Early Observations of the Afterglow of GRB000301c

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ABSTRACT

We report multiband observations of the Optical Transient (OT) associated with GRB000301c carried out between 2–4 March 2000 using the 2.34-m Vainu Bappu Telescope (VBT) at Kavalur, India. When combined with other reported data, the initial decline in the R-band magnitude with log (t − t\textsubscript{0}), the time since the burst is fit with a slope $\alpha_1 = -0.70 \pm 0.07$ 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 (1997) and Van Paradijs (1997) detected the first ever counterpart, associated with GRB970228, identification of the optical counterparts of Gamma Ray Bursts (GRB) 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 modelling. 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.

GRB000301c was detected by All Sky Monitor (ASM) on board Rossi X-Ray Timing Explorer (RXTE) on 2000, March 1.4108UT and also by two other spacecrafts Ulysses and NEAR. The burst had a single peak with slow decay structure lasting 10 seconds and was localized by an error

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box of area 50 sq. arcmin centred at (J2000.) RA=16^h20^m21.^s.5, DEC=+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 ± 0.1 by Smette et al. (2000) using HST and to be z=2.03 ± 0.003 by Castro et al. (2000) using the Keck-II telescope. The OT was visible at R=27.9±0.15 from the late-time HST imaging on 19 Apr 2000 (Fruchter et al. 2000a), but there was no evidence for a host galaxy underlying the GRB to a magnitude ∼ 28.5.

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

2. Observations, Analysis and Results

At the 2.34m Vainu Bappu Telescope (VBT), the follow-up observations in the B, R and I bands \(^3\) of GRB000301c began 3 hours after the e-mail notification of the burst event on March 2, 2000. We could 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 24µ × 24µ pixels positioned at the f/3.25 prime focus of the telescope covering a FOV of about 10′ × 10′ with an image scale of 0."61/pixel. 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 pre-processing of CCD frames viz. de-biasing, flat-fielding and removal of cosmic rays is accomplished in a 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 (2000) at a distance of about 6″. In such instances we have also estimated the magnitude of 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 and the magnitudes thus estimated have uncertainties less than 0.01m and the values agree with those provided by Henden (2000) for some select stars.

\(^3\)CCD images are available at [http://www.iiap.ernet.in/new\_results/GRB000301c.html](http://www.iiap.ernet.in/new\_results/GRB000301c.html)
3. Discussions & Conclusions

In the preceding sections we presented our observations and analysis of GRB000301c afterglow observations using Vainu Bappu Telescope, Kavalur, India. 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) in Table 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 < 0.01 m and falls within the uncertainty in the observations.

We attempt to fit the data on intensities in R-band to a time evolution defined by Eq. 1.

\[
I(t) = \begin{cases} 
I(t_1)(t/t_1)^{\alpha_1} & \text{for } t < t_1 \\
(I(t_1)(t/t_1)^{\alpha_1} + (1 - g)(t_1)(t/t_1)^{\alpha_2}) & \text{for } t_1 \leq t < t_2 \\
\{g(t_2/t_1)^{\alpha_1} + (1 - g)(t_2/t_1)^{\alpha_2}\}I(t_1)(t/t_2)^{\alpha_2} & \text{for } t \geq t_2
\end{cases}
\]

This form is motivated by the feature observed in the R-band light curve at \( t - t_0 \approx 4.5 \) 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 \( \alpha_1 \) which at later times steepens to a slope \( \alpha_2 \). The function given in Eq. (1) is designed to test this hypothesis. Notice that this function has 6 parameters \( I(t_1), g, t_1, t_2, \alpha_1 \) and \( \alpha_2 \), two more than the functional form adopted by Jensen et al. (2000) The values of the parameters and their 1\( \sigma \) errors which provide the best fit to the data along with the normalized \( \chi^2 \) are computed using '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 \( \chi^2 \) 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 Eq. 1 of Jensen et al. (2000) and find that the \( \chi^2_{64} \) 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 \( \chi^2 \) reduces to 1.8 (\( \nu = 65 \)) for two-break form and to 1.95 (\( \nu = 64 \)) for single-break form. The improvement on the \( \chi^2 \) with double-break is significant at 38% level as seen from F-distribution test, although we can not rule out the fact that the high \( \chi^2 \) may be due to a genuine variations due to inhomogeneities in the medium surrounding the GRB host.

The motivation for the function given in Eq. (1) is clearly seen in Fig. 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 which may be expected in some supernova-shock models (Meszaros, Rees and Weijers 1998). In case of GRB980228 the re-brightening 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 SN explosion which 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 GRB980228 using the supernova hypothesis.

