 telescope during 23–26 February 2001 and from the Giant Metrewave Radio Telescope on 8 March 2001, yielding upper limits of ~ 5 mJy at 3.9 GHz and ~ 1 mJy at 610 MHz respectively. The millimeter wave observations obtained with the IRAM Plateau de Bure Interferometer during 24 and 25 February 2001 and 16 March 2001 at 93 GHz and 230 GHz also indicate no flux detection from the afterglow. The light curve and the spectrum indicate that the synchrotron cooling frequency lies in the sub-millimeter region, which also explains the observed sub-millimeter excess. Attributing the observed break in the light curve to the sideways expansion of collimated ejecta, we estimate a jet opening angle of $\sim 2.0n^{1/8}$ deg.

Keywords : Photometry – Radio observations – GRB afterglow – flux decay – spectral index

1. Introduction

GRB 010222 was detected simultaneously by the Gamma Ray Burst Monitor (40–700 keV) and Wide Field Camera Unit 1 (2–28 keV) instruments aboard Beppo-SAX on 2001 February 22 at 07:23:30 UT (Piro 2001). In the Beppo-SAX error box, the optical transient (OT) was detected at $\alpha_{2000} = 14^h52^m12.^s6; \delta_{2000} = +43°01'06.''4$ independently by Henden (2001a) and McDowell et al. (2001). Coincident with the OT, Gandolfi et al. (2001) detected bright afterglow in 1.6–10 keV range about 9 hours after the burst by Beppo-SAX TOO observations. Light curve and spectral index in the $X-$ray region have been presented by in 't Zand et al. (2001). Berger & Frail (2001) detected a radio source at 22 GHz at the OT location with flux of 0.7±0.15 mJy on 2001 February 22.62 UT. Fich et al. (2001) detected 850 μm sub-millimeter flux of 4.2±1.2 mJy at the same location. Near-IR J and K band observations of the GRB afterglow have been reported by Di Paola et al. (2001). A spectrum of the OT taken about 5 hours after the burst by Garnavich et al. (2001a) reveals a blue continuum with many superposed features corresponding to metal absorption lines at $z = 1.477$, 1.157 and possibly at 0.928 (Jha et al. 2001). The existence of 3 absorption systems has been confirmed by low resolution spectra taken with Keck-I 10-m telescope (Bloom et al. 2001) and 3.58-m Telescopio Nazionale Galileo (Masetti et al. 2001) as well as by high resolution spectra obtained on 2001 February 23.61 UT with Keck-II 10-m telescope (Castro et al. 2001). Absorption at $z = 1.4768 \pm 0.0002$ appears to be associated with the host galaxy, while $z = 1.1561 \pm 0.0001$ and 0.9274 ± 0.0001 are typical for foreground systems at comparable redshifts (Jha et al. 2001; Masetti et al. 2001).

The Sloan Digital Sky Survey multi-colour observations taken about 5 hours after the burst have been reported by Lee et al. (2001). The optical and near-IR photometric light curves along with broad-band spectral energy distribution have been studied by Cowsik et al. (2001), Masetti et al. (2001) and Stanek et al. (2001c). Henden (2001b) presents $UBVRI$ photometric calibration for the GRB 010222 field region. However, the value of $R = 17.175 \pm 0.015$ mag assigned to star **A** by Henden (2001b) differs significantly from the value of 17.42 ± 0.01 mag obtained by Valentini et al. (2001). We therefore imaged a number of standard regions of Landolt (1992) along with the field of GRB 010222 for providing accurate photometric magnitudes of the OT. A total of 31 stars in the field have been calibrated and their standard $BVRI$ magnitudes are given here. We present the details of our optical observations in the next section. Our millimeter and radio measurements and discussion of the light curves and other results are given in the remaining sections.

Table 1. Log of CCD photometric observations of GRB 010222 and of Landolt (1992) PG and SA standard fields

Date	Field	Filter	Exposure (in seconds)
22/23 Feb 2001	PG 1047+003	*V*	60
22/23 Feb 2001	PG 1047+003	*R*	30
22/23 Feb 2001	PG 1047+003	*I*	30
22/23 Feb 2001	PG 1323-086	*V*	40
22/23 Feb 2001	PG 1323-086	*R*	20
22/23 Feb 2001	PG 1323-086	*I*	20
22/23 Feb 2001	PG 1530+057	*V*	100
22/23 Feb 2001	PG 1530+057	*R*	40
22/23 Feb 2001	PG 1530+057	*I*	40
22/23 Feb 2001	PG 1633+099	*V*	60
22/23 Feb 2001	PG 1633+099	*R*	30
22/23 Feb 2001	PG 1633+099	*I*	30
22/23 Feb 2001	GRB 010222	*R*	300×3, 600×2
22/23 Feb 2001	GRB 010222	*V*	600×2
22/23 Feb 2001	GRB 010222	*I*	300×2, 600×2
23/24 Feb 2001	GRB 010222	*R*	300×2
26/27 Feb 2001	GRB 010222	*B*	720
26/27 Feb 2001	GRB 010222	*V*	600
26/27 Feb 2001	GRB 010222	*R*	600×3
26/27 Feb 2001	GRB 010222	*I*	600
26/27 Feb 2001	SA 104	*B*	120
26/27 Feb 2001	SA 104	*V*	60
26/27 Feb 2001	SA 104	*R*	30
26/27 Feb 2001	SA 104	*I*	30
26/27 Feb 2001	PG 1047+003	*B*	120×4
26/27 Feb 2001	PG 1047+003	*V*	60×4
26/27 Feb 2001	PG 1047+003	*R*	30×4
26/27 Feb 2001	PG 1047+003	*I*	30×4

