MULTIBAND OPTICAL FOLLOW-UP OBSERVATIONS OF GRB 020813 AT THE KISO AND BISEI OBSERVATORIES

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ABSTRACT

Observations were made of the optical afterglow of GRB 020813 (Fox, Blake, & Price) with the Kiso observatory 1.05 m Schmidt telescope and the Bisei astronomical observatory 1.01 m telescope. Four-band (B, V, R, and I) photometric data points were obtained on 2002 August 13 (10:52–16:46 UT), or 0.346–0.516 days after the burst. In order to investigate the early-time (<1 day) evolution of the afterglow, four-band light curves were produced by analyzing the data taken at these two astronomical observatories as well as the publicly released data taken using the Magellan Baade telescope (Gladders & Hall). The light curves can be approximated by a broken power law, of which the indices are approximately 0.46 and 1.33 before and after a break at ~0.2 days, respectively. The optical spectral index stayed approximately constant at ~0.9 over 0.17–4.07 days after the burst. Since the temporal decay index after the break and the spectral index measured at that time are both consistent with those predicted by a spherical expansion model, the early break is unlikely to be a jet break but is likely to represent the end of an early bump in the light curve, as was observed in the optical afterglow of GRB 021004.

Subject headings: cosmology: observations — gamma rays: bursts

1. INTRODUCTION

The afterglow of a gamma-ray burst (GRB), observed in X-ray through radio frequencies, can be interpreted in the fireball models, wherein a shock produced by the interaction of relativistic ejecta with the circumburst environment expands into the surrounding medium, producing broadband synchrotron emission (Mészáros & Rees 1997; Sari, Piran, & Narayan 1998). If the GRB is collimated into a jet, the entire jet surface becomes visible to the observers at some time tj. As the jet starts to expand laterally at around tj (Rhoads 1999), its sweeping area increases faster than before, leading to a stronger deceleration and hence a faster afterglow decay. The rapid decay of some GRB afterglows, observed recently, provides evidence of such jetlike or collimated ejecta (Sari, Piran, & Halpenny 1999). The jet model would relax the energy requirements on some of the more extreme GRBs by a factor of several hundred (Frail et al. 2001).

The bright and long event, GRB 020813, was detected on 2002 August 13, with the High-Energy Transit Explorer 2 (HETE-2) spacecraft (Ricker et al. 2003). The flight localization was reported in a GCN Position Notice at 02:48:33 UT, 4 minutes and 14 s after the burst trigger. The subsequent ground analysis of the HETE-2 data produced a refined burst location, which was reported in a GCN Position Notice at 05:48:35 UT, 184 minutes after the burst. The location, with a 90% confidence error radius of 60" (due entirely to systematic errors), is centered at α2000 = 19h46m38s, δ2000 = 19°36′05″ (Villasenor et al. 2002).

The optical afterglow was found within the 60" radius error circle at 0.078 days (112 minutes) after the burst, at the coordinates of α2000 = 19h46m41s.88, δ2000 = 19°36′05″ (Fox, Blake, & Price 2002). Optical spectra of the afterglow taken with the Keck observatory exhibit numerous absorption lines, indicating a minimum redshift of 1.254 ± 0.005 (Price et al. 2002). Early optical light curves of the afterglow are suggested to have undergone a temporal break at 3.5–5 hr after the burst (Bloom, Fox, & Hunt 2002).

The Kiso observatory of the University of Tokyo and the Bisei Astronomical Observatory (BAO) have established, for the first time in Japan, the capability of multiband follow-up observations of GRBs (Urata et al. 2003a). The two sites serve as valuable additions to the world-wide optical and infrared follow-up network because the Japan area would otherwise be blank for the network.

In order to investigate the early (within 1 day of the burst) evolution of the optical afterglow of GRB 020813 in the flux (e.g., temporal decay and the existence of a jet break) and the spectral slope, we have analyzed the Kiso and BAO data. In addition, we analyze the publicly released data of the afterglow obtained using the Magellan Baade telescope (Gladders & Hall 2002b).

2. OBSERVATIONS

We carried out follow-up observations of the optical afterglow of GRB 020813 with the 1.05 m Schmidt telescope and a 2k × 2k CCD camera at the Kiso observatory, starting in 2002 August 13 (10:52 UT; 0.339 days after the burst). The field of view is 51.2 × 51.2, and the pixel size is 1.5 square. We performed B-, V-, R-, and I-band observations using a system prepared for the GRB’s follow-up observations (Urata et al. 2003a). We obtained the mult-band data as described in Table 1, with each data set consisting of triple frames.

