Optical Afterglow Observations of the Unusual Short-Duration Gamma-Ray Burst 040924

K. Y. Huang1, Y. Urata2,3, A. V. Filippenko4, J. H. Hu1, W. H. Ip1, P. H. Kuo1, W. Li4, H. C. Lin1, Z. Y. Lin1, K. Makishima2,5, K. Onda2,6, Y. Qiu7, and T. Tamagawa2

ABSTRACT

The 1-m telescope at Lulin Observatory and the 0.76-m Katzman Automatic Imaging Telescope at Lick Observatory were used to observe the optical afterglow of the short-duration (1.2–1.5 s) gamma-ray burst (GRB) 040924. This object has a soft high-energy spectrum, thus making it an exceptional case, perhaps actually belonging to the short-duration tail of the long-duration GRBs. Our data, combined with other reported measurements, show that the early $R$-band light curve can be described by two power laws with index $\alpha = -0.7$ (at $t = 16$–50 min) and $\alpha = -1.06$ (at later times). The rather small difference in the spectral indices can be more easily explained by an afterglow model invoking a cooling break rather than a jet break.

Subject headings: gamma rays: bursts

1. Introduction

Gamma-ray bursts (GRBs) are among the most powerful explosions in the Universe. It is generally believed that the impulsively injected fireball results from core collapse in a
massive star (Woosley 1993; MacFadyen & Woosley 1999), or from the merging of either two neutron stars or a neutron star and a black hole (e.g., Ruffert et al. 1997; Popham et al. 1999; Narayan et al. 1992, 2001; Rosswog & Davies 2002; Lee & Ramirez-Ruiz 2002). After the explosion, the relativistic ejecta collide with the ambient interstellar medium causing X-ray, optical, and radio emission. These so-called “afterglows” thus carry important information on the injection mechanism, the configuration of the (possibly collimated) fireball, and the surrounding environment (e.g., Mészáros 2002).

Two kinds of GRBs have been defined according to whether their gamma-ray emission has duration longer or shorter than 2 s. Although their frequency distributions overlap, that of the short-duration GRBs peaks at 0.3 s, while that of the long-duration GRBs peaks at 30–40 s (Kouveliotou et al. 1993). In addition, the duration is weakly correlated with the spectral hardness ratio at high energies: short GRBs tend to be harder and long GRBs tend to be softer (Kouveliotou et al. 1993).

The optical afterglows of short GRBs were elusive until the detection (Fenimore et al. 2004) of GRB 040924 by the High Energy Transient Explorer 2 (HETE–2) on 2004 Sep. 24, at 11:52:11 (UT dates are used throughout this paper). This event lasted about 1.2 s and was X-ray rich according to the HETE–2 flux in the 7–30 keV and 30–400 keV bands. The Konus-Wind satellite also detected this event with 1.5 s duration in the 20–300 keV band (Golenetskii et al. 2004). Since the high-energy spectrum of GRB 040924 is soft (Fenimore et al. 2004), the object might actually be near the short-duration end of the long GRBs. A detailed study of the associated optical afterglow could provide further information on whether this is indeed the case, thus probing the nature of GRBs in the boundary region.

About \( t = 16 \) min after the burst, Fox (2004) detected the corresponding optical afterglow with an \( R \)-band magnitude of \( \sim 18 \). This was shortly followed by Li et al. (2004), who reported \( R \approx 18.3 \) mag at 26 min after the burst. From then on, a number of observatories joined in the follow-up observations (Fynbo et al. 2004; Hu et al. 2004; Khamitov et al. 2004a; Terada, Akiyama, & Kawai 2004). Radio observations failed to detect the afterglow at \( t = 12.54 \) hr and \( t = 5.79 \) d (Frail & Soderberg 2004; van de Horst, Rol, & Wijers 2004a,b). Spectral measurements by the Very Large Telescope (VLT) of a galaxy located at the position of the optical afterglow indicated a redshift \( z = 0.859 \) for this event (Wiersema et al. 2004).
2. Observations and Data Analysis