2. Optical observations, data reduction and calibrations

The optical observations of the GRB 010222 afterglow were carried out during 2001 February 22 to 27. We used a 2048 × 2048 pixel^2 CCD system attached at the f/13 Cassegrain focus of the 104-cm Sampurnanand telescope of the State Observatory, Nainital. One pixel of the CCD chip corresponds to $0.''38$, and the entire chip covers a field of $\sim 13' \times 13'$ on the sky. The CCD observations of the GRB 010222 field along with Landolt (1992) standard regions have been carried out for calibration purposes during photometric sky conditions. The log of CCD observations is given in Table 1. In addition to these observations, several twilight flat field and bias frames were also observed.

The CCD frames were cleaned using standard procedures. Image processing was done using ESO MIDAS and DAOPHOT softwares. Atmospheric extinction coefficients were determined from the observations of the brightest star present in the standard fields and these were used in further analysis. Standard magnitudes of 27 stars in the standard fields were taken from Landolt (1992). They cover a wide range in colour ($-0.3 < (V-I) < 1.7$) as well as in brightness ($12.1 < V < 16.1$). The transformation coefficients were determined by fitting least square linear regressions to the aperture instrumental magnitudes as function of the standard *BVRI* photometric indices. The following colour equations were obtained for the system.

$$\Delta b_{CCD} = \Delta B - (0.03 \pm 0.01)(B-V)$$
$$\Delta v_{CCD} = \Delta V - (0.04 \pm 0.01)(V-R)$$
$$\Delta r_{CCD} = \Delta R - (0.02 \pm 0.002)(V-R)$$
$$\Delta i_{CCD} = \Delta I - (0.075 \pm 0.002)(R-I)$$

where $\Delta b_{CCD}, \Delta v_{CCD}, \Delta r_{CCD}$ and Δi_{CCD} represent the differential instrumental magnitudes. The errors in the zero points are ~ 0.02 mag in B, V, R and I passbands.

For increasing the photometric precision of fainter stars, the data are binned in 2×2 pixel^2 and also all the CCD images of GRB 010222 field taken in R on 23/24 and 26/27 February 2001 are co-added in the same filter. From these images, profile-fitting magnitudes are determined using DAOPHOT software. The standard magnitudes of the stars are determined using the above transformations. *BVRI* photometric magnitudes of 31 stars in the GRB 010222 field are listed in Table 2. Fig. 1 shows the location of the GRB 010222 afterglow and the photometered stars on a CCD image taken by us.

The present *BVRI* magnitudes are compared with those determined by Henden (2001b) in Fig. 2. There are 26 stars common between the two data sets. They range in brightness from $V = 14.3$ to 18.5 mag. There is no trend in Δ except a constant offset which can be understood in terms of zero-point errors in the two photometries. We can therefore conclude that present and Henden (2001b) photometric calibrations are secure and calibration carried out by Valentini et al. (2001) may be in error.

The magnitude of the OT of GRB 010222 determined by us are given in Table 3. A comparison of these with those determined independently from our CCD images by Henden et al. (2001c) indicates agreement well within the zero-point uncertainties of the two photometric calibrations. The magnitudes listed in Table 2 have also been used for calibrating other photometric measurements of GRB 010222 afterglow published in the GCN circular by Holland et al. (2001), Oksanen et al. (2001), Orosz (2001), Price et al. (2001), Stanek & Falco (2001), Stanek et al. (2001a, b), Valentini et al. (2001), Veillet (2001a, b), Watanabe et al. (2001) and Garnavich et al. (2001b) by the time of paper submission. In order to avoid errors arising due to different photometric calibrations, we have used only those published *UBVRI* photometric measurements whose magnitudes could be determined relative to the stars given in Table 2 or by Henden (2001b). The optical and near-IR magnitudes published by Cowsik et al. (2001) and Masetti et al. (2001) along with the Sloan Digital Sky Survey observations presented by Lee et al. (2001) have also been used in our analysis. The photometric calibrations given by Fukugita et al. (1995) are used to

