Discovery of a short plateau phase in the early evolution of a gamma-ray burst afterglow

Makoto Uemura, Taichi Kato, Ryoko Ishioka
Department of Astronomy, Faculty of Science, Kyoto University, Sakyou-ku, Kyoto 606-8502
uemura@kusastro.kyoto-u.ac.jp

and

Hitoshi Yamaoka
Faculty of Science, Kyushu University, Fukuoka 810-8560

(Received 2003 January 29; accepted 2003 March 5)

Abstract

We report optical observations during the first hour of the gamma-ray burst (GRB) afterglow of GRB021004. Our observation revealed the existence of a short plateau phase, in which the afterglow remained at almost constant brightness, before an ordinary rapid fading phase. This plateau phase lasted for about 2 hours from 0.024 to 0.10 d after the burst, which corresponds to a missing blank of the early afterglow light curve of GRB990123. We propose that the plateau phase can be interpreted as the natural evolution of synchrotron emission from the forward shock region of a blast wave. The time when the typical frequency of the synchrotron emission passes through the optical range has been predicted to be about 0.1 d after the burst, which is consistent with the observed light curve. Our scenario hence implies that the observed feature in GRB021004 is a common nature of GRB afterglows.

Key words: gamma rays: bursts

1. Introduction

Gamma-ray bursts (GRBs) are the most energetic phenomena in the universe, which appear only for 0.01–100 s as brightest sources at the gamma-ray range (Klebesadel et al. 1973; Wijers et al. 1997). In a number of GRBs, afterglows have been detected in all wavelengths (Costa et al. 1997; Frail et al. 1997). While their central engine is still poorly understood, it has been proposed that their behaviour can be well explained with a picture called the fireball model. In this model, a blast wave produced from a fireball propagates outward initially at highly relativistic velocity, and then, gradually decelerated by the collision with interstellar medium (Waxman 1997). The GRB afterglow is proposed to be synchrotron emission from a forward shock region in an expanding shell colliding with external medium, whereas the GRB itself is from an internal shock region between shells (Wijers et al. 1997; Waxman 1997; Sari, Piran 1999). Early phase observations of afterglows would provide crucial clues for the initial extremely relativistic state of GRBs, however their rapid fading has prevented us from successful observations.

GRB021004 was detected by the HETE-2 satellite on 4 October 2002 at 12:06:13.57 UT (Shirasaki et al. 2002). A prompt identification of its burst position, which was notified 48 s after the burst, enabled observers to make observations of a very early phase of the afterglow of the GRB. A new bright optical source of $R_e = 15.34$ was discovered $6.56 \times 10^{-3}$ day after the burst within the errorbox of the burst position, and then continuously monitored by a number of observers (Fox 2002). Owing to the quick notification and the apparently bright afterglow, GRB021004 provided a dense optical sampling of the time evolution of the GRB afterglow. Optical spectroscopic observations showed its redshift of $z = 2.32$ and its isotropic energy of $E_{iso} = 5.6 \times 10^{52}$ erg s$^{-1}$ (Malesani et al. 2002).

2. Observation and Result

Our unfiltered CCD photometric observations were performed with 25-cm and 30-cm telescopes at Kyoto University. The dark current image was subtracted from obtained CCD images, and then flat fielding was performed. We calculated differential magnitudes of GRB021004 with neighbour comparison stars (GSC1183.403, GSC1183.1526, and GSC1183.1261), whose constancy is better than 0.08 mag during our observation. We discarded images taken under heavily low transparency conditions to avoid systematic errors. Our equipment yields a magnitude system near the $R_c$-system since the sensitivity peak of the camera is near the peak of the $R_c$-system and spectra of GRB afterglows have smooth continuum without strong emission lines or absorption edge in the optical range. The difference between our unfiltered CCD and the $R_c$-system is less than 0.02 mag when the spectrum is described with a simple power law ($f(\nu) \propto \nu^p$) of the index $-2.0 < p < 0.3$, which is consistent with observed spectra of GRB afterglows (Sari et al. 1998). Our magnitude system was translated to the $R_c$-system by taking cross-correlation with other observations reported in GRB Coordinate Network (GCN). The resulting light curve and magnitudes are shown in figure 1 and table 1. In figure 1, the abscissa and the
detected a fading of the source from $6.56 \times 10^{-3}$ to $1.19 \times 10^{-2}$ day after the burst. Our observation covers a subsequent period from $2.44 \times 10^{-2}$ to 0.292 day. As can be seen in figure 1, the first fading trend was terminated before our run. Our observations show that, after the initial fading phase, the object experienced a plateau phase during which it remained at almost constant brightness. The object again drastically changed its fading rate during our observation, and then entered an ordinary decay phase. Our $\chi^2$-fitting with two power laws ($f \propto t^{-\alpha}$) and a transition time yields the best-fit parameters of a transition time of $0.13\pm0.02$ d, $\alpha_1 = -0.03\pm0.12$ ($t < 0.13$ d), and $\alpha_2 = 1.20\pm0.36$ ($t > 0.13$ d). We hence confirm that neither significant fading nor brightening is detectable in the light curve from $2.44 \times 10^{-2}$ to 0.132 day. Even when we use only the earliest period up to $4.8 \times 10^{-2}$ day, the fitting shows no significant fading or brightening trend. The fading rate after the plateau phase ($\alpha_2$) is in agreement with that calculated from other observations reported in GCN ($\alpha = 1.31\pm0.03$). This value of $\alpha_2$ during the ordinary decay phase is standard one among known afterglows.

