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EARLY OBSERVATIONS OF THE AFTERGLOW OF GRB 000301c

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ABSTRACT

We report multiband observations of the optical transient associated with GRB 000301c carried out 2000 March 2–4 using the 2.34 m Vainu Bappu Telescope at Kavalur, India. When combined with other reported data, the initial decline in the R-band magnitude with $\log(t - t_0)$, the time since the burst is fitted with a slope of $\alpha_1 = -0.70 \pm 0.07$, which steepens after about 6.0 days to a slope of $\alpha_2 = -2.44 \pm 0.29$. This change in slope does not occur smoothly, but there is an indication for a bimodal distribution. The available measurements of the evolution of $(B-R)$ color do not show any discernible evolution in the first 12 days.

Subject headings: cosmology: observations — gamma rays: bursts

1. INTRODUCTION

Ever since in a pioneering effort Costa et al. (1997) and van Paradijs et al. (1997) detected the first ever counterpart, associated with GRB 970228, identification of the optical counterparts of gamma-ray bursts (GRBs) and rapid follow-up observations in other wavelength bands have given impetus to GRB astronomy during the last 3 years. The fading counterpart of a GRB, also known as "afterglow," is generally monitored down to the faintest detection limit of a telescope to study its brightness variation as a function of time since the occurrence of the burst event to derive the decay law from the light curve and to try to locate precisely the burst counterpart with respect to the host galaxy, if any has been identified. A study of all the afterglows so far detected shows a diversity of light-curve properties, and it is necessary to accumulate a statistically significant set of such observations for the classification of the bursts and for subsequent theoretical modeling. Two excellent reviews by Kulkarni et al. (2000) and by Piran (1999) provide a clear picture of the current status of this rapidly evolving field of astronomy.

GRB 000301c was detected by the All-Sky Monitor on board the *Rossi X-Ray Timing Explorer* (*RXTE*) on 2000 March 1.4108 UT and also by two other spacecrafts, *Ulysses* and *NEAR*. The burst had a single peak with slow decay structure lasting 10 s and was localized by an error box of area 50 arcmin^2 centered at (J2000) R.A. $= 16^{\rm h}20^{\rm m}21^{\rm s}.5$, decl. $= +29°24'56''.37$ (Smith, Hurley, & Cline 2000). The optical counterpart was first reported by Fynbo et al. (2000a), and the redshift has been measured to be $z = 1.95 \pm 0.1$ by Smette et al. (2000) using the *Hubble Space Telescope* (*HST*) and to be $z = 2.03 \pm 0.003$ by Castro et al. (2000) using the Keck-II telescope. The optical transient (OT) was visible at $R = 27.9 \pm 0.15$ from the late-time *HST* imaging on 2000 April 19 (Fruchter et al. 2000a), but there was no evidence for a host galaxy underlying the GRB to a magnitude ~28.5.

In § 2 we present the details of our observations, data analysis, and results. In § 3 we discuss briefly our conclusions.

2. OBSERVATIONS, ANALYSIS, AND RESULTS

At the 2.34 m Vainu Bappu Telescope (VBT), the follow-up observations in the B, R, and I bands[3] of GRB 000301c began 3 hr after the e-mail notification of the burst event on 2000 March 2. We were able to continue the observations on March 3 and 4 also, as the telescope time was already allotted for our ongoing program on GRBs. Our observations were carried out with a Tek 1024 CCD with 24 × 24 μm pixels positioned at the f/3.25 prime focus of the telescope covering a field of view of about $10' \times 10'$ with an image scale of $0''.61$ pixel^{-1}. The sky conditions were clear with an average seeing of $2''.5$; however, the quality of the acquired data was found to be better on March 2 and 4 compared to those obtained on March 3. The details of the observations along with the magnitudes are summarized in Table 1.

The preprocessing of CCD frames, viz., debiasing, flat-fielding, and removal of cosmic rays, is accomplished in a

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[3] CCD images are available at http://www.iiap.ernet.in/new_results/GRB000301c.html.

TABLE 1
LOG OF THE OBSERVATIONS AT VBT

UT (days)	Filter	Total Exposure (s)	Magnitude of Optical Transient	Magnitude Error	Remarks
Mar 2.9618	*R*	2400	20.02	0.028	4 × 600 s summed
Mar 2.9986	*B*	1200	20.99	0.17	Single frame
Mar 3.9323	*R*	1800	20.45	0.12	3 × 600 s summed
Mar 3.9976[a]	*R*	1200	20.49	0.10	2 × 600 s summed
Mar 3.9694	*I*	3000	20.09	0.10	2 × 600 s + 2 × 900 s
Mar 4.9087	*R*	3600	20.57	0.05	6 × 600 s summed
Mar 4.9799	*B*	1800	21.29	0.12	Single frame
Mar 4.9517	*I*	1800	19.96	0.05	3 × 600 s summed

[a] On March 3, between two sets of R-band observations, sky conditions varied and therefore the frames are combined separately. It may be noted that we have considered the second set in our light-curve plot.