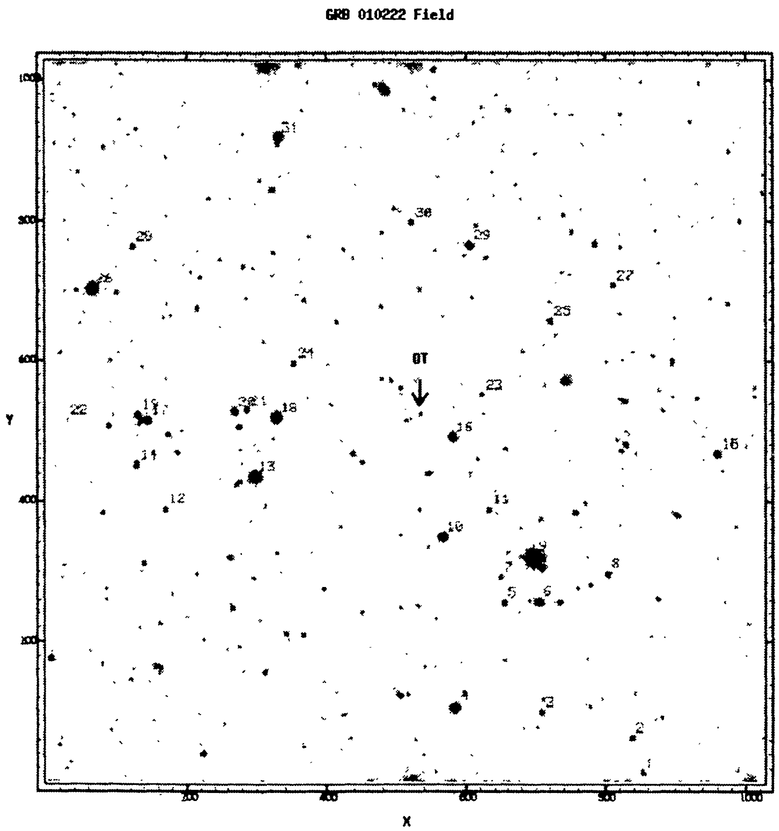

Figure 1. Finding chart for GRB 010222 field is produced from the CCD image taken by us on 2001 February 22.9 UT in R filter with exposure time of 10 minutes. The optical transient (OT) and the stars with present $BVRI$ magnitudes are marked. The (X,Y) are the pixel coordinates and the corresponding sky coordinates are $\Delta\alpha = 767.2\pm0.8 + (0.004\pm0.001)X - (1.038\pm0.001)Y$ and $\Delta\delta = -308.8\pm0.6 + (0.760\pm0.001)X + (0.001\pm0.001)Y$, where $\Delta\alpha$ and $\Delta\delta$ are offsets in arcsec with respect to RA=14^h 52^m and Dec=43 deg respectively.

convert the Sloan data into the Johnson UB and Cousins RI system. All these in combination with our observations provide a dense coverage of photometric observations of GRB 010222 afterglow in R passband.

3. Optical photometric light curves

We have used the published data in combination with our measurements to study the optical flux decay of GRB 010222 afterglow in $BVRI$ photometric passbands. Fig. 3 shows a plot of the photometric measurements as a function of time. The X−axis is log $(t - t_0)$ where t is the time

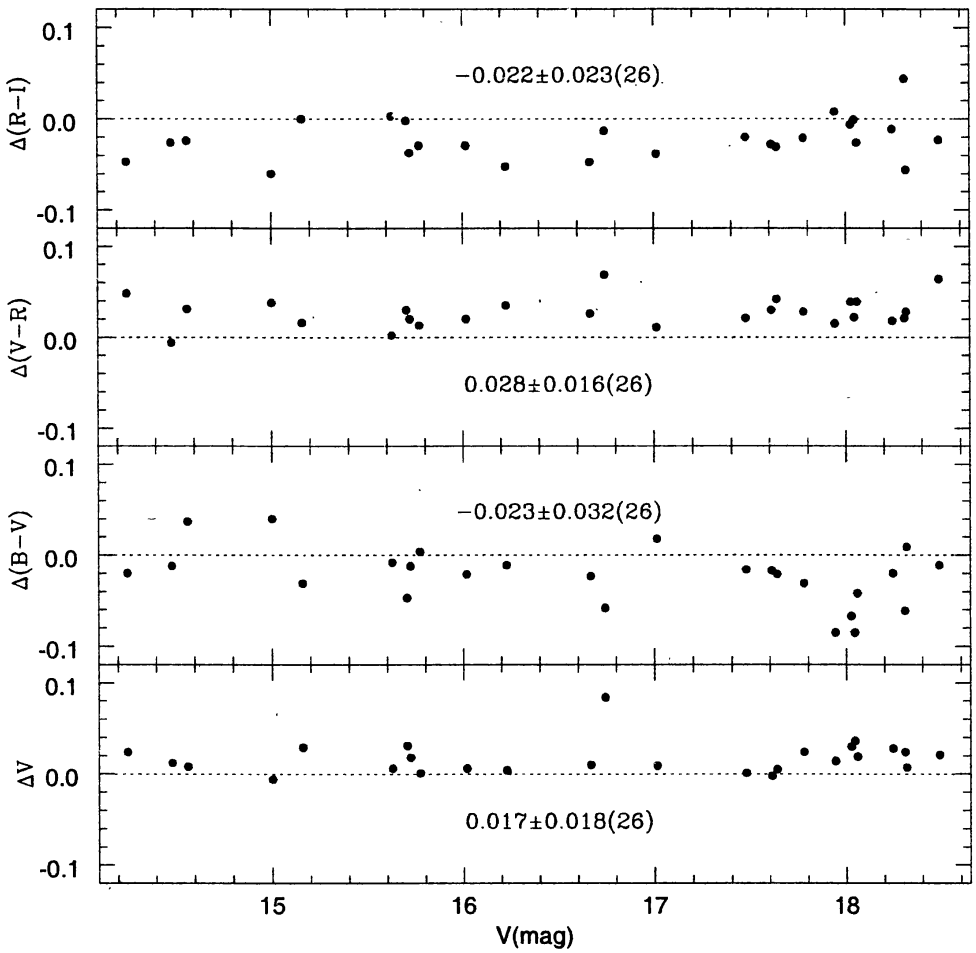

Figure 2. A comparison of our *BVRI* photometry in the field of GRB 010222 with data given by Henden (2001b). The differences (Δ) are Henden minus present, plotted against the present CCD photometry. The mean value of Δ along with number of data points (inside the bracket) are indicated on each panel. Dotted lines represent $\Delta = 0$.

of observation and t_0 (= 2001 February 22.308 UT) is the time of GRB trigger. All times are measured in unit of day.