Upon receiving the burst alert message from HETE–2 and the optical position reported by Fox & Moon (2004), multi-band (Johnson $B$ and $V$; Bessell $R$ and $I$) follow-up observations of GRB 040924 with the Lulin One-meter Telescope (LOT, in Taiwan) were initiated according to the previously approved Target-of-Opportunity procedure. Photometric images were obtained with the PI1300B CCD camera ($1300 \times 1340$ pixels, $\sim 11' \times 11'$ field of view; Kinoshita et al. 2005) during the interval 14.31–20.89 on Sep. 24 (i.e., 2.4–9.0 hr after the burst). Unfortunately, the earliest observations ($t < 3.1$ hr) were not successful because of poor weather and short exposure times. These problems also affected all of the $B$ and $I$ data, and many of the $V$ and $R$ images as well. Nevertheless, our observations reveal unusual early-time evolution of the afterglow brightness, as discussed below.

A standard routine including bias subtraction and flat-fielding corrections with appropriate calibration data was employed to process the data using IRAF. The afterglow was clearly seen in the $V$-band and $R$-band images (Figure 1). The position of the afterglow is $\alpha(J2000) = 02^h06^m22^s.52, \delta(J2000) = +16^\circ06'48''.82 (\pm0''.23$ in each coordinate). Next, the DAOPHOT package (Stetson 1989) was used to perform aperture photometry of the GRB field by choosing ten field stars for differential photometry. The LOT data were combined with median filtering to improve the signal-to-noise ratio. For the photometry, the aperture diameter was set to 4 times the FWHM of the objects. The magnitude error was estimated as $\sigma_e^2 = \sigma_{ph}^2 + \sigma_{sys}^2$, where $\sigma_{ph}$ is the photometric error of the afterglow estimated from the DAOPHOT output, and $\sigma_{sys}$ is the systematic calibration error estimated by comparing the instrumental magnitudes of the ten field stars. Besides the calibration data obtained by the USNOFS 1.0-m telescope (Henden 2004), we used the measurements of four Landolt (1992) standard-star fields (SA92, PG2331+055, SA95, and PG2317+046) taken by LOT on a photometric night. The difference between the two flux calibrations is within 0.04 mag. The magnitudes derived for the $R$ and $V$ observations are summarized in Table 1.

In addition to the LOT data, we have also included two early measurements from the 0.76-m Katzman Automatic Imaging Telescope (KAIT; Li et al. 2003b) at Lick Observatory at $t = 0.43$ and 1.06 hr. The KAIT data were taken without filters, but the transformation of the unfiltered magnitude to $R$ can be determined from the $V - R$ colors of the GRB field stars and of the optical afterglow (Li et al. 2003a,b). The calibration of the GRB 040924 field is adopted from Henden (2004), and the value $V - R = 0.57$ mag of the afterglow is taken from LOT data at 0.292 d after the burst. KAIT observed the GRB at low airmass.

---

IRAF is distributed by the National Optical Astronomy Observatory, which is operated by AURA, Inc., under cooperative agreement with the National Science Foundation.
(1.26–1.4), and the local standard stars have $V - R$ colors (0.39–0.85 mag) similar to that of the GRB. Moreover, from three photometric nights we found that the coefficient for the second-order extinction is only 0.04; thus, the errors caused by second-order extinction of GRB 040924 are small, and are included in the overall uncertainties of the KAIT data.

3. Results

The light curve of GRB 040924 in Figure 2 is a combination of the early observations reported by Fox (2004) at 0.012 d and 0.033 d after the burst, the work reported here, and the measurements by Khamitov et al. (2004b,c) at $t = 0.37$ d, 0.62 d, and 1.56 d, Fynbo et al. (2004) at $t = 0.73$ d, and Silvey et al. (2004) around $t = 0.9$ d. To put all of the data onto a consistent magnitude scale, we recalibrated the above-mentioned published data by using the Henden (2004) standard stars for the GRB 040924 field. The data of Fox (2004) were calibrated by GSC 2.2 stars$^9$ with F-emulsion magnitude which corresponds closely to the $R$-band magnitude; the GSC stars are 0.11 mag brighter than the Henden standard stars in the average of our images. Since two reference stars are provided by Khamitov et al. (2004b,c) and Fynbo et al. (2004), we measured these stars from LOT $R$-band combined images and obtained the average magnitudes and root-mean-square errors; the results were then used to recalibrate the reported afterglow magnitudes.

