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OPTICAL AFTERGLOW OBSERVATIONS OF THE UNUSUAL SHORT-DURATION GAMMA-RAY BURST GRB 040924

K. Y. Huang,[1] Y. Urata,[2,3] A. V. Filippenko,[4] J. H. Hu,[1] W. H. Ip,[1] P. H. Kuo,[1] W. Li,[4] H. C. Lin,[1] Z. Y. Lin,[1]
K. Makishima,[2,5] K. Onda,[2,6] Y. Qiu,[7] and T. Tamagawa[2]
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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 minutes) and $\alpha = -1.06$ (at later times). The rather small difference in the spectral indices can be explained more easily by an afterglow model invoking a cooling break than by one with a jet break.

Subject heading: 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 (ISM), 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 September 24 at 11:52:11 (UT dates are used throughout this Letter). This event lasted about 1.2 s and was X-ray–rich according to the *HETE-2* flux in the 7–30 and 30–400 keV bands. The Konus experiment on the *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 $t = 16$ minutes after the burst, Fox (2004) detected the corresponding optical afterglow with an *R*-band magnitude of ∼18. This was shortly followed by Li et al. (2004), who reported $R \approx 18.3$ mag at 26 minutes 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 et al. 2004). Radio observations failed to detect the afterglow at $t = 12.54$ hr and $t = 5.79$ days (Frail & Soderberg 2004; van de Horst et al. 2004a, 2004b). Spectral measurements by the Very Large Telescope of a galaxy located at the position of the optical afterglow indicated a redshift of $z = 0.859$ 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), multiband (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 (Huang et al. 2005; Urata et al. 2005). Photometric images were obtained with the PI1300B CCD camera (1300 × 1340 pixels, ∼11′ × 11′ field of view; Kinoshita et al. 2005) during the interval 14.31–20.89 on September 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.[8] The afterglow was clearly seen in the *V*-band and *R*-band images (Fig. 1). The position of the afterglow (J2000.0) is $\alpha = 2^{h}6^{m}22^{s}.52$, $\delta = +16°6'48''.82$ ($\pm 0''.23$ in each coordinate). Next, the DAOPHOT package (Stetson 1987) was used to perform aperture photometry of the GRB field by choosing 10 field stars for differential photometry. The LOT data were combined with median filtering

[1] Institute of Astronomy, National Central University, Chung-Li 32054, Taiwan (Huang e-mail: d919003@astro.ncu.edu.tw).
[2] RIKEN (Institute of Physical and Chemical Research), 2-1 Hirosawa, Wako, Saitama 351-0198, Japan.
[3] Department of Physics, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8551, Japan.
[4] Department of Astronomy, University of California, Berkeley, CA 94720-3411.
[5] Department of Physics, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan.
[6] Department of Physics, Saitama University, Shimookubo, Urawa 338-8570, Japan.
[7] National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China.

[8] IRAF is distributed by the National Optical Astronomy Observatory, which is operated by AURA, Inc., under cooperative agreement with the NSF.