The emission from GRB 010222 OT is fading in all B, V, R and I passbands. As noted by Masetti et al. (2001) and Holland et al. (2001), the optical light curves of GRB 010222 (Fig. 3) can not be fitted by a single power-law of type $F(t) \propto (t - t_0)^{-\alpha}$, where $F(t)$ is the flux of the afterglow at time t and α is the flux decay constant. Overall the OT 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). There is no signature of flattening due to contamination of background galaxy in any light curve though a number of galaxies are visible within $10''$ of the OT (cf. Garnavich et al. 2001b). As the galaxies are located more than $4''$ away from the GRB

Table 2. Standard $V, (B-V), (V-R)$ and $(R-I)$ photometric magnitudes of the stars in the region of GRB 010222. Right Ascension (α) and Declination (δ) are for epoch 2000. Star 16 and 24 are the comparison stars A mentioned by Henden (2001b).

Star	α_{2000}	δ_{2000}	V	$(V-R)$	$(R-I)$	$(B-V)$
1	$14^h\,52^m\,48.^s00$	$43°\,05'\,07.''2$	18.36	0.82	0.78	1.34
2	14 52 44.60	43 04 55.6	18.18	0.40	0.42	0.75
3	14 52 42.04	43 03 17.9	17.85	0.34	0.42	0.64
4	14 52 41.52	43 01 43.8	15.16	0.39	0.44	0.72
5	14 52 31.23	43 02 37.4	17.64	0.31	0.41	0.57
6	14 52 31.13	43 03 15.0	15.63	0.35	0.38	0.60
7	14 52 28.69	43 02 33.2	18.03	0.50	0.50	0.96
8	14 52 28.39	43 04 29.9	17.01	0.24	0.31	0.38
9	14 52 26.77	43 03 08.8	12.55			0.67
10	14 52 24.71	43 01 30.7	15.70	0.78	0.74	1.37
11	14 52 22.08	43 02 20.4	18.31	0.90	1.01	1.48
12	14 52 21.87	42 56 29.2	18.06	0.41	0.44	0.78
13	14 52 18.67	42 58 06.9	13.93	0.43	0.40	0.75
14	14 52 17.31	42 55 58.1	17.94	0.84	0.87	1.45
15	14 52 16.64	43 06 29.1	16.23	0.33	0.41	0.57
16	14 52 14.83	43 01 41.5	14.56	-0.15	-0.12	-0.22
17	14 52 13.09	42 56 09.8	15.72	0.48	0.49	0.93
18	14 52 12.81	42 58 29.7	14.48	0.33	0.35	0.54
19	14 52 12.56	42 55 59.3	16.67	0.40	0.48	0.75
20	14 52 12.22	42 57 44.9	16.02	0.36	0.39	0.67
21	14 52 12.09	42 57 58.0	17.48	0.58	0.50	1.05
22	14 52 11.69	42 54 57.3	18.60	0.55	1.97	1.64
23	14 52 10.67	43 02 12.7	18.49	0.54	0.53	0.99
24	14 52 07.54	42 58 48.7	17.61	0.41	0.44	0.78
25	14 52 03.40	43 03 27.1	17.78	0.84	0.84	1.44
26	14 52 00.09	42 55 10.3	14.25	0.32	0.39	0.63
27	14 51 56.98	43 04 35.9	18.32	0.24	0.32	0.38
28	14 51 55.95	42 55 54.0	18.24	0.96	1.12	1.56
29	14 51 55.95	43 02 00.2	15.77	0.34	0.38	0.61
30	14 51 53.71	43 00 56.5	18.04	0.91	0.96	1.54
31	14 51 45.17	42 58 31.7	15.00	0.31	0.36	0.50

010222 afterglow, it appears that they have not contaminated the photometric measurements of the OT appreciably. However, possibility of some light contamination can not be ruled out. We have therefore empirically fitted the following type of broken power-law in these light curves (see Sagar et al. 2000b and references therein for details)

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

Table 3. V, R and I magnitudes of GRB 010222 OT along with epochs of observations

Middle UT (day)	filter	Magnitude±error
2001 Feb 22.911	R	19.48±0.02
2001 Feb 22.921	R	19.59±0.02
2001 Feb 22.930	R	19.66±0.02
2001 Feb 22.938	I	19.07±0.03
2001 Feb 22.949	I	19.14±0.03
2001 Feb 22.990	V	20.05±0.02
2001 Feb 22.999	V	20.09±0.02
2001 Feb 23.005	R	19.80±0.02
2001 Feb 23.010	R	19.70±0.03
2001 Feb 23.015	I	19.24±0.04
2001 Feb 23.020	I	19.28±0.06
2001 Feb 23.870	R	20.77±0.35
2001 Feb 26.911	R	22.2 ±0.10

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. In collimated fireball models, an achromatic break in the light curve of the afterglow is expected when the jet makes the transition to sideways expansion after the bulk Lorentz factor drops below the inverse of the initial opening angle of the beam (cf. Rhoads 1999).