The time evolution of the light curve can be expressed in terms of a power law with $F(t) \propto t^\alpha$, where $t$ is the time after the burst and $\alpha$ is the index. We find $\alpha = -0.87 \pm 0.02$ ($\chi^2/\nu= 0.06$ for $\nu = 2$) for the very sparse $V$-band data (only three closely spaced LOT observations and one later observation from Silvey et al. 2004). Similarly, we derive $\alpha = -0.99 \pm 0.02$ ($\chi^2/\nu = 2.08$ for $\nu = 12$) from all 14 available $R$-band observations. These two values of $\alpha$ fall within the range of long GRBs ($\alpha = -0.62$ to $-2.3$), so the afterglow of GRB 040924 is consistent with the standard model of cosmic-ray electrons accelerated by the internal and external shocks of the expanding fireball (Mészáros 2002), as in the case of typical long-duration GRBs.

Upon closer scrutiny, the first three $R$-band observations (at $t = 16$–50 min) indicate $\alpha = -0.7$, consistent with the conclusion of Fox (2004), while the subsequent data (starting from the third $R$-band observation) give a somewhat steeper value of $\alpha = -1.06 \pm 0.03$ (with $\chi^2/\nu = 1.09$ for $\nu = 10$). [Essentially the same late-time result, $\alpha = -1.06 \pm 0.02,$ $\chi^2/\nu = 1.09$ for $\nu = 10$.]  

$^9$The GSC 2.2 is a magnitude-selected subset of GSC II, an all-sky catalog based on 1″ resolution scans of the photographic Sky Survey plates, at two epochs and three bandpasses, from the Palomar and UK Schmidt telescopes (http://www-gss.sron.nl/gsc/gsc2/GSC2home.htm).
is found when we use only our own LOT and KAIT data, together with the Sibley et al. (2004) observation at $t = 0.91\ d$. The data thus suggest the presence of a mild break, the significance of which is discussed below.

Finally, our LOT observations of GRB 040924 at $t = 7.10\ hr$ indicate a color index of $V - R = 0.57 \pm 0.18\ mag$, corrected for foreground reddening of $E(B - V) = 0.058\ mag$ (Schlegel, Finkbeiner, & Davis 1998). We have also calculated the color of observations by Silvey et al. (2004) at $t = 0.91\ d\ (22.1\ hr)$ to be $V - R = 0.35 \pm 0.10\ mag$, corrected for foreground reddening. While these two values are consistent with the color of typical long GRBs ($V - R = 0.40 \pm 0.13\ mag$; Simon et al. 2001), they also may suggest the interesting possibility of a color change during the time evolution of this afterglow. However, the color change is only marginally significant, given the uncertainties. Future GRB afterglow measurements should shed new light on this tantalizing behavior.

4. Discussion

The brightness variations of the optical afterglows of GRBs potentially yield important information on the expansion of the ejecta. For example, breaks in the light-curve power laws at several hours to several days after the bursts have been observed in a number of GRBs. This effect is generally believed to be associated with the evolution as a collimated jet (Rhoads 1999). In the case of GRB 040924, because of the small variation from $\alpha = -0.7$ to $\alpha = -1.06$ around $t = 50\ min$, the break is not well constrained. On the other hand, this small break could be indicative of some interesting physical process. Note that the amplitude of the break ($\Delta\alpha = \alpha_2 - \alpha_1$; here $\alpha_1$ and $\alpha_2$ are the power-law indices before and after the break, respectively) is independent of extinction under the assumption of no color change. In the case of GRB 040924, from $\alpha_1 = -0.7$ and $\alpha_2 = -1.06$ we find $\Delta\alpha \approx -0.36$. According to theoretical work (Rhoads 1999), $\Delta\alpha = -3/4$ for a collimated jet with a fixed angle, and $\Delta\alpha = \alpha_1/3 - 1 \approx -1.23$ for a sideways-expanding jet in the framework of a constant ambient density model. It is clear that the amplitude of the break in GRB 040924 is much smaller than values expected of jet expansion with power-law indices much steeper after the break. The interpretation of a jet break for GRB 040924 is thus uncertain. Next we will explore an alternative possible explanation.

