EARLIEST DETECTION OF THE OPTICAL AFTERGLOW OF GRB 030329 AND ITS VARIABILITY

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ABSTRACT

We report the earliest detection of an extremely bright optical afterglow of the gamma-ray burst GRB 030329 using a 30 cm telescope at the Tokyo Institute of Technology (Tokyo, Japan). Our observation started 67 minutes after the burst and continued for two succeeding nights until the afterglow faded below the sensitivity limit of the telescope (approximately 18 mag). Combining our data with those reported in GCN Circulars, we find that the early afterglow light curve of the first half-day is described by a broken power-law ($\alpha_1$) function with indices $\alpha_1 = 0.88 \pm 0.01$ (0.047 days $< t < t_{b1}$), $\alpha_2 = 1.18 \pm 0.01$ ($t_{b1} < t < t_{b2}$), and $\alpha_3 = 1.81 \pm 0.04$ ($t_{b2} < t < 1.2$ days), where $t_{b1} \sim 0.26$ days and $t_{b2} \sim 0.54$ days, respectively. The change of the power-law index at the first break at $t \sim 0.26$ days is consistent with that expected from a “cooling break” when the cooling frequency crossed the optical band. If the interpretation is correct, the decay index before the cooling break implies a uniform interstellar medium environment. 

Subject headings: gamma rays: bursts — radiation mechanisms: nonthermal

1. INTRODUCTION

The overall behavior of gamma-ray burst (GRB) afterglows has been successfully explained by the standard fireball model (e.g., Piran 1999). It is expected that the deviation from a simple power law in the afterglow light curve will provide a wealth of information on the environment and physical parameters of GRBs. For example, observations of early GRB afterglows confirmed that “breaks” exist in the light curves of a number of GRBs. Such breaks may be understood in the framework of the standard fireball model as either a “jet break,” in which the bulk Lorentz factor of the relativistic jet decreases to the inverse of the jet opening angle (Sari, Piran, & Halpern 1999; Rhoads 1999), or a “cooling break,” in which the high-energy electrons start to rapidly lose most of their energy by the synchrotron emission emitting the observed optical photons (Sari, Piran, & Narayan 1998). While there are number of convincing cases for jet breaks, identification of a cooling break in the optical light curve has been difficult since it requires detection of a subtle change in the power-law index ($\Delta \alpha \sim 0.25$). In order to study afterglow light curves in detail, continuous coverage and a high signal-to-noise ratio are required.

The situation has been dramatically improved since the advent of the High Energy Transit Explorer 2 (HETE-2). HETE-2 can determine the positions of GRBs on board and can notify ground-based observers of the GRB coordinates within 1–10 minutes after the burst (Ricker et al. 2002). For example, the locations of GRB 021004 (e.g., Fox 2002) and GRB 021211 (e.g., Fox & Price 2002) were disseminated within less than a minute after the bursts, which prompted detailed studies of GRB afterglows in the very initial phases while they were bright. 

GRB 030329 was detected by the HETE-2 satellite on 2003 March 29 at 11:37:14.7 UT. The position was determined by the ground analysis, and the location was reported to the GRB Coordinates Network (GCN) 73 minutes after the burst (Vanderspek et al. 2003). A very bright ($R \sim 13$ mag) optical transient (OT) was reported at $\alpha = 10^{5}44^{"}50^{"}0$, $\delta = +21^{\circ}31^{\prime}17^{\prime\prime}8$ (J2000.0; Peterson & Price 2003; Torii 2003) inside the soft X-ray camera (SXC) error circle. This is the brightest GRB ever detected by HETE-2 with a 30–400 keV fluence of $1.2 \times 10^{-4}$ ergs cm$^{-2}$, and precise and continuous follow-up observations were carried out by dozens of telescopes located around the world. Optical spectroscopic observations have determined its redshift as $z = 0.1685$ (Greiner et al. 2003), which is one of the closest ever known and is possibly related to the exceptional brightness of this afterglow. Moreover, spectra taken after several days reveal the evolution of broad peaks in the spectra, which is characteristic of a supernova. The spectral similarity to SN 1998bw (e.g., Galama et al. 1998; Iwamoto et al. 1998) and other energetic supernovae such as 1997ef provides strong evidence that GRB 030329 is associated with core-collapse supernovae (Dado, Dar, & Rújula 2003; Hjorth et al. 2003; Stanek, Martini, & Garnavich 2003a; Stanek et al. 2003b; Kawabata et al. 2003). In order to investigate the kinetic energy of a GRB and the immediate vicinity of its progenitor, the early light curve is important. In this Letter, we report the earliest detection of the optical afterglow of GRB 030329 starting 67 minutes after the burst.