We use the dense temporal observations in R to determine the parameters of the jet model using the above function. In order to avoid a fairly wide range of model parameters for a comparable χ^2 due to degeneracy between t_b, m_b and m_g (magnitudes corresponding to F_0 and F_g respectively), α_1, α_2 and s, we have used fixed values of s in our analyses and find that the minimum value of χ^2 is achieved around $s = 4$. This indicates that the observed break in the light curve is sharp, unlike the smooth break observed in the optical light curve of GRB 990510 (cf. Stanek et al. 1999; Harrison et al. 1999) but similar to the sharp break observed in the optical light curves of GRB 000301C (cf. Berger et al. 2000, Sagar et al. 2000b) and GRB 000926 (cf. Harrison et al. 2001, Sagar et al. 2001). The least square fit values of the parameters t_b, m_b, α_1, and α_2 are 0.71±0.07 day, 19.73±0.12 mag, 0.76±0.03 and 1.37±0.02 respectively in R band, with a corresponding χ^2 of 1.87 per degree of freedom (DOF). The relatively large value of χ^2 possibly results from slight underestimate of systematic errors between different data sources used in this paper. The fit yields the constant contaminating flux to be m_g=26±1 mag in R, indicating that there is little contribution from the host or nearby galaxies (Garnavich et al. 2001b) to the photometric measurements of the GRB 010222 afterglow till at least a week after the burst. We therefore ignore the constant flux term in fitting the B, V and I light curves. The available data in these passbands are sparse and also insufficient for determining t_b independently. Following Masetti et al. (2001) and Stanek et al. (2001c), we then assume that the break occurs at the same

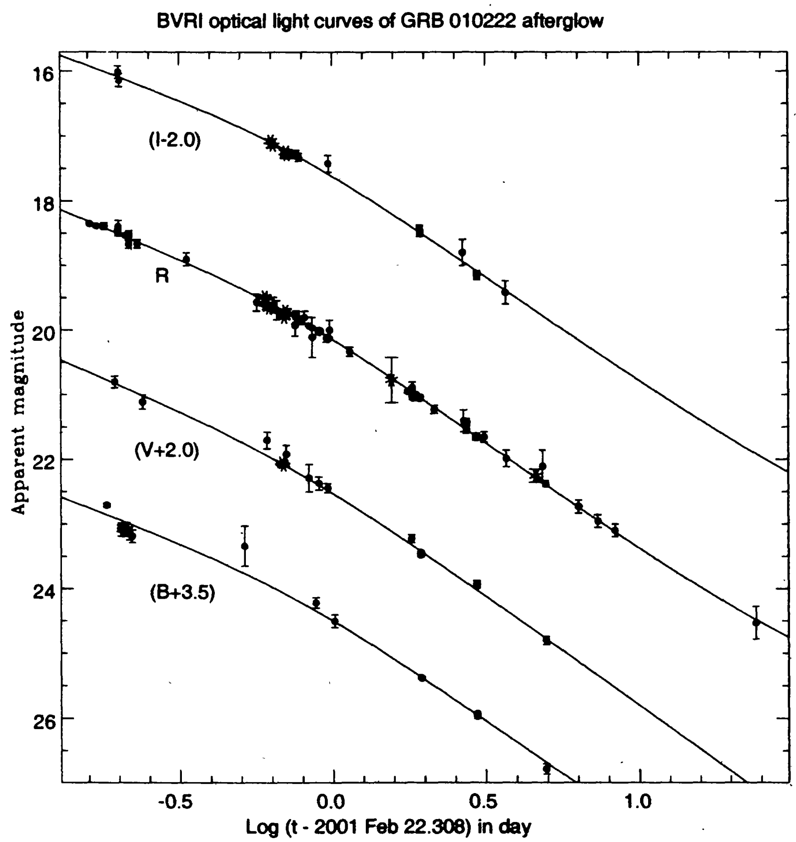

Figure 3. Light curve of GRB 010222 afterglow in optical B, V, R and I photometric passbands. Present measurements have been indicated as asterisk. Suitable offsets have been applied to avoid overlapping in data points of different passbands. Flux decay can not be fitted by a single power-law. Solid lines represent the least square non-linear fit for jet models (see text). In all cases, the value of sharpness is taken as 4.

time in all the bands, and use the data to determine the decay slopes. A fit with fixed $s = 4$ and $t_b = 0.71$ day to the B light curve yields α_1=0.72±0.03, α_2=1.31±0.03 with a χ^2/DOF of 4.0; to the V light curve yields α_1=0.79± 0.05, α_2=1.35±0.01 with a χ^2/DOF of 2.0 while such a fit in the I light curve yields $\alpha_1 = 0.69 \pm 0.06$, $\alpha_2 = 1.33 \pm 0.02$ with a χ^2/DOF of 0.9. The best fit light curves obtained in this way are shown in Fig. 3 for all passbands. It can be seen that our own observations follow the fitted curves very well. Present observations taken on 22/23 February 2001 are around t_b while those taken on other epochs fill gaps in the R light curve. They are thus valuable for the study of flux decay of the OT.