Panaitescu & Kumar (2000) pointed out that a light-curve break could also be caused by the spectral cooling frequency moving through the optical band. This property might be used as a diagnostic tool to differentiate among different possible scenarios of GRB afterglow formation. In the standard GRB afterglow model, it is usually assumed that the synchrotron emission observed in optical bands originates from the expansion of a blast wave
of constant energy into an interstellar medium (ISM) of constant density. However, there is also increasing evidence that some GRBs have massive-star progenitors. Consequently, the corresponding relativistic blast waves should actually be expanding into the stellar wind of the progenitor stars with a density variation of $\rho \propto r^{-2}$ (Dai & Lu 1998; Mészáros et al. 1998; Panaitescu et al. 1998). Zhang & Mészáros (2004) listed the broad-band optical spectra of the synchrotron radiation from a power-law distribution of energetic electrons with a spectral index ($p$) accelerated by the blast wave; accordingly, we can obtain the values of $p$ before and after the cooling break.

As shown in Table 2, the ISM model provides the only possible fit (for $p > 2$) to the GRB 040924 observations which satisfies the requirement that $p$ should remain nearly the same ($p \approx 1.93$ to 2.08) as the spectrum evolves from $\nu_{\text{opt}} < \nu_c$ to $\nu_{\text{opt}} > \nu_c$. Note that within the framework of the ISM model, $p = 2.33$ for $\nu_{\text{opt}} < \nu_c$ and $p = 2.00$ for $\nu_{\text{opt}} > \nu_c$ if the corresponding light curve can be characterized by a single power-law index ($\alpha = -0.99 \pm 0.02$).

Another interesting estimate can be made concerning the relation between the cooling-break frequency $\nu_c$, the break time $t_{\text{day}}$ (in units of days), the redshift $z$, the magnetic energy $\varepsilon_B$, the kinetic energy $E_{52}$ (in units of $10^{52}$ erg), and the density $n_0$ of the ISM. According to Granot & Sari (2004),

$$\nu_c = 6.37(p - 0.46)10^{13}e^{-1.16p}(1 + z)^{-1/2}\varepsilon_B^{-3/2}n_0^{-1}E_{52}^{-1/2}t_{\text{day}}^{-1/2}. \quad (1)$$

Now, with $t_{\text{day}} = 0.035$, $\nu_c = 4.7 \times 10^{14}$ Hz in the $R$ band, $z = 0.859$, $p \approx 2.08$, and the assumptions that $E_{52} = 1.48$ and $n_0 = 1 \text{ cm}^{-3}$, we find $\varepsilon_B \approx 0.16$. This value is consistent with the normal assumption for the magnetic-energy fraction of $\varepsilon_B \approx 0.1$, though slightly larger. For the case of a single power-law index ($\alpha = -0.99 \pm 0.02$), $\varepsilon_B < 0.01$, which is much smaller than the normal value. Our analysis thus suggests that the observed light curve of GRB 040924 could be the result of the spectral cooling frequency moving through the optical band. In other words, the apparent break in GRB 040924 might not be a jet break but rather a cooling break.

5. Conclusion

The 1.2–1.5 s duration of GRB 040924, though formally in the domain of short GRBs, overlaps the short end of long-duration GRBs. Moreover, it has a soft high-energy spectrum, characteristic of long GRBs. Our optical afterglow observations show that the temporal evolution, power-law index, and $V - R$ color of GRB 040924 are also consistent with those of well-observed long GRBs. The signature of a low-amplitude break in the light curve,
suggested by our present data, can be explained by the afterglow model invoking a cooling break at early times. However, note that the jet break usually occurs 1–2 d after the burst, and there are few observations of GRB 040924 at \( t > 1 \) d. Thus, we cannot exclude the possibility that the true jet break occurred outside the range of our observations.

Due to the general lack of information on the optical afterglows of short GRBs, we cannot compare our observations of GRB 040924 to this class of objects. The Swift satellite, with higher gamma-ray sensitivity and more accurate localization than previous missions, will provide more opportunities to understand the properties of typical short GRBs and of GRBs near the boundary between short and long GRBs.