TABLE 2
PHOTOMETRIC DATA FROM LITERATURE

UT (days)	R	Error (R)	Reference
2.930	20.42	0.06	1
2.962	20.02	0.028	2
3.140	20.09	0.04	3
3.144	20.25	0.05	4
3.170	19.94	0.04	5
3.170	20.15	0.04	3
3.190	20.11	0.04	3
3.191	20.11	0.05	6
3.200	20.14	0.05	3
3.205	20.25	0.05	4
3.210	20.14	0.04	3
3.220	20.11	0.05	3
3.240	20.12	0.06	3
3.250	20.16	0.04	3
3.260	20.09	0.08	3
3.270	20.08	0.07	3
3.510	20.28	0.05	7
3.510	20.27	0.04	8
3.510	20.24	0.05	9
3.930	20.53	0.05	10
3.998	20.49	0.1	2
4.038	20.53	0.06	4
4.052	20.46	0.09	11
4.079	20.57	0.06	12
4.140	20.59	0.11	3
4.178	20.22	0.20	6
4.380	20.56	0.05	7
4.390	20.53	0.12	3
4.410	20.44	0.06	3
4.420	20.61	0.06	3
4.430	20.42	0.12	3
4.458	20.54	0.06	13
4.480	20.58	0.04	3
4.490	20.54	0.04	3
4.500	20.61	0.04	14
4.500	20.60	0.04	3
4.520	20.51	0.05	3
4.909	20.58	0.048	2
5.135	20.47	0.07	4
5.230	20.73	0.13	3
5.390	20.61	0.05	3
5.630	20.86	0.04	8
5.960	21.18	0.05	10
6.145	21.60	0.20	6
6.220	21.50	0.15	15
6.390	21.43	0.26	3
6.968	21.70	0.13	4
7.135	21.63	0.15	6
7.220	21.59	0.07	3
7.230	21.62	0.155	3
7.240	21.52	0.08	3
7.650	21.74	0.07	16
7.930	21.95	0.1	1
8.157	21.63	0.1	6
8.180	21.80	0.05	3
8.200	21.88	0.09	3
8.210	21.98	0.08	3
8.250	22.09	0.13	3
8.950	22.13	0.1	1
9.150	22.11	0.15	3
9.200	22.29	0.21	3
9.240	22.10	0.11	3
9.260	22.21	0.155	3
9.520	22.28	0.09	17
10.050	22.34	0.20	3
10.400	22.49	0.30	3
11.21	23.12	0.27	3
11.39	23.12	0.18	3
11.63	23.02	0.1	18
12.44	23.10	0.22	3
14.60	23.82	0.1	19

TABLE 2
(*CONTINUED*)

UT (days)	R	Error (R)	Reference
	$B-R$[a]		
2.975	0.9686	0.207	2
3.162	0.82	0.07	4
3.195	0.94	0.056	3
3.218	0.85	0.13	4
3.51	0.84	0.06	8
4.415	0.74	0.078	3
4.51	0.82	0.056	3
4.52	0.77	0.06	14
4.9375	0.734	0.14	2
5.1435	1.13	0.21	4
6.149	0.80	0.25	4
7.137	0.75	0.212	4
8.195	1.09	0.09	3
9.195	0.9	0.186	3
14.6	1.01	0.12	19

[a] $B-R$ colors used in Fig. 2.

REFERENCES.—(1) Sagar et al. 2000; (2) Bhargavi & Cowsik 2000; (3) Jensen et al. 2000; (4) Masetti et al. 2000; (5) Fynbo et al. 2000b; (6) Bernabei et al. 2000; (7) Garnavich et al. 2000; (8) Veilet & Boer 2000a; (9) Halpern et al. 2000a; (10) Mohan et al. 2000; (11) Castro-Tirado et al. 2000; (12) Gal-Yam et al. 2000; (13) Mujica et al. 2000; (14) Halpern et al. 2000b; (15) Fruchter et al. 2000b; (16) Veilet & Boer 2000b; (17) Halpern & Kemp 2000; (18) Veilet & Boer 2000c; (19) Veilet & Boer 2000d.

standard manner using the IRAF software package. Thereafter the images taken with the same filters are co-added after aligning them. The magnitudes were determined at an aperture of 7″.2 with aperture corrections applied for fainter objects including the OT. Since the average seeing was 2″.5, in some of our R-band exposures the OT is blended with the nearby star A of Garnavich et al. (2000) at a distance of about 6″. In such instances we have also estimated the magnitude of the OT by masking the nearby bright star after fitting a circularly symmetrical Gaussian profile and obtained consistent results.