We also performed R-band observations using the 1.01 m telescope with a Mutoh CV16HE CCD camera (Kodak KAF1602E chip) at the BAO, starting in 2002 August 13 (11:44:19 UT; 0.375 days after the burst). The field of view is 7.8 × 5.2, and the pixel size is 0.9 square. We obtained 36 frames of R-band data, each with 60 s exposure (Table 1).

An extensive observation of the afterglow was also per-
formed with the Magellan Baade 6.5 m telescope, on the nights of August 13 and 14 (0.13–0.94 days after the burst). These data were obtained in the B, V, R, and I bands, each for 60 s, using a Tek5 camera (Gladders & Hall 2002b). The four-band images, after bias subtraction and flat-fielding, were made publicly available by Gladders & Halls (2002b). We have retrieved the images from the ftp site introduced by them. The data consist of 4, 13, 14, and 21 frames in the B, V, R, and I bands, respectively.

3. ANALYSIS AND RESULTS

3.1. Photometry

We processed the Kiso and BAO data by a standard method using the NOAO IRAF. We used appropriate calibration data for the bias subtraction and flat-fielding corrections. An example of the I-band images that we obtained is shown in Figure 1. Thus, the afterglow is clearly detected in the images of all observations listed in Table 1.

The Kiso, BAO, and Baade data have been combined, and their median value has been assigned to each pixel. Flux calibrations among the different sites were done using the APHOT package in IRAF, referring to the standard stars suggested by Henden (2002). Specifically, we utilized three of them, at the J2000 coordinates of α, δ = 19°46′41.1672, −19°36′00.4545, α, δ = 19°46′43.9488, −19°36′01.166, and α, δ = 19°46′44.5416, −19°35′41.662. We set the aperture size to 4 times as large as the FWHM of objects for each data. We summarize the results of our photometry in Table 1.

3.2. Light Curves

Figure 2 shows four-band light curves of the optical afterglow based on our measurements. We thus cover a time period of 0.17–0.94 days after the burst in the V, R, and I band, with the Kiso, BAO, and Baade data sets. The Baade data sets densely cover the early phase (<0.2 days), with an additional coverage at 0.94 days. The Kiso and BAO data, in contrast, constrain the light curves in the intermediate (0.35–0.52 days) range.

First, we tried to fit the V-, R-, and I-band light curves by a simple power law of the form proportional to $t^{-\alpha}$, where $t$ is the time after the burst onset and $\alpha$ is a constant called the decay index. This gave $\alpha = 1.05$ with a reduced $\chi^2(\nu) = 2.44$ for the V band, $\alpha = 1.03$ with $\chi^2(\nu) = 4.12$ for the R band, and $\alpha = 0.89$ with $\chi^2(\nu) = 53.6$ for the I band. Thus, none of the three light curves are consistent with a single-power-law decay.

Next, we tried to fit the light curves with a broken power-law model expressed as

$$F_i = f_a(t/t_a)^{-\alpha_1}[1 - \exp(-J)]J,$$

$$J(t, t_a, \alpha_1, \alpha_2) = (t/t_a)^{(\alpha_2-\alpha_1)},$$

where $f_a$, $t_a$, $\alpha_1$, and $\alpha_2$ are four parameters. This functional form has no physical significance, but it provides a good description to the GRB 990510 data, with the asymptotic power-law indices being $\alpha_1$ and $\alpha_2$ at early and late times, respectively (Harrison et al. 1999).

We have successfully fitted the above function to the V-, R-, and I-band light curves. For the V band, we have obtained $\alpha_1 = 0.46 \pm 0.05$, $\alpha_2 = 1.35 \pm 0.01$, and $t_a = 0.22 \pm 0.01$ ($\chi^2(\nu) = 0.60$ with $\nu = 11$); for the R band, $\alpha_1 = 0.46 \pm 0.06$, $\alpha_2 = 1.33 \pm 0.01$, and $t_a = 0.21 \pm 0.01$ ($\chi^2(\nu) = 0.92$ with $\nu = 12$); and for the I band, $\alpha_1 = 0.30 \pm 0.02$, $\alpha_2 = 1.30 \pm 0.01$, and $t_a = 0.23 \pm 0.01$ ($\chi^2(\nu) = 1.19$ with $\nu = 12$).