2. OBSERVATION AND PHOTOMETRY

Our observation was performed at the Tokyo Institute of Technology using a 30 cm telescope (Meade LX-200) and an unfiltered CCD camera (Apogee AP6E) equipped with a front-illuminated 1024 $\times$ 1024 CCD chip (Kodak KAF-1001E). The dark-current images were subtracted from the obtained CCD images, and then flat-fielding was applied to all images. We used IRAF/NOAO/DIGIPHOT/APPHOT/PHOT packages to analyze the data.

We started observing the preliminary SXC position at 12:44:13 UT on 2003 March 29, 67 minutes (0.047 days) after the burst. The magnitude of the GRB afterglow at the very beginning was $R_c \sim 12.4$ mag. This is the earliest detection of the afterglow of GRB 030329 ever reported in the literature.

We continued observations for the rest of the night, covering $t \sim 0.05$–0.30 days, and we performed observations on the following two nights covering the period of $t \sim 0.93$–1.21 days

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and $t \sim 2.03-2.08$ days, respectively, where $t$ refers to the time since the burst onset. The exposure time of each CCD frame was 10 s ($0.047 \text{ days} < t < 1.21 \text{ days}$, when the afterglow was relatively bright) or 30 s ($2.03 \text{ days} < t$). The magnitude of the comparison stars were calibrated using three stars in the same field of view, which has been calibrated in detail by Henden (2003).

Then we determined the magnitude of the OT in each frame relative to the weighted average of 15 bright comparison stars.

Since the peak sensitivity of our camera is very close to the $R_c$ band, we have calibrated the magnitude of the OT by converting our magnitude system ($\Delta R$) into the system assuming the color correction with the color ($V-I$) = 0.74 mag [Zeh, Klose, & Greiner 2003; a($r$) = ($R_{\text{mag}}$) - 0.1514($V-I$), where a($r$) is the zero point between the instrumental system and the standard magnitude]. The statistical error is $\sim 0.017-0.02$ mag. Although Henden (2003) found that the zero-point errors were $\sim 0.03$ mag for the reference stars, we found that our data were consistently brighter than the $R$-band–filtered observations (e.g., Burenin et al. 2003). We therefore introduced an additional zero-point correction (+0.11 mag) to match the light curves in the overlapped interval. The resulting light curve of the GRB 030329 afterglow in the $R_c$ band is shown by combining data from other observations (see Fig. 1).

The light curve from the first day cannot be fitted with a single–power-law function. We therefore tried to fit the light curve using two different forms of broken power-law functions. One is given by Beuermann et al. (1999):

$$F(t) \propto \left[ \frac{\delta t_b}{(\delta t_{b,1})^{n} + (\delta t_{b,2})^{n}} \right]^{-b} \quad \text{for } t < t_{b,1},$$

$$\quad \left[ \frac{\delta t_b}{(\delta t_{b,1})^{n} + (\delta t_{b,2})^{n}} \right]^{-b} \quad \text{for } t > t_{b,1},$$

where $t_{b,1}$ and $t_{b,2}$ are the break times and $n$ provides a measure of the relative width and the smoothness of the break. Here we excluded the “bump” at $t \sim 0.08-0.09$ days, which is discussed in § 3.3.