In the light of above, we conclude that the values of t_b, α_1 and α_2 derived from the $BVRI$ light curves are 0.7±0.07 day, 0.74±0.05 and 1.35±0.04 respectively. The late time flux decay constant is in excellent agreement with the corresponding value of 1.33±0.04 at X−ray wavelength (in 't Zand 2001). They also agree very well with the values of t_b = 0.72±0.1 day, $\alpha_1 = 0.80 \pm 0.05$ and $\alpha_2 = 1.30 \pm 0.05$ given by Stanek et al. (2001c). However, Cowsik et al.

(2001) and Masetti et al. (2001) have derived some what earlier time for break with $t_b = 0.43 \pm 0.1$ day and 0.48 ± 0.02 day respectively. The values of α_1 derived by them are 0.6 ± 0.01 while those of α_2 are 1.24 ± 0.01 and 1.31 ± 0.03 respectively.

4. Radio and millimeter observations of the GRB 010222 afterglow

We attempted radio and millimeter observations of the GRB 010222 afterglow using the RATAN-600 telescope during 23–26 February 2001; the Giant Metrewave Radio Telescope (GMRT) on 8 March 2001 and with the IRAM Plateau de Bure Interferometer in a compact five antenna configuration during February 24.94 - 25.11 UT and March 16.14 - 16.40 UT.

At RATAN-600 telescope, observations were carried out at 0.96, 2.3, 3.9, 7.7, 11.2 and 21.7 GHz using the northern sector antenna with an effective collecting area $\sim$ 1000 m^2. Drift scans were obtained at the upper culmination of the source, and flux density calibration was performed using observations of 3C 286 and NGC 7027. The best sensitivity was at 3.9 GHz, with a noise level of 5 mJy for a single scan. Three scans were averaged and no detectable signal was found at the GRB location, giving a 3-σ upper limit of $\sim$ 10 mJy at 3.9 GHz.

At GMRT (see Swarup et al. 1991 for a description of the telescope) a $\sim 40' \times 40'$ field centered on the OT location was imaged at 617 MHz by an 8-hour synthesis on 8 March 2001. The resolution was about $10''$ and the map sensitivity was about 0.25 mJy (the image can be viewed at `http://www.ncra.tifr.res.in/~pramesh/images/GRB01222_8mar2001_610MHz.gif`). No compact emission was seen at the location of the OT, and we can place a firm upper limit of 1 mJy on the afterglow flux on this day.

At the IRAM Plateau de Bure Interferometer, weather conditions were good for observations at 3mm but marginal for 1mm. The flux calibration is relative to source CRL 618 (1.55 Jy at 3mm and 2 Jy at 1mm) and is accurate to about 10%. The source was not detected in any of the two observations within the primary beam. UV fits on the phase center give the following upper limits (fit errors are one sigma) after the correction for atmospheric decorrelation.

(i) During 24 February 2001 UT 22:34 to 25 February 2001 UT 2:38 the flux values are -0.49 ± 0.32 mJy/beam at 93.109 GHz with a synthesized beam of size $9.3'' \times 5.2''$ at position angle of -57 degrees while the flux values are -0.09 ± 1.6 mJy/beam at 232.032 GHz with beam size of $3.6'' \times 2.3''$ at position angle of -46 degrees.

(ii) During UT 3:18 to 9:43 on 16 March 2001, the fluxes are -0.42 ± 0.23 mJy/beam at 93.109 GHz and -4.57 ± 1.5 mJy/beam at 227.239 GHz for the beam sizes of $9.5'' \times 4.9''$ at position angle of 56 degrees and $3.2'' \times 2.0''$ at position angle of 57 degrees.

5. Spectral index of the GRB 010222 afterglow

We have constructed the GRB 010222 afterglow spectrum at three epochs: Δt = 0.35, 0.77 and 9.13 day corresponding to before, around and after t_b respectively. The epochs were selected for the long wavelength coverage possible at the time of X−ray and near-IR observations. UJK data borrowed from Masetti et al. (2001) and $BVRI$ data along with decay slopes presented in Fig. 3 were used to derive the fluxes at the corresponding wavelengths for the epochs under consideration. The fluxes at 22, 220 and 350 GHz are taken from Berger & Frail (2001), Kulkarni et al. (2001) and Fich et al. (2001) respectively. We used the reddening map provided by Schlegel et al. (1998) for estimating Galactic interstellar extinction towards the burst and found a small value of $E(B-V) = 0.023$ mag. We used the standard Galactic extinction reddening curve given by Mathis (1990) in converting apparent magnitudes into fluxes and used the effective wavelengths and normalisations by Fukugita et al. (1995) for $UBVR$ and I and by Bessell & Brett (1988) for J and K. The fluxes thus derived are accurate to $\sim$ 15% in optical and $\sim$ 25% in JK. Fig. 4 shows the spectrum of GRB 010222 afterglow from X−ray to radio region. It is observed that at an epoch as the frequency decreases the flux increases from X−ray to radio wavelengths. For a chosen frequency interval, we describe the spectrum by a single power law: $F_\nu \propto \nu^{-\beta}$, where F_ν is the flux at frequency ν and β is the spectral index.