In the photometric reduction standard methods have been applied; the magnitudes thus estimated have uncertainties less than 0.01 m, and the values agree with those provided by Henden (2000) for some select stars.

3. DISCUSSIONS AND CONCLUSIONS

In the preceding sections we presented our observations and analysis of GRB 000301c afterglow observations using the VBT. In order to place our observations in the context of other observations in the R band, we have collected the data available through GCN circulars and those given by Jensen et al. (2000) inTable 2, who reported the most extensive coverage of the event. Following the standard practice in combining the photometric data obtained by different groups and different instruments, we renormalize all measurements to that of Jensen et al. (2000). The corrections applied to various data sets is shown in Table 3. Notice the correction for our observations at VBT is less than 0.01 m and falls within the uncertainty in the observations.

We attempt to fit the data on intensities in the R band to a

TABLE 3
Magnitude Corrections

Data Set	Magnitude Shift
VBT	−0.009
Masetti et al. 2000	0.088
Bernabei et al. 2000	−0.02
Sagar et al. 2000	0.232
Other GCN data	0.03

TABLE 4
Fit Parameters

Parameter	Value	Error
$I(t_1)$ (μJy)	14.88	1.28
g	0.169	0.30
t_1 (days)	4.12	0.30
t_2 (days)	6.07	0.44
α_1	−0.70	0.07
α_2	−2.44	0.29
χ^2_{65}	1.80	...
Goodness of fit	2.65×10^{-4}	...

time evolution defined by equation (1):

$$I(t) = I(t_1)(t/t_1)^{\alpha_1} \text{ for } t < t_1,$$
$$I(t) = gI(t_1)(t/t_1)^{\alpha_1} + (1-g)I(t_1)(t/t_1)^{\alpha_2} \text{ for } t_1 \leq t < t_2,$$
$$I(t) = [g(t_2/t_1)^{\alpha_1} + (1-g)(t_2/t_1)^{\alpha_2}]I(t_1)(t/t_2)^{\alpha_2} \text{ for } t \geq t_2. \tag{1}$$

This form is motivated by the feature observed in the *R*-band light curve at $t - t_0 \simeq 4.5$ days. This might have been generated by a major burst followed after a short interval by a minor burst, each being represented by a power-law form with a slope α_1, which at later times steepens to a slope α_2. The function given in equation (1) is designed to test this hypothesis. Notice that this function has six parameters—$I(t_1)$, g, t_1, t_2, α_1, and α_2—two more than the functional form adopted by Jensen et al. (2000). The values of the parameters and their 1 σ errors that provide the best fit to the data along with the normalized χ^2 are computed using the Levenberg-Marquardt method (Press et al. 1992) and are listed in Table 4. Notice that our fit for very early and very late times coincides quite closely with the fit obtained by Jensen et al. (2000) and has a $\chi^2_{65} = 1.80$. Even though Jensen et al. (2000) obtain with a single break an excellent fit to their own data, the single-break form fails to reproduce the compilation of world data, which have a slightly closer coverage around the break point at 4–5 days after the burst; the χ^2 they quote for the fit to the world data is 3.687 for $\nu = 88$. After applying the corrections given in Table 3 to the data in Table 2, we fit the single-break form in equation (1) of Jensen et al. (2000) and find that the χ^2_{64} reduces to 1.95 from its value of 2.85 for the same data points when no magnitude corrections are applied. Thus, with suitable corrections for normalizing different photometric data the χ^2 reduces to 1.8 ($\nu = 65$) for the two-break form and to 1.95 ($\nu = 64$) for the single-break form. The improvement on the χ^2 with double break is significant at the 38% level as seen from the *F*-distribution test, although we cannot rule out the fact that the high χ^2 may be due to genuine variations due to inhomogeneities in the medium surrounding the GRB host.

The motivation for the function given in equation (1) is clearly seen in Figure 1. The OT is fit with two events, each of the type where a power-law decay sharply steepens into another power law several days after the burst. The light curve in the *K* band reported by Rhoads & Fruchter (2000) agrees broadly with the fit we have obtained here for the first break (eq. [1]). If their curve is simply extrapolated and compared with the data obtained by Jensen et al. (2000) in the later and fainter epochs, then one may find an apparent color evolution. More accurate photometry with better coverage is needed to confirm and characterize the possible existence of secondary events that may be expected in some supernova-shock models