We found that the former is not acceptable with a reduced $\chi^2$ of 1.72 (285 degrees of freedom [dof]), whereas the latter improves the fit significantly (a reduced $\chi^2$ of 1.06 with 283 dof; see Fig. 2). As a result, it is well described by a broken power law of the form $\alpha_1 = 0.88 \pm 0.01$ ($0.047 \text{ days} < t < t_{b,1}$), $\alpha_2 = 1.18 \pm 0.01$ ($t_{b,1} < t < t_{b,2}$), and $\alpha_3 = 1.81 \pm 0.04$ ($t_{b,2} < t < 1.2 \text{ days}$), where $t_{b,1} \sim 0.26 \text{ days}$ and $t_{b,2} \sim 0.54 \text{ days}$, respectively, and $n = 18.8 \pm 5.1$. Here, $\alpha_1$ is determined by essentially the full Tokyo Tech data. The earliest phase of the light curve is well fitted by the single power law with an index of $\alpha_1$; $\alpha_2$ and $\alpha_3$ are determined by the measurements reported by Burenin et al. (2003) and the GCN (see the caption to Fig. 1).

3. Discussion

3.1. Light Curve at $0.05 \text{ days} < t < 0.26 \text{ days}$

We have presented a light curve of the early phase of the optical afterglow of GRB 030329 starting 67 minutes after the burst. This is the earliest detection of GRB 030329 ever reported (Peterson & Price 2003; Torii 2003; Uemura et al. 2003).

Burenin et al. (2003) reported follow-up observations of GRB 030329 as early as 6 hr after the burst, using BVRi filters. In each of the filters, they observed a gradual flux decay that can be accurately described as a power-law $F \propto t^{-1.9}$. They also found a characteristic break in the light curve $t_b \sim 0.57$ days, after which the afterglow flux started to decline faster. The power-law slopes of the light curves changed from $-1.19 \sim -1.9$ for $t \geq t_b$. Notably, this break is nicely consistent with our second break ($t_{b,2}$) within error bars, where the power-law slopes changes from $-1.18 \pm 0.01$ to $-1.81 \pm 0.04$ after the break of $t_{b,2} \sim 0.54$ days (see above). The first break ($t_{b,1}$) is not discussed in Burenin et al. (2003) because they started their observations just around this break ($t_{b,1} \sim 0.26$ days).

Price et al. (2003), Burenin et al. (2003), and Tiengo et al. (2003) found that the results of their observations are consistent with the model in which the afterglow emission is generated during the deceleration of the ultrarelativistic collimated jet. They found that the break in the power-law light curve, at $t \sim 0.5-0.6$ days, can be interpreted as the jet break, i.e., the break that occurs when the angular structure of the ultrarelativistic collimated jet becomes observable (Sari et al. 1999; Rhoads 1999). This interpretation is supported by the fact that the break occurred simultaneously in different colors. Furthermore, the change in power-law slope from $-1.19$ to $-1.9$ is approximately consistent with that generally observed in a jet
break. Therefore, our major concern in this Letter is to understand the nature of the first break, \( t_{\text{b,1}} \), and examine the consistency of the above scenario in the framework of standard GRB fireball theories (Piran 1999).

### 3.2. Break at \( t \sim 0.26 \) days

There are two possible break frequencies in the spectra, \( \nu_m \) and \( \nu_r \), where \( \nu_m \) is the synchrotron frequency and \( \nu_r \) is the cooling frequency above which electrons lose their energy rapidly by synchrotron radiation (Sari et al. 1998). Since \( \nu_m \) and \( \nu_r \) are the functions of time, a break in the light curve could be observed when \( \nu_r \) and/or \( \nu_m \) crossed over the observed frequency \( \nu_\text{obs} \). Therefore, we examined six possible cases in order to understand the first break (\( t_{\text{b,1}} \)), according to the relation between \( \nu_\text{obs} \), \( \nu_m \), and \( \nu_r \). In the standard GRB scenario, \( \nu_r \leq \nu_\text{obs} \) is often called “fast cooling” since all electrons cool rapidly, whereas \( \nu_m \geq \nu_\text{obs} \) is referred to “slow cooling” since only the high-energy population of electrons cool efficiently. We will also extend our discussion to discriminate between “a homogeneous interstellar medium (ISM) model” (e.g., Sari & Piran 1999) and “a preexisting stellar wind model” (e.g., Chevalier & Li 1999) for the GRB environment. The relationships between the observed spectral index and model predictions are compared in Table 1.