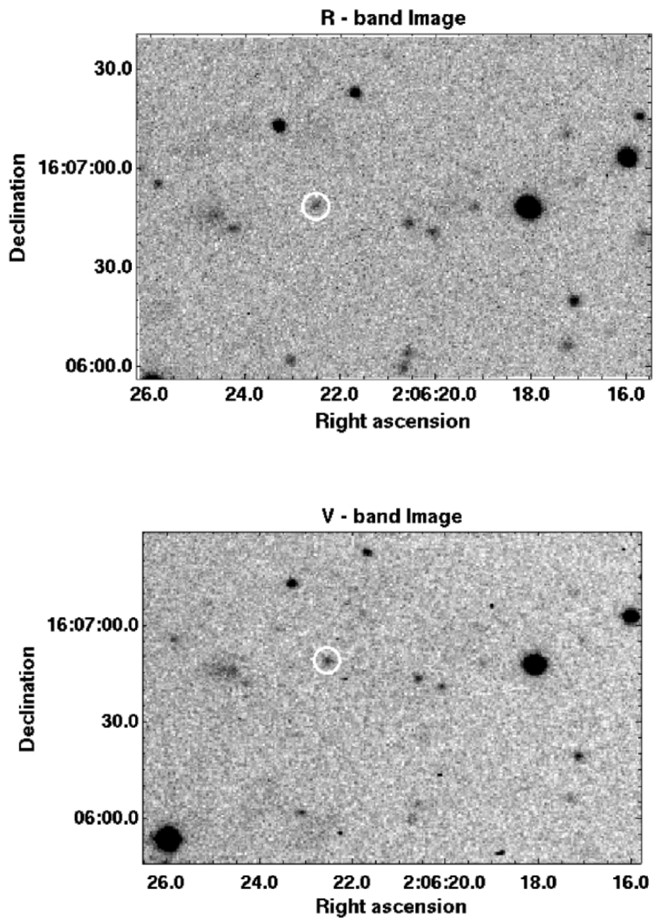

Fig. 1.—*R*-band and *V*-band images of GRB 040924 taken with LOT. The location of the afterglow is indicated by a circle in each image.

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 σ_{ph} is the photometric error of the afterglow estimated from the DAOPHOT output, and σ_{sys} is the systematic calibration error estimated by comparing the instrumental magnitudes of the 10 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 (SA 92, PG 2331+055, SA 95, and PG 2317+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, 2003b). 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 days after the burst. KAIT observed the GRB at low air mass (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 and 0.033 days after the burst, the work reported here, and the measurements by Khamitov et al. (2004b, 2004c) at $t = 0.37$, 0.62, and 1.56 days, Fynbo et al. (2004) at $t = 0.73$ days, and Silvey et al. (2004) around $t = 0.9$ days. 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 Guide Star Catalog (GSC; ver. 2.2)[9] stars 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, 2004c) and Fynbo et al. (2004), we measured these stars from LOT *R*-band combined images and obtained the average magnitudes and rms errors; the results were then used to recalibrate the reported afterglow magnitudes.

The time evolution of the light curve can be expressed in

[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-gsss.stsci.edu/gsc/gsc2/GSC2home.htm).

TABLE 1
Log of GRB 040924 Optical Afterglow Observations

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

[a] KAIT measurements were unfiltered but transformed to *R* (Li et al. 2003a, 2003b).

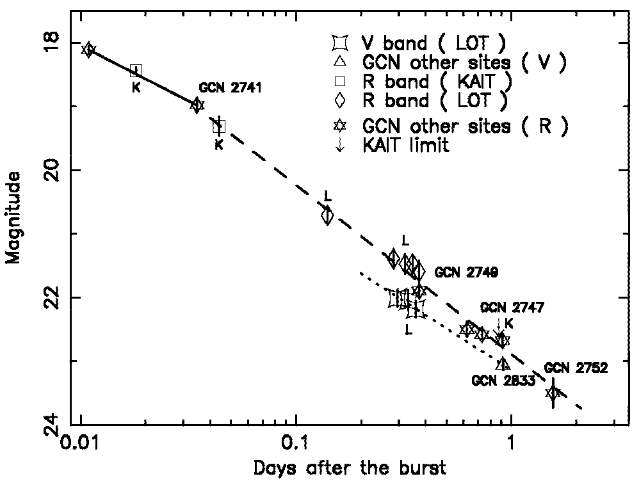

FIG. 2.—*V*-band and *R*-band light curves based on our (LOT and KAIT) observations and the recalibrated data points of Fox (2004), Fynbo et al. (2004), Khamitov et al. (2004b, 2004c), and Silvey et al. (2004). The lines represent the power-law models [$F(t) \propto t^{\alpha}$] fitted to the data points. *Solid line*: *R*-band $\alpha = -0.7$ at early times (based on the first three observations). *Dashed line*: Late-time *R*-band best fit of $\alpha = -1.06 \pm 0.03$ starting from the third observation. *Dotted line*: *V*-band best fit of $\alpha = -0.87 \pm 0.02$ from LOT and Silvey et al. (2004).