The spectra at $\Delta t = 9.13$ and 0.35 day correspond to epochs of X−ray flux measurement by Harrison et al. (2001) and in 't Zand et al. (2001) respectively. The corresponding values of β derived from observed flux values in X−ray and optical regions are 0.75 ± 0.02 and 0.61 ± 0.02 respectively. Fig. 4 indicates that these values fit the data very well. We therefore conclude that the values of β have not varied significantly during the two epochs under discussion. When we extend the line corresponding to $\Delta t = 0.35$ day to radio region, then the flux at 350 GHz fall close to this line while fluxes at $\nu < 220$ GHz are well below the line indicating that the peak frequency may lie in the millimeter region of the spectrum. This peak frequency is thus similar to that of GRB 970508 (cf. Galama et al. 1998), GRB 000301C (cf. Sagar et al. 2000b) and GRB 000926 (cf. Sagar et al. 2001) but different from that of GRB 971214 for which the peak is in optical/near-IR waveband (Ramaprakash et al. 1998).

In the optical to near-IR region at $\Delta t = 0.77$ day, the value of β is 0.83±0.13 which agrees within error with the values of 0.89±0.03 and 0.90±0.03 derived about 5 hours after the burst by Jha et al. (2001) and Lee et al. (2001) in the optical region. All these in agreement with Masetti et al. (2001), perhaps, indicate no appreciable change in the optical to near-IR spectral slope of GRB 010222 afterglow till $\Delta t < 5$ day. However, the values of β at $\Delta t = 0.35$ and 9.13 day derived from observed fluxes in X−ray and optical region are somewhat smaller than those derived from optical to near-IR region. The discrepancy is even larger with the value of 1.1±0.1 or larger quoted by Masetti et al. (2001). Fig. 4 shows that at $\Delta t = 0.77$ day, the fluxes corresponding to U, J and K passbands deviate significantly from the linear relation. Both Masetti et al. (2001) and Lee et al. (2001) consider presence of intrinsic extinction due to host galaxy as a possible reason for this discrepancy. This as well as the relatively small wavelength coverage between optical to near-IR region makes the determination of β somewhat uncertain. On the other hand, β derived from X−ray to optical fluxes is accurately determined due to long wavelength coverage.

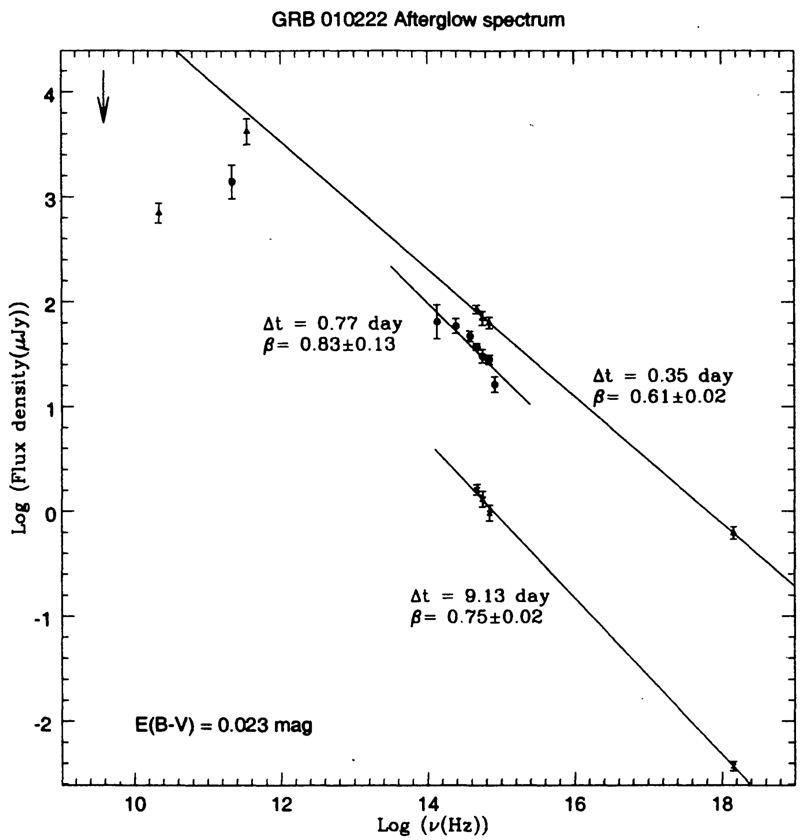

Figure 4. The spectral flux distribution of the GRB 010222 afterglow at ~0.35, 0.77 and ~9.13 day after the burst. Arrow denotes the upper limit derived by us at 3.9 GHz on 2001 February 23. The least square linear relations derived using fluxes at *UBVRI* optical and *JK* near-IR for $\Delta t = 0.77$ day while the fluxes at X−ray and optical *BVR* for $\Delta t = 9.13$ and 0.35 day are shown by solid lines. Crosses, filled circles and triangles denote points corresponding to $\Delta t = 9.13$, 0.77 and 0.35 day respectively.

We therefore consider only the values of β derived at Δt = 0.35 and 9.13 day in our further discussions.