3. Discussion

Our observation first revealed the presence of a plateau phase preceding the ordinary decay of the afterglow. According to the fireball model, the optical afterglow is predicted to start rapid fading when the observed frequency becomes larger than the typical synchrotron frequency, which rapidly moves to lower-frequency regions with time. On the other hand, during a very early phase when the optical flux is still dominated by the emission under the typical synchrotron frequency, the flux is predicted to increase, as $f \propto t^{1/2}$ in a case that the ambient medium has a constant density distribution (Sari et al. 1998). The time when the typical frequency passes through the optical range has been theoretically estimated to be $\sim 0.1$ d after the burst with typical physical parameters for GRB afterglows (Sari, Piran 1999). We propose that the plateau phase of GRB021004 corresponds to a part of such an early phase of the ordinary afterglow from the forward decay phase. Our observations showed that after the initial fading phase, the object experienced a plateau phase during which it remained at almost constant brightness. The object again drastically changed its fading rate during our observation, and then entered an ordinary decay phase. Our $\chi^2$-fitting with two power laws ($f \propto t^{-\alpha}$) and a transition time yields the best-fit parameters of a transition time of $0.13\pm0.02$ d, $\alpha_1 = -0.03\pm0.12$ ($t < 0.13$ d), and $\alpha_2 = 1.20\pm0.36$ ($t > 0.13$ d). We hence confirm that neither significant fading nor brightening is detectable in the light curve from $2.44 \times 10^{-2}$ to 0.132 day. Even when we use only the earliest period up to $4.8 \times 10^{-2}$ day, the fitting shows no significant fading or brightening trend. The fading rate after the plateau phase ($\alpha_2$) is in agreement with that calculated from other observations reported in GCN ($\alpha = 1.31\pm0.03$). This value of $\alpha_2$ during the ordinary decay phase is standard one among known afterglows.

### Table 1. $R_c$-magnitudes obtained by our observation

| $T$ (day) * | $R_c$ mag. | err. |
|------------|------------|------|
| 0.026568   | 16.86      | 0.53 |
| 0.031431   | 16.45      | 0.35 |
| 0.037184   | 16.36      | 0.38 |
| 0.043990   | 16.60      | 0.38 |
| 0.072837   | 16.37      | 0.19 |
| 0.086169   | 16.50      | 0.07 |
| 0.101942   | 16.69      | 0.06 |
| 0.120601   | 16.56      | 0.10 |
| 0.142676   | 16.76      | 0.07 |
| 0.168792   | 16.91      | 0.08 |
| 0.199688   | 17.17      | 0.13 |
| 0.236239   | 17.26      | 0.23 |

* Time from the burst (12:06:13.57 UT).

**Fig. 1.** Light curve of the optical afterglow of GRB021004. The abscissa and ordinate denote the time after the burst in day and the $R_c$-magnitude, respectively. Our observations are shown in the filled circle. The other symbols are observations reported in GCN 1564, 1573, 1576, 1577, 1578, 1580, 1582, 1584, 1585, 1586, 1587, 1591, 1593, 1594, 1597, 1598, 1602, 1603, 1606, 1607, 1614, 1615, 1616, 1618, 1623, 1628, 1638, 1645, 1652, 1654, and 1661. The reported magnitudes in GCN were translated using the standard sequence presented in GCN 1630. The dashed line is the best fitted model light curve (see the text). Upper panel: The whole light curve of the afterglow. Lower panel: Enlarged light curve around our observations.

ordinate denote the time from the burst in day and the $R_c$-magnitude, respectively. Our observations are shown with the filled circles. Other symbols denote observations reported in GCN. The exposure time of each frame was 30 s, and the filled circles denote averaged points of several frames in the bin of $\Delta \log \tau_{\text{day}} \sim 0.07$. The reason why the first four points have relatively large error bars is due to low transparency of the sky and shorter total exposure times of averaged data. Even in these early points, the afterglow was actually detected at 4-$\sigma$ level, which is high enough for the discussion in the text.

We initiated time-series CCD photometric observations of GRB021004 on October 4 at 12:41:09 UT, about 0.024 day after the burst. The earliest positive observations
shock. On the nature of the plateau phase, an alternative scenario may be possible that it is one of wiggles observed during the late phase ($\gtrsim 1$ d), which are apparently unusual compared with other GRB afterglows. However, the observed transition time from the early plateau to the decay phase is just what is expected from the theoretical calculation, which favors our scenario for the plateau phase. The fading trend cannot actually be described by a simple power-law between the first fading around 0.01 d and the late afterglow after 0.1 d (Malesani et al. 2002). The late wiggles in the afterglow light curve may have just been overlooked in previous GRBs because of their sparse sampling. The increase of the fading rate can be naturally interpreted as a normal break as seen in other GRB afterglows.