We thank the staff and observers at the Lulin telescope for various arrangements that made possible the observations reported herein. This work is supported by grants NSC 93-2752-M-008-001-PAE and NSC 93-2112-M-008-006. Y.U. acknowledges support from the Japan Society for the Promotion of Science (JSPS) through a JSPS Research Fellowship for Young Scientists. A.V.F. is grateful for NSF grant AST-0307894, and for a Miller Research Professorship at UC Berkeley during which part of this work was completed. KAIT was made possible by generous donations from Sun Microsystems, Inc., the Hewlett-Packard Company, AutoScope Corporation, Lick Observatory, the NSF, the University of California, and the Sylvia and Jim Katzman Foundation.

REFERENCES

Dai, Z. G., & Lu, T. 1998, MNRAS, 298, 87

Fenimore, E. E., et al. 2004, GCN Circ. 2735

Fox, D. B. 2004, GCN Circ. 2741

Fox, D. B., & Moon, D. S. 2004, GCN Circ. 2734

Frail, D. A., & Soderberg, A. 2004, GCN Circ. 2758

Fynbo, J. P. U., Hornstrup, A., Hjorth, J., Jensen, B. L., & Anderson, M. I. 2004, GCN Circ. 2747

Henden, A. 2004, GCN Circ. 2811

Hu, J. H., Lin, H. C., Huang, K. Y., Urata, Y., Ip, W. H., & Tamagawa, T. 2004, GCN Circ. 2744
Golenetskii, S., Aptekar, R., Mazets, E., Pal’shin, V., Frederiks, D., & Cline, T. 2004, GCN Circ. 2754

Khamitov, I., et al. 2004a, GCN Circ. 2740
Khamitov, I., et al. 2004b, GCN Circ. 2749
Khamitov, I., et al. 2004c, GCN Circ. 2752

Kinoshita, D., et al. 2005, ChJAA, 5, 315

Kouveliotou, C., et al. 1993, ApJ, 463, 570

Lee, W. H., & Ramirez-Ruiz, E. 2002, ApJ, 577, 893

Li, W., Filippenko, A. V., Chornock, R., & Jha, S. 2003a, ApJ, 586, L9
Li, W., Filippenko, A. V., Chornock, R., & Jha, S. 2003b, PASP, 115, 844
Li, W., Filippenko, A. V., Chornock, R., & Jha, S. 2004, GCN Circ. 2748

Landolt, A. U. 1992, AJ, 104, 340

MacFadyen, A. I., & Woosley, S. E. 1999, ApJ, 524, 262

Mészáros, P., Rees, M. J., & Wijers, R. A. M. J. 1998, ApJ, 499, 301
Mészáros, P. 2002, ARA&A, 40, 137

Narayan, R., et al. 1992, ApJ, 395, 83
Narayan, R., et al. 2001, ApJ, 557, 494

Panaitescu, A., & Kumar, P. 2000, ApJ, 543, 66
Panaitescu, A., Mészáros, P., & Rees, M. J. 1998, ApJ, 503, 314

Popham, R. 1999, ApJ, 518, 356

Rhoads, J. E. 1999, ApJ, 525, 737

Rosswog, S., & Davies, M. B. 2002, MNRAS, 334, 481

Ruffert, M., et al. 1997, A&A, 319, 122

Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Silvey, J., et al. 2004, GCN Circ. 2833
Simon, V. 2001, A&A, 377, 450
Stetson, P. B. 1987, PASP, 99, 191
Terada, H., Akiyama, M., & Kawai, N. 2004, GCN Circ. 2745
van der Horst, A. J., Rol, E., & Wijers, R. A. M. J. 2004a, GCN Circ. 2746
van der Horst, A. J., Rol, E., & Wijers, R. A. M. J. 2004b, GCN Circ. 2759
Wiersema, K., et al. 2004, GCN Circ. 2800
Woosley, S. E. 1993, ApJ, 405, 273
Zhang, B., & Mészáros, P. 2004, Int. J. Mod. Phys. A., 19, 2385