TABLE 1

| Start Time (UT) | Filter | Exposure | Magnitude | Site |
|-----------------|--------|----------|-----------|------|
| 11:58:04 ...... | B      | 3 x 300 s| 19.96 ± 0.29 | Kiso |
| 13:29:06 ...... | B      | 3 x 300 s| 20.20 ± 0.09 | Kiso |
| 14:57:03 ...... | B      | 3 x 300 s| 20.30 ± 0.18 | Kiso |
| 13:07:08 ...... | V      | 3 x 300 s| 19.77 ± 0.09 | Kiso |
| 14:35:12 ...... | V      | 3 x 300 s| 19.77 ± 0.25 | Kiso |
| 10:52:26 ...... | R      | 3 x 300 s| 19.16 ± 0.07 | Kiso |
| 11:44:19 ...... | R      | 36 x 60 s| 19.35 ± 0.13 | Bisei |
| 12:23:20 ...... | R      | 3 x 300 s| 19.21 ± 0.09 | Kiso |
| 13:51:16 ...... | R      | 3 x 300 s| 19.55 ± 0.06 | Kiso |
| 11:14:23 ...... | I      | 3 x 300 s| 18.47 ± 0.14 | Kiso |
| 12:45:17 ...... | I      | 3 x 300 s| 18.87 ± 0.15 | Kiso |
| 14:13:19 ...... | I      | 3 x 300 s| 18.79 ± 0.10 | Kiso |

Fig. 1.—I-band image of the GRB 020813 field obtained at the Kiso observatory, with a 300 s exposure starting at 2002 August 13 (11:14 UT). The afterglow is indicated by a circle near the image center.

Fig. 2.—B-, V-, R-, and I-band light curves based on the photometry of Kiso, Bisei, and Baade. The curves represent the broken power-law model (Harrison et al. 1999) fitted to the V-, R-, and I-band light curves.
Thus, the decay is relatively independent of color, as evidenced by nearly the same values of \( t_\alpha \) ~ 0.2 days found among the three bands. An initial analysis of the optical light curve suggested \( t_\alpha \sim 3.5–5 \) hr (Bloom et al. 2002; Gladders & Hall 2002a).

We fitted a single power law to the B-band data because we lack data before the break. The obtained index is \( \alpha = 1.32 \pm 0.03 \), with \( \chi^2/\nu = 0.26 \). Thus, the slope agrees with the values of \( \alpha_B \) found in the three longer wavelengths.

The X-ray afterglow, observed by the Chandra High Energy Transmission Grating at 0.88–1.78 days after the burst, faded in brightness according to a power law, with a decay index of 1.42 ± 0.05 (Vanderspek et al. 2002). This is close to the optical values that we measured after the break.

### 3.3. Spectral Flux Distributions

We have converted the BVRI magnitudes to fluxes using the effective wavelengths and normalizations of Fukugita, Shiemasu, & Ichikawa (1995). To remove the effects of the Galactic interstellar extinction, we used the reddening map of Schlegel, Finkbeiner, & Davis (1998). The Galactic reddening toward the burst is significant, \( E(B-V) = 0.101 \), which implies a Galactic extinction of \( A_B = 0.44, A_V = 0.34, A_R = 0.27, \) and \( A_I = 0.20 \).

In Figure 3, we plot the spectral flux distributions obtained in this way using the Kiso data (0.43 days after the burst) and the Baade data (0.17, 0.20, and 0.94 days after the burst). We fitted them with a power-law function as \( f (\nu) \propto \nu^{\beta} \), where \( f (\nu) \) is the flux density at frequency \( \nu \) and \( \beta \) is the spectral index. We have obtained \( \beta = 0.93 \pm 0.04, 0.82 \pm 0.03, 0.93 \pm 0.16, \) and \( 0.91 \pm 0.07 \) at \( t = 0.17, 0.20, 0.43, \) and 0.94 days, respectively. The former two values of \( \beta \) were calculated using the V-, R-, and I-band data, and the latter two values utilized the four-band data. Thus, the measured values of \( \beta \) are consistent with being constant at \( \beta = 0.87 \pm 0.03 \) because fitting them with a constant yields \( \chi^2/\nu = 1.82 \) with \( \nu = 3 \).