To check if there are any such color changes during the evolution of GRB000301c we display in Fig. 2. the behaviour of the light curve both in the B and in the 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) finds shift in R–K' color towards blue. Running a F-test (Press et al. 1992) gives 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 behaviour of the B–R evolution. Hence chromatic behaviour 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 brief paper we would like to add that Vainu Bappu Observatory and the Uttar Pradesh State Observatory being located at a longitude of ~ 78°E in India could make the earliest set of observations of the afterglow of GRB000301c and that excellent observational opportunities have opened up at longitude 78°57'51"E, latitude 32°46'46"N with the commissioning of a 2-m telescope at Hanle (~15000ft) in September 2000.

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Fig. 1.— GRB000301c 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.— GRB000301c light curve in B and R bands. The data points from VBT are marked by 'filled circles'.
Table 1. Log of the observations at VBT.

| UT(days) | Filter | Total exp (sec) | Magnitude of OT | mag error | Remarks                  |
|----------|--------|----------------|----------------|-----------|-------------------------|
| Mar 2.9618 | R      | 2400           | 20.02          | 0.028     | 4 x 600sec summed       |
| Mar 2.9986 | B      | 1200           | 20.99          | 0.17      | single frame            |
| Mar 3.9323 | R      | 1800           | 20.45          | 0.12      | 3 x 600sec summed       |
| Mar 3.9976 | R      | 1200           | 20.49          | 0.10      | 2 x 600sec summed       |
| Mar 3.9694 | I      | 3000           | 20.09          | 0.10      | 2 x 600s + 2 x 900s     |
| Mar 4.9087 | R      | 3600           | 20.57          | 0.05      | 6 x 600s summed         |
| Mar 4.9799 | B      | 1800           | 21.29          | 0.12      | single frame            |
| Mar 4.9517 | I      | 1800           | 19.96          | 0.05      | 3 x 600s summed         |

\(^b\)On Mar 3, between 2 set of R-band observations sky conditions varied and therefore the frames are combined seperately. 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     | err(R) | Authors               |
|----------|-------|--------|-----------------------|
| 2.930    | 20.42 | 0.06   | Sagar et al.          |
| 2.962    | 20.02 | 0.028  | Bhargavi & Cowsik     |
| 3.140    | 20.09 | 0.04   | Jensen et al.         |
| 3.144    | 20.25 | 0.05   | Masetti et al.        |
| 3.170    | 19.94 | 0.04   | Fynbo et al.          |
| 3.170    | 20.15 | 0.04   | Jensen et al.         |
| 3.190    | 20.11 | 0.04   | Jensen et al.         |
| 3.191    | 20.11 | 0.05   | Bernabei et al.       |
| 3.200    | 20.14 | 0.05   | Jensen et al.         |
| 3.205    | 20.25 | 0.05   | Masetti et al.        |
| 3.210    | 20.14 | 0.04   | Jensen et al.         |
| 3.220    | 20.11 | 0.05   | Jensen et al.         |
| 3.240    | 20.12 | 0.06   | Jensen et al.         |
| 3.250    | 20.16 | 0.04   | Jensen et al.         |
| 3.260    | 20.09 | 0.08   | Jensen et al.         |
| 3.270    | 20.08 | 0.07   | Jensen et al.         |
| 3.510    | 20.28 | 0.05   | Garnavich et al.      |
| 3.510    | 20.27 | 0.04   | Veilet & Boer         |
| 3.510    | 20.24 | 0.05   | Halpern et al.        |
| 3.930    | 20.53 | 0.05   | Mohan et al.          |
| 3.998    | 20.49 | 0.1    | Bhargavi & Cowsik     |
| 4.038    | 20.53 | 0.06   | Masetti et al.        |
| 4.052    | 20.46 | 0.09   | Castro-Tirado et al.  |
| 4.079    | 20.57 | 0.06   | Gal-Yam et al.        |
| 4.140    | 20.59 | 0.11   | Jensen et al.         |
| 4.178    | 20.22 | 0.20   | Bernabei et al.       |
| 4.380    | 20.56 | 0.05   | Garnavich et al.      |
| 4.390    | 20.53 | 0.12   | Jensen et al.         |
| 4.410    | 20.44 | 0.06   | Jensen et al.         |
| 4.420    | 20.61 | 0.06   | Jensen et al.         |
| 4.430    | 20.42 | 0.12   | Jensen et al.         |
| 4.458    | 20.54 | 0.06   | Mujica et al.         |
| 4.480    | 20.58 | 0.04   | Jensen et al.         |
| 4.490    | 20.54 | 0.04   | Jensen et al.         |
| 4.500    | 20.61 | 0.04   | Halpern et al.        |
| 4.500    | 20.60 | 0.04   | Jensen et al.         |
| 4.520    | 20.51 | 0.05   | Jensen et al.         |
| 4.909    | 20.58 | 0.048  | Bhargavi & Cowsik     |
Table 2—Continued