6. Discussions and Conclusions

GRB 010222 afterglow is rather unusual in exhibiting a relatively slow broken power-law decay of the light curve accompanied with flat spectral index. Typically the decay indices observed in such other well observed GRB afterglows are ~ 1 before the break and ≥ 2 after the break (GRB 980519, Jaunsen et al. 2001; GRB 990123, Castro-Tirado et al. 1999, Kulkarni et al. 1999, Sagar et al. 1999; GRB 990510, Stanek et al. 1999; GRB 990705, Masetti et al. 2000a; GRB 991208, Castro-Tirado et al. 2001, Sagar et al. 2000a; GRB 991216, Halpern et al. 2000, Sagar et al. 2000a; GRB 000301C, Masetti et al. 2000b, Sagar et al. 2000b; GRB 000926, Sagar et al. 2001;

and see also Sagar 2001). In the case of this GRB, however, the decay index is ~ 0.7 before and ~ 1.4 after the break. This unusual behaviour has prompted Masetti et al. (2001) to conjecture that the break observed in GRB 010222 afterglow is caused not by traditional sideways expansion but by the transition of the expansion from relativistic to non-relativistic regime.

Our determination that the X-ray to optical spectral index of the afterglow has a value $\beta \leq 0.75$, significantly smaller than that quoted by Masetti et al. (2001), however, affords a different explanation of the behaviour of the OT. If we attribute the break in the light curve to the traditional sideways expansion of the jet, then the decay index after the break is expected to be p, which is the index of the power-law energy distribution of the electrons (Rhoads 1999). We notice then that $\beta \sim p/2$, a relation that obtains at frequencies above the synchrotron cooling frequency ν_c. This would suggest that ν_c is below the optical band but above ν_m after the break. We then find that the same spectral regime describes the light curve well even before the break. The observed decay index of $\alpha_1 =\sim 0.7$ fits nicely with the expected value of $(3p-2)/4$ (Sari et al. 1998; Rhoads 1999).

The behaviour of the light curve is therefore well modelled by having the synchrotron cooling frequency below the optical range but above ν_m for nearly the entire range of observations, and attributing the break at ~ 0.7 days to the sideways expansion of the jet. Such a low value of cooling frequency so early in the evolution (at $t < 0.5$ day) is certainly unusual, and indicates the presence of a very strong postshock magnetic field.

In the above discussion we have tacitly assumed that the expressions for light curve evolution derived in the literature (cf. Sari et al. 1998; Rhoads 1999) apply to the case of GRB 010222 afterglow without modification. However, these expressions are derived assuming $p > 2$, while in our interpretation of this afterglow $p \sim 1.2 - 1.5$, well below 2. For such a flat spectral distribution, the upper cutoff γ_u of the electron energy distribution becomes important in the estimate of the total energy content, and as described in the accompanying paper by Bhattacharya (2001), a variety of decay laws can be expected depending on the behaviour of γ_u with time. Nevertheless, the decay laws corresponding to $p > 2$ would apply also in this case if $\gamma_u \propto \gamma$, the bulk Lorenz factor of the shock (Bhattacharya 2001). Judging by the behaviour of the GRB 010222 afterglow, this proportionality appears to have been closely followed in the present case.

An interesting consequence of p being less than 2 is that just below the synchrotron 'cooling energy' γ_c the cooling electrons pile up, producing a 'bump' in the energy distribution (cf. Pacholczyk 1970, chapter 6), and a consequent 'excess emission' around ν_c. Such an effect has indeed been noticed in the GRB 010222 afterglow at the sub-millimeter wavelengths (Kulkarni et al. 2001; Ivison et al. 2001; see also Fig. 4). The values of 350 GHz flux at $\Delta t = 0.23$, 1.15 and 2.37 day are 4.2±1.2, 3.6±0.9 and 4.2±1.3 mJy respectively while it becomes undetectable at the level of 0.7±1.1 mJy on $\Delta t = 7.4$ and 8.4 day. In contrast to the bright sub-millimeter emission during $\Delta t < 3$ day, the GRB 010222 afterglow emission is weak or undetectable at millimeter wavelengths (Bremer et al. 2001; Kulkarni et al. 2001; section 4). The location of ν_c in the sub-millimeter region would naturally explain these observations.

The break time t_b can be used to determine the jet opening angle of the afterglow. For this, by combining the observed fluence of $(1.2 \pm 0.03) \times 10^{-4}$ ergs/cm^2 above 2 keV (in 't Zand 2001) with the measured redshift $z = 1.4768 \pm 0.0001$ (Castro et al. 2001; Jha et al. 2001), we derive an 'isotropic equivalent' energy release $E_{\rm iso} \sim 8 \times 10^{53}$ erg (for $H_0 = 65$ km/s/Mpc, $\Omega_0 = 0.2$ and $\Lambda_0 = 0$). Using this value we find, from eq. (44) of Rhoads (1999), the jet opening angle

$$\theta = 2\overset{\circ}{.}0(v_l/c)E_{\rm iso,53}^{-1/8}n^{1/8}$$

where v_l is the lateral expansion speed, $E_{\rm iso,53}$ is the 'isotropic equivalent' energy in units of 10^{53} erg and n is the number density in the circumburst medium.

The peculiarity in the light curve and spectrum of GRB 010222 have been noticed mainly due to multi-wavelength observations obtained during early times within few hours to a day after the burst. Such multi-wavelength observations of recent GRB afterglows (see Sagar 2001) have thus started revealing features which require explanations other than generally accepted so far. We may therefore expect new surprises in GRB afterglows physics, once HETE and other satellites start providing accurate positions of GRB afterglows within few minutes of the burst.

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