This preprint was prepared with the AAS L\LaTeX\ macros v5.0.
Fig. 1.— The $R$-band and $V$-band images of GRB 040924 taken with LOT. The location of the afterglow is indicated by a circle in each image.
Fig. 2.— The $V$-band and $R$-band light curves based on our (LOT and KAIT) observations and the recalibrated data points of Fox (2004), Fynbo et al. (2004), Khamitov et al. (2004b,c), and Silvey et al. (2004). The straight lines represent the power-law models $[F(t) \propto t^\alpha]$ fitted to the data points: solid is for the $R$-band $\alpha = -0.7$ at early times (based on the first three observations), dashed is the late-time $R$-band best fit of $\alpha = -1.06 \pm 0.03$ starting from the third observation, and dotted is the $V$-band best fit of $\alpha = -0.87 \pm 0.02$ from LOT and Silvey et al. (2004).
Table 1: Log of GRB 040924 Optical Afterglow Observations

| UT Date   | Start Time | Mean Delay (days) | Filter | Exposure (s) | mag       | Site      |
|-----------|------------|-------------------|--------|--------------|-----------|-----------|
| 2004-09-24| 18:52:37   | 0.296             | V      | 300 s × 3    | 22.01±0.13| LOT       |
| 2004-09-24| 19:46:02   | 0.333             | V      | 300 s × 3    | 22.05±0.16| LOT       |
| 2004-09-24| 20:24:54   | 0.360             | V      | 300 s × 3    | 22.18±0.13| LOT       |
| 2004-09-24| 12:18:21   | 0.018             | R      | 120 s × 1    | 18.44±0.05| KAIT\textsuperscript{a} |
| 2004-09-24| 12:55:21   | 0.044             | R      | 120 s × 1    | 19.31±0.15| KAIT\textsuperscript{a} |
| 2004-09-24| 15:00:55   | 0.140             | R      | 600 s × 2    | 20.71±0.13| LOT       |
| 2004-09-24| 18:34:37   | 0.284             | R      | 300 s × 3    | 21.39±0.15| LOT       |
| 2004-09-24| 19:28:57   | 0.321             | R      | 300 s × 3    | 21.47±0.15| LOT       |
| 2004-09-24| 20:07:48   | 0.348             | R      | 300 s × 3    | 21.47±0.14| LOT       |
| 2004-09-24| 20:42:17   | 0.372             | R      | 300 s × 3    | 21.59±0.17| LOT       |
| 2004-09-25| 08:35:00   | 0.873             | R      | 300 s × 3    | >22.47    | KAIT\textsuperscript{a} |

\textsuperscript{a}KAIT measurements were unfiltered, but transformed to R (Li et al. 2003a,b).
Table 2: Electron Spectral Index ($p$) Calculated from the Measured Spectral Index ($\alpha$)

| Frequency $^a$ | model | $p > 2$ | $1 < p < 2$ |
|---------------|-------|---------|-------------|
|               |       | relation $^b$ | $p_1^c$ | $p_2^c$ | relation $^b$ | $p_1^c$ | $p_2^c$ |
| $\nu_{\text{opt}} < \nu_c$ | ISM | $p = 1 - 4\alpha/3$ | 1.93 | 2.41 | $p = -2\alpha - 10/3$ | -1.93 | -1.21 |
| $\nu_{\text{opt}} > \nu_c$ | ISM | $p = 2/3 - 4\alpha/3$ | 1.60 | 2.08 | $p = -2 - 16\alpha/3$ | 1.73 | 3.65 |
| $\nu_{\text{opt}} < \nu_c$ | Wind | $p = 1/3 - 4\alpha/3$ | 1.26 | 1.74 | $p = -6 - 8\alpha$ | -0.4 | 2.48 |
| $\nu_{\text{opt}} > \nu_c$ | Wind | $p = 2/3 - 4\alpha/3$ | 1.6 | 2.08 | $p = -8 - 8\alpha$ | -2.4 | 0.48 |
| $\nu_{\text{opt}} < \nu_c$ | Jet | $p = -\alpha$ | 0.7 | 1.06 | $p = -6 - 4\alpha$ | -3.2 | -1.76 |
| $\nu_{\text{opt}} > \nu_c$ | Jet | $p = -\alpha$ | 0.7 | 1.06 | $p = -6 - 4\alpha$ | -3.2 | -1.76 |

$^a$The frequency at which the spectrum breaks due to synchrotron cooling is $\nu_c$, whereas the typical visible-light frequency is $\nu_{\text{opt}}$.

$^b$The GRB afterglow model relation of Zhang & Mészáros (2004).

$^c$The electron spectral index calculated from $\alpha_1 = -0.70$ and $\alpha_2 = -1.06$. 