We first consider the cases in which both \( \nu_m \) and \( \nu_r \) are above the observed optical frequencies (\( \nu_m < \nu_\text{obs} < \nu_r \); cases 3 and 6 in Table 1, respectively). In these two situations, the observed flux at \( \nu_\text{obs} \) should increase with time, which strongly conflicts with the observed declining light curve. On the contrary, if both the cooling frequency \( \nu_r \) and the minimum frequency \( \nu_m \) are below the optical band (\( \nu_m < \nu_\text{obs} < \nu_r \); cases 1 and 4 in Table 1, respectively), the predicted optical spectral index would be \( \beta = p/2 \), where \( p \) is the electron spectral index. Since the photon spectral index of this afterglow was \( \beta = 0.66 \) at \( t = 0.26 \) days (Burenin et al. 2003), we expect \( p = 1.32 \), which is unusually flat for an electron population accelerated in a GRB. Furthermore, the power-law index in the light curve should be \( \alpha = (2 - 3p)/4 \sim 0.49 \), which is again inconsistent with \( \alpha \sim 0.88 \) obtained with our data.

Case 5 (\( \nu_r < \nu_\text{obs} < \nu_m \)) in Table 1 is also ruled out because the predicted power-law index \( \alpha = 0.25 \) (Sari et al. 1998) is too flat compared with the observed value of \( \alpha \sim 0.88 \). Therefore, we argue that the possible solution is \( \nu_m < \nu_\text{obs} < \nu_r \) for the time region of \( t \leq t_{\text{b,1}} \). In this case, however, if the burst occurred in a preexisting stellar wind, the optical decay slope is predicted to be \( \alpha = 3\beta/2 - 1/(8 - 2\delta) \sim 1.49 \), with \( \delta = 2 \) for a wind model (Panaitescu, Mészáros, & Rees 1998), which is quite steeper than that observed, and hence we can rule out the wind-interaction model. In summary, \( \nu_m < \nu_\text{obs} < \nu_r \), and the ISM model (case 2 in Table 1) is the only possible solution to reproduce both the temporal and spectral index of the optical afterglow of GRB 030329 at 0.05 days < \( t \) < 0.26 days.

In such a slow cooling case, the time variation of the afterglow flux is given by \( F \propto t^{-3p-1/2} \) for \( \nu < \nu_r \) and \( F \propto t^{-0.3p-2/3} \) for \( \nu < \nu_m \) (Sari et al. 1998). By assuming \( \alpha_r = 0.88 \), the electron spectral index is estimated as \( p = 2.17 \). Note that this electron spectral index agrees well with those of electrons accelerated in relativistic shock waves (e.g., Dado et al. 2003). Furthermore, we expect that the power-law slope of the light curve would change from 0.88 to 1.13 for \( \nu_r < \nu_r \). Again, this is approximately consistent with the observed spectral index after \( t_{\text{b,1}} \), where \( \alpha_r = 1.18 \pm 0.01 \). Therefore, we conclude that the first break in the optical afterglow light curve at \( t_{\text{b,1}} \) is the most probably cooling break where the cooling frequency crosses down the observed optical frequency.

Under this assumption, we can determine important physical parameters for the GRB emission. For example, we can estimate \( \epsilon_e \) and \( \epsilon_\gamma \), the fractions of the shock energy given to the magnetic field and the electrons at the shock, respectively (Sari et al. 1998). In the case of slow cooling, \( \nu_m \) < \( \nu_r < t_b \) would be expected. Since we started our observation 0.047 days after the burst, we can limit the range of \( \nu_r \) as \( t_b \leq \nu_r < 0.047 \) days. For \( t_b = t_{\text{b,1}} = 0.26 \) days, \( \nu_m < 0.047 \) days, \( E = 10^{52} \) ergs, \( n = 1 \) cm\(^{-3} \), and \( \nu = 0.5 \times 10^{15} \) Hz, we obtain

\[
\epsilon_e \sim 0.05 \left( \frac{\nu_m}{0.26} \right)^{-1/3} \left( \frac{E_{52}}{1.0} \right)^{-1/3} \left( \frac{\nu_\text{15}}{0.5} \right)^{2/3}, \quad (2)
\]

\[
\epsilon_\gamma < 0.20 \left( \frac{\nu_\text{15}}{0.05} \right)^{1/4} \left( \nu_{10} \right)^{1/4} \left( \frac{E_{52}}{1.0} \right)^{1/4} \left( \frac{\nu_\text{15}}{0.5} \right)^{1/2}. \quad (3)
\]