terms of a power law with $F(t) \propto t^{\alpha}$, where t is the time after the burst and α 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 α 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 minutes) 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, $\alpha = -1.06 \pm 0.02$, is found when we use only our own LOT and KAIT data, together with the Silvey et al. [2004] observation at $t = 0.91$ days.) 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 et al. 1998). We have also calculated the color of observations by Silvey et al. (2004) at $t = 0.91$ days (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 -1.06 around $t = 50$ minutes, 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 α_1 and α_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 ISM of constant density. However, there is 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 broadband 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 that satisfies the requirement that p should remain nearly the same ($p \approx 1.93$–2.08) as the spectrum evolves from $\nu_{\rm opt} < \nu_c$ to $\nu_{\rm opt} > \nu_c$. Note that within the framework of the ISM model, $p = 2.33$ for $\nu_{\rm opt} < \nu_c$ and $p = 2.00$ for $\nu_{\rm opt} > \nu_c$ 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 ν_c, the break time $t_{\rm days}$ (in units of days), the redshift z, the magnetic energy ϵ_B, the kinetic energy E_{52} (in units of 10^{52} ergs), and the density n_0 of the ISM. According to Granot & Sari (2002),

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

Now, with $t_{\rm days} = 0.035$, $\nu_c = 4.7 \times 10^{14}$ Hz in the *R* band, $z = 0.859$, $p \approx 2.08$, and the assumptions that $E_{52} = 1.48$ and $n_0 = 1\ {\rm cm}^{-3}$, we find $\epsilon_B \approx 0.16$. This value is consistent with the normal assumption of a magnetic energy fraction of $\epsilon_B \approx 0.1$, although slightly larger. For the case of a single power-law index ($\alpha = -0.99 \pm 0.02$), $\epsilon_B < 0.01$, 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.

TABLE 2
ELECTRON SPECTRAL INDEX (p) CALCULATED FROM THE MEASURED SPECTRAL INDEX (α)

	$p > 2$			$1 < p < 2$		
Frequency[a]	Relation[b]	p_1[c]	p_2[c]	Relation[d]	p_1[c]	p_2[c]
ISM model:						
$\nu_{opt} < \nu_c$	$p = 1 - 4\alpha/3$	1.93	2.41	$p = -2\alpha - 10/3$	−1.93	−1.21
$\nu_{opt} > \nu_c$	$p = 2/3 - 4\alpha/3$	1.60	2.08	$p = -2 - 16\alpha/3$	1.73	3.65
Wind model:						
$\nu_{opt} < \nu_c$	$p = 1/3 - 4\alpha/3$	1.26	1.74	$p = -6 - 8\alpha$	−0.4	2.48
$\nu_{opt} > \nu_c$	$p = 2/3 - 4\alpha/3$	1.6	2.08	$p = -8 - 8\alpha$	−2.4	0.48
Jet model:						
$\nu_{opt} < \nu_c$	$p = -\alpha$	0.7	1.06	$p = -6 - 4\alpha$	−3.2	−1.76
$\nu_{opt} > \nu_c$	$p = -\alpha$	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 ν_c, whereas the typical visible-light frequency is ν_{opt}.
[b] The GRB afterglow model relation of Zhang & Mészáros (2004).
[c] The electron spectral index calculated from $\alpha_1 = -0.70$ and $\alpha_2 = -1.06$.
[d] The GRB afterglow model relation of Dai & Cheng (2001).

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, although formally in the domain of short GRBs, overlaps the short end of long 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, as 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 days after the burst, and that there are few observations of GRB 040924 at $t > 1$ days. 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.

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