| UT(days) | R    | err(R) | Authors        |
|----------|------|--------|----------------|
| 5.135    | 20.47| 0.07   | Masetti et al. |
| 5.230    | 20.73| 0.13   | Jensen et al.  |
| 5.390    | 20.61| 0.05   | Jensen et al.  |
| 5.630    | 20.86| 0.04   | Veilet & Boer  |
| 5.960    | 21.18| 0.05   | Mohan et al.   |
| 6.145    | 21.60| 0.20   | Bernabei et al.|
| 6.220    | 21.50| 0.15   | Fruchter et al.|
| 6.390    | 21.43| 0.26   | Jensen et al.  |
| 6.968    | 21.70| 0.13   | Masetti et al. |
| 7.135    | 21.63| 0.15   | Bernabei et al.|
| 7.220    | 21.59| 0.07   | Jensen et al.  |
| 7.230    | 21.62| 0.155  | Jensen et al.  |
| 7.240    | 21.52| 0.08   | Jensen et al.  |
| 7.650    | 21.74| 0.07   | Veilet & Boer  |
| 7.930    | 21.95| 0.1    | Sagar et al.   |
| 8.157    | 21.63| 0.1    | Bernabei et al.|
| 8.180    | 21.80| 0.05   | Jensen et al.  |
| 8.200    | 21.88| 0.09   | Jensen et al.  |
| 8.210    | 21.98| 0.08   | Jensen et al.  |
| 8.250    | 22.09| 0.13   | Jensen et al.  |
| 8.950    | 22.13| 0.1    | Sagar et al.   |
| 9.150    | 22.11| 0.15   | Jensen et al.  |
| 9.200    | 22.29| 0.21   | Jensen et al.  |
| 9.240    | 22.10| 0.11   | Jensen et al.  |
| 9.260    | 22.21| 0.155  | Jensen et al.  |
| 9.520    | 22.28| 0.09   | Halpern et al. |
| 10.050   | 22.34| 0.20   | Jensen et al.  |
| 10.400   | 22.49| 0.30   | Jensen et al.  |
| 11.21    | 23.12| 0.27   | Jensen et al.  |
| 11.39    | 23.12| 0.18   | Jensen et al.  |
| 11.63    | 23.02| 0.1    | Veilet & Boer  |
| 12.44    | 23.10| 0.22   | Jensen et al.  |
| 14.60    | 23.82| 0.1    | Veilet & Boer  |

...  
B–R  a  e(B–R)  ...

2.975  0.9686  0.207  Bhargavi & Cowsik
3.162  0.82   0.07  Masetti et al.
3.195  0.94  0.056  Jensen et al.
3.218  0.85  0.13  Masetti et al.
Table 2—Continued

| UT(days) | R    | err(R) | Authors          |
|---------|------|--------|------------------|
| 3.51    | 0.84 | 0.06   | Veillet & Boer  |
| 4.415   | 0.74 | 0.078  | Jensen et al.   |
| 4.51    | 0.82 | 0.056  | Jensen et al.   |
| 4.52    | 0.77 | 0.06   | Halpern et al.  |
| 4.9375  | 0.734| 0.14   | Bhargavi & Cowsik|
| 5.1435  | 1.13 | 0.21   | Masetti et al.  |
| 6.149   | 0.80 | 0.25   | Masetti et al.  |
| 7.137   | 0.75 | 0.212  | Masetti et al.  |
| 8.195   | 1.09 | 0.09   | Jensen et al.   |
| 9.195   | 0.9  | 0.186  | Jensen et al.   |
| 14.6    | 1.01 | 0.12   | Veillet & Boer  |

*a*B-R colors used in Fig. 2.

Table 3. magnitude corrections.

| data set       | magnitude shift |
|----------------|-----------------|
| vbt            | -0.009          |
| Masetti        | 0.088           |
| Bernabei       | -0.02           |
| Sagar          | 0.232           |
| Other GCN data | 0.03            |
Table 4. Fit parameters.

| parameter | value       | error       |
|-----------|-------------|-------------|
| $I(t_1)$  | 14.88 $\mu$Jy | 1.28 $\mu$Jy |
| g         | 0.169       | 0.30        |
| $t_1$     | 4.12 days   | 0.30 days   |
| $t_2$     | 6.07 days   | 0.44 days   |
| $\alpha_1$| -0.70       | 0.07        |
| $\alpha_2$| -2.44       | 0.29        |
| $\chi^2_{65}$ | 1.80       | –           |
| goodness-of-fit | $2.65 \times 10^{-4}$ | –           |
Fig. 1.— GRB000301c 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.— GRB000301c light curve in B and R bands. The data points from VBT are marked by 'filled circles'. 