The optical spectral index of the GRB 020813 afterglow was reported as \( \beta = 1.06 \pm 0.01 \) from the red side of the Keck spectra (5600–9400 Å) taken at about \( t = 0.19 \) days (Barth et al. 2003). Correcting it for the Galactic extinction quoted above, we obtain \( \beta \sim 0.7 \). Levan et al. (2002) reported \( \beta = 0.8 \) from the Hubble Space Telescope imaging data taken at \( t = 4.08 \) days. Since these measurements consistently imply \( \beta = 0.7–0.9 \), the spectral slope \( \beta \) is suggested to have remained rather constant over a period of \( t = 0.17–4.08 \) days.

### 4. Discussion

We analyzed the GRB 020813 afterglow images in four bands, observed over a period of 0.33–0.52 days after the burst at the Kiso and Bisei observatories. We also reanalyzed the publicly released four-band images taken with the Baade 6.5 m telescope (Gladders & Hall 2003b). These data sets, when combined, define relatively well-sampled light curves (in the B, V, R, and I bands) covering \( t = 0.17–0.94 \) days. The V-, R-, and I-band light curves are rather similar and can be described by a broken power law of \( \alpha_V \sim 0.4 \) and \( \alpha_R \sim 1.3 \), with a break point at \( t \sim 0.2 \) days. Meanwhile, the spectral index of the afterglow remained at \( \beta \sim 0.9 \). As can be seen from Figure 2, the present Kiso and BAO data are essential in the determination of the overall light curves.

Optical light curves of several GRBs exhibit a temporal break at \( t \sim 1 \) day or later. The decay index of the light curve is typically \( \sim 1 \) and \( \sim 2 \), before and after the break, respectively. In contrast, the afterglow of GRB 020813 showed an unusually early break time at 0.2 days. So far, the earliest break was observed in GRB 010222, at 0.73 days (Watanabe et al. 2001).

In addition, the decay index of \( \alpha_V \sim 0.46 \) observed from the present afterglow is smaller than those of other afterglows, while \( \alpha_V \) is similar to the \( \alpha_R \) of other bursts. These are reminiscent of the afterglow of GRB 021004; its light curve showed an early bump characterized by a brightening phase lasting until \( \sim 0.07 \) days, followed by a dimming with a decay index of \( \sim 0.2 \) (Urata et al. 2003b) that is close to the present \( \alpha_V \).

Usually, these temporal breaks are successfully interpreted by the jet model (Rhoads 1999; Sari et al. 1999). The jet model predicts the time-dependent spectral flux to vary as \( F_{\nu} (t) \propto \nu^{-\beta} \), wherein the temporal decay index \( \alpha \) and the spectral index \( \beta \) are both determined uniquely by the electron power-law spectral index \( p \). In order to examine whether or not the jet model is applicable to the present afterglow, we utilized the relations by Sari et al. (1999) and calculated the values of \( p \) and \( \alpha \) based on the observed \( \beta \). The results are shown in Table 2 together with the employed relations. Thus, the values of \( \alpha_V = 0.3–0.46 \) that we observed are too flat to be reproduced by the jet model under any condition, while those of \( \alpha_R = 1.30–1.35 \) agree with the model prediction, assuming that we are observing a spherical fireball (i.e., before the break) in the frequency range below the synchrotron cooling.

In the above discussion suggests that the behavior of the present light curves after their apparent break at 0.2 days is consistent with what is expected before the jet break in terms of the standard jet model. Therefore, the observed break is
probably distinct from the usual jet break. If so, the electron spectral index is inferred from Table 2 to be \( p = 2.8 \), which falls at the steepest end of the distribution of \( p \) (1.4–2.8; Panaitescu & Kumar 2001); it is close to that of GRB 980519 \( (p \sim 2.8) \). If the jet break exists in this burst, it should occur later than \( t = 0.94 \) days. We suggest that the mild break observed in the present light curves is reminiscent of a similar break that was observed in the decay phase of an early bump in the GRB 021004 afterglow. The GRB 021004 afterglow showed a brightening phase over 0.05–0.07 days after the burst based on the Kiso observation, followed by a temporal break around 0.2 days across which the decay index changed from 0.2 to 0.7 (Urata et al. 2003b). In the case of GRB 021004, the optical color changed over the bump but remained constant across the break, like in the present light curves; the behavior may be explained by a crossing of the typical synchrotron frequency through the optical band (Kobayashi & Zhang 2003).

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