We can also constrain the peak time of the reverse shock \( t_{\text{peak}} \) days after the burst (Sari & Piran 1999):

\[
t_{\text{peak}} \sim 0.03 \left( \frac{\epsilon_e}{0.05} \right)^{-1} \left( \frac{\nu_{15}}{1.0} \right)^{-1} \left( \frac{E_{52}}{1.0} \right) \left( \frac{\nu_\text{15}}{0.5} \right)^{-2}. \quad (4)
\]

The Lorentz factor depends on the time, \( \gamma(t) \sim (3E/256\pi n_\nu^2 \epsilon_e^2 t^2)^{1/3} \) (Piran 1999). And the magnetic field is calculated using \( \epsilon_\gamma \) and the Lorentz factor by \( B = \gamma c (32\pi \epsilon_\gamma \nu_\text{15}^2)^{1/2} \). Assuming \( E = 10^{52} \) ergs, the Lorentz factor and the magnetic field strength at two characteristic break times are \( \gamma = 9.7 \), \( B = 0.86 \) G at \( t_{\text{b,1}} = 0.26 \) days and \( \gamma = 7.4 \), \( B = 0.64 \) G at \( t_{\text{b,2}} = 0.54 \) days, respectively.

The values of \( \epsilon_e \) and \( \epsilon_\gamma \) estimated in the preceding section are in good agreement with the averages of these parameters for GRBs calculated by Panaitescu & Kumar (2001), which are log \( \epsilon_e = -2.4 \pm 1.2 \) and \( \epsilon_\gamma = 0.062 \pm 0.045 \).

### 3.3. Bump at \( t \sim 0.08–0.09 \) days

Finally, we comment on a small “bump” of the light curves at \( t \sim 0.08–0.09 \) days (\( t_{\text{bump}} \)) with an amplitude of \( \sim 0.1 \) mag. Uemura et al. (2003) reported a change of slopes from 0.74 to 0.95 at \( t = 0.085 \) days. However, our earliest data at \( t < 0.08 \) days have a slope steeper than 0.74. The light curve at \( t > 0.09 \) days lies on the extrapolation of this earliest segment. We consider this feature as a bump rather than a break. Short time variabilities, i.e., “bumps and wiggles,” may be associated with the forward/reverse-shock structures along the afterglow.
emitting regions (Kobayashi & Zhang 2003), the repeated energy injection from the central engine, or the fluctuation in the density of the ISM (Nakar, Piran, & Granot 2003).

First, we can rule out a case with the forward-/reverse-shock structure since it predicts that the light curve should not have the same power-law index before and after the bump. A case with repeated energy injection is also ruled out since after the injection, the light curve after the bump should have the same power-law decay slope, but with a larger normalization. Therefore, we conclude that the bumps in the light curve are likely due to the fluctuation in the external density of the ISM (Nakar et al. 2003).

We can estimate the distance from the central engine $R(t)$ (Piran 1999) and the density variation (Nakar et al. 2003) at $t_{bump}$:

$$R(t) \sim 2.2 \times 10^{17} \left[ \frac{E_{52}}{3} \frac{t_{s}}{1.0 \times 7300} \right]^{1/4} \frac{n_{p}}{1.1} \frac{1}{\left( \frac{F_{0}}{1.1} \right)^{1/3}} \text{ cm}, \quad (5)$$

$$n(n_{0}) \sim 1.1 \left( \frac{F_{0}}{1.1} \right)^{1/3} \text{,} \quad (6)$$

We find that density is enhanced about 10% at a distance of $2.2 \times 10^{17}$ cm.

4. SUMMARY

We observed an extremely bright optical afterglow of GRB 030329 67 minutes after the burst. Our observational results show that the shocked electrons are in the slow cooling regime, with an electron index of 2.17 in this burst, and that the burst occurred in a uniform ISM; i.e., GRB 030329 can be understood very well in the predicted “standard” model. We conclude that the first break changes the power-law index by $\sim 0.3$, consistent with the cooling break in the framework of the standard external shock model.

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