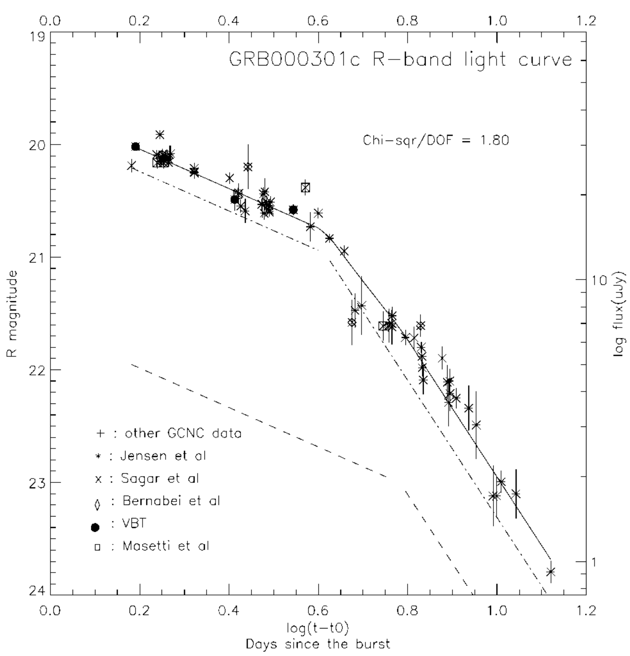

Fig. 1.—GRB 000301c *R*-band light curve. The dotted and dashed lines represent the major and minor burst, which add up to give the light curve shown as a solid line. The data points from VBT are marked by filled circles.

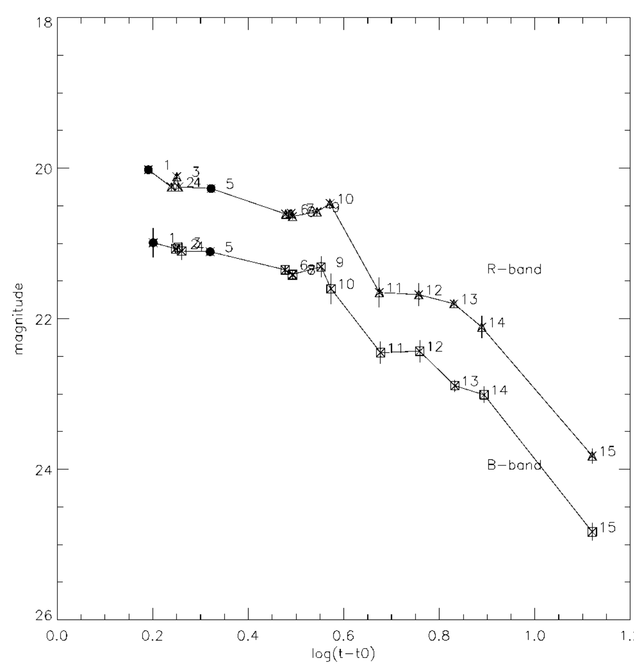

Fig. 2.—GRB 000301c light curve in the *B* and *R* bands. The data points from VBT are marked by filled circles.

(Mészáros, Rees, & Weijers 1998). In the case of GRB 980228, the rebrightening of the afterglow ∼3 weeks after the burst event and the reddening of the spectrum have been hypothesized (Bloom et al. 1999) to be due to an underlying supernova explosion that was triggered from the energy released by a "collapsar" (MacFadyen & Woosely 1999) that gave rise to the initial GRB event. Reichart (1999) also explained the color evolution in case of GRB 980228 using the supernova hypothesis.

To check if there are any such color changes during the evolution of GRB 000301c we display in Figure 2 the behavior of the light curve in both the B and R bands. It is seen that the evolution of R and B magnitudes are nearly the same within the photometric uncertainties. This result has been reported by Jensen et al. (2000) and Masetti et al. (2000) with a smaller sample, although Rhoads & Fruchter (2000) find a shift in $R-K'$ color toward blue. Running an F-test (Press et al. 1992) gives a 90% probability that the two distributions are equal. The color $B-R$ can be fit with a function $(B-R) = a(t - t_0)^n$, where a and n are the two fitted parameters. Our best-fit values are $a = 0.793 \pm 0.073$ and the slope $n = 0.073 \pm 0.074$ with a reduced $\chi^2 = 1.3$. This is consistent with the achromatic behavior of the $B-R$ evolution. Hence, chromatic behavior is not established on the basis of $B-R$ data, and the suggestions of color variations are based on comparison of R-evolution with the K data by Rhoads & Fruchter (2000).

As a closing remark to this Letter, we would like to add that Vainu Bappu Observatory and the Uttar Pradesh State Observatory, being located at a longitude of ∼E78° in India, could make the earliest set of observations of the afterglow of GRB 000301c and that excellent observational opportunities have opened up at longitude E78°57′51″, latitude N32°46′46″ with the commissioning of a 2 m telescope at Hanle (∼15,000 feet) in 2000 September.

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