The dashed line shown in figure 1 is the best fitted model light curve based on our picture for the plateau phase. We chose the smoothly broken power-law model $f(t) = (f_1(t)^{-n} + f_2(t)^{-n})^{-1/n}$ with $f_i(t) = k_i t^{\alpha_i}$ to describe our observations assuming $\alpha_1 = 0.5$ and $\alpha_2 = 1.31$ (Beuermann et al. 1999). The parameter $n$ provides a measure of the smoothness of the transition. It was calculated to be $n = 0.92 \pm 0.34$, indicating a very smooth transition as expected in theoretical predictions (Granot, Sari 2002). As can be seen in figure 1, this model well describes our observation. The transition time is calculated to be $0.10 \pm 0.02$ d in this case, which is in agreement with the result from fitting two power-laws within errors.

The initial rapid fading trend around 0.01 d should have another emission source, since, according to the forward shock model, the optical afterglow reaches its peak just before the ordinary decay phase. The first fading can be interpreted to be a tail of the optical flash which was detected only in one GRB afterglow, GRB990123 (Akerlof et al. 1999; Kulkarni et al. 1999). It has been proposed that the optical flash originated from a reverse shock, while the ordinary afterglow originates from a forward external shock (Sari, Piran 1999; Meszaros, Rees 1999). In the case of GRB990123, the optical flash was observed until at least 0.01 d after the burst (Kulkarni et al. 1999). As seen in figure 1, the transition time from the flash to the plateau phase was also 0.01–0.02 d in the case of GRB021004.

As well as the similar activity around 0.01 d of these two GRBs, the beginnings of the ordinary decay phase were also observed at similar times around 0.1 d both in GRB021004 and GRB990123 (Kulkarni et al. 1999). These two GRBs hence have quite analogous light curves of afterglows, except for the plateau phase which were observed not in GRB990123, but in GRB021004. Our observation has first filled in the missing blank between the optical flash and the ordinary decay. The similarity of these two GRBs and our interpretation with the natural evolution of afterglows imply that the early light curve of the afterglow of GRB021004 is common, most fundamental features for GRB afterglows.

On the other hand, it is notable that the first fading, which we propose to be the optical flash, is more gradual compared with the fading branch of the optical flash in GRB990123 (Sari, Piran 1999). The relatively rapid fading after 0.1 d (in other words, a large $\alpha_2$) may also be rather atypical for other GRB afterglows (Sari, Piran, & Halpern 1999). These observational features are possibly inconsistent with the picture which we propose, however, it is too premature to conclude it because we have only few dense, early phase samples of the light curve of GRB afterglows, like GRB021004. The validity of our proposed scenario will be evaluated by observations of color variations during the early phase of afterglows since the color of afterglows should dramatically change when the typical synchrotron frequency passes an observational band.

This work is partly supported by a grant-in-aid (13640239) from the Japanese Ministry of Education, Culture, Sports, Science and Technology. Part of this work is supported by a Research Fellowship of the Japan Society for the Promotion of Science for Young Scientists (MU).

References

Akerlof, C., et al. 1999, Nature, 398, 400
Beuermann, K., et al. 1999, A&A, 352, L26
Costa, E., et al. 1997, Nature, 387, 783
Fox, D. W. 2002, GCN, 1564
Frayl, D. A., Kulkarni, S. R., Nicastro, S. R., Feroci, M., & Taylor, G. B. 1997, Nature, 389, 261
Frayl, D. A., et al. 2001, ApJ, 562, L55
Granot, J. & Sari, R. 2002, ApJ, 568, 820
Klebesadel, R. W., Strong, I. B., & Olson, R. A. 1973, ApJ, 182, L85
Kulkarni, S. R., et al. 1999, Nature, 398, 389
Malesani, D., et al. 2002a, GCN, 1607
Malesani, D., et al. 2002b, GCN, 1645
Meszaros, P. & Rees, M. J. 1999, MNRAS, 306, L39
Rhoads, J. E. 1999, ApJ, 525, 737
Sari, R. & Piran, T. 1999a, ApJ, 517, L109
Sari, R. & Piran, T. 1999b, ApJ, 520, 641
Sari, R., Piran, T., & Halpern, J. P. 1999c, ApJ, 519, L17
Sari, R., Piran, T., & Narayan, R. 1998, ApJ, 497, L17
Shirasaki, Y. et al. 2002, GCN, 1565
Stanek, K. Z., Garnavich, P. M., Kaluzny, J., Pych, W., & Thompson, I. 1999, ApJ, 522, L39
Waxman, E. 1997a, ApJ, 489, L33
Waxman, E. 1997b, ApJ, 485, L5
Wijers, R. A. M. J., Rees, M. J., & Meszaros, P. 1997, MNRAS, 288, L51