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RAPTOR OBSERVATIONS OF DELAYED EXPLOSIVE ACTIVITY IN THE HIGH-REDSHIFT GAMMA-RAY BURST GRB 060206

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ABSTRACT

The *Rap*id *T*elescopes for *O*ptical *R*esponse (RAPTOR) system at Los Alamos National Laboratory observed GRB 060206 starting 48.1 minutes after γ-ray emission triggered the Burst Alert Telescope on board the *Swift* satellite. The afterglow light curve measured by RAPTOR shows a spectacular rebrightening by ~1 mag about 1 hr after the trigger and peaks at $R \sim 16.4$ mag. Shortly after the onset of the explosive rebrightening, the optical transient doubled its flux on a timescale of about 4 minutes. The total R-band fluence received from GRB 060206 during this episode is 2.3×10^{-9} ergs cm^{-2}. In the rest frame of the burst ($z = 4.045$), this yields an isotropic equivalent energy release of $E_{\rm iso} \sim 0.7 \times 10^{50}$ ergs in just a narrow UV band, $\lambda \simeq 130 \pm 22$ nm. We discuss the implications of RAPTOR observations for untriggered searches for fast optical transients and studies of GRB environments at high redshift.

Subject headings: cosmology: observations — gamma rays: bursts — shock waves

Online material: machine-readable table

1. INTRODUCTION

Since the launch of the *Swift* satellite (Gehrels et al. 2004) in the fall of 2004, the number of gamma-ray bursts (GRBs) with known high redshifts has been rapidly increasing. The sample of classical long-soft GRBs with $z > 2.5$ includes at least 10 objects (Jakobsson et al. 2006a, 2006b). The current record holder, GRB 050904 at $z = 6.295$ (Kawai et al. 2006), is located close to the boundary of the reionized universe (Watson et al. 2006; Totani et al. 2006), on par with the most distant galaxies and quasars known today (e.g., Kodaira et al. 2003; Fan et al. 2003).

These developments are due to both *Swift*'s sensitivity to high-z events and high-precision rapid localizations from the BAT instrument (cf. Berger et al. 2005). The immediate self–follow-up capability of *Swift* in X-ray and optical/UV bands (Gehrels et al. 2004), combined with observations from fast-slewing robotic telescopes on the ground (e.g., Akerlof et al. 2003; Bloom 2004; Boër 2001; Covino et al. 2004; Guidorzi et al. 2006b; Pérez-Ramírez et al. 2004; Vestrand et al. 2002), greatly improves the probability of catching an optical counterpart before it is too faint to grant a high-resolution spectrum. An equally important outcome is well-sampled, multiwavelength light curves that enable studies of broadband spectral evolution reaching into the critical first minutes of the explosion (e.g., Blustin et al. 2006; Vestrand et al. 2005, 2006; Rykoff et al. 2005).

Fast response technology played an important role in the recent discoveries of prompt optical/IR light in GRBs (Vestrand et al. 2005, 2006; Blake et al. 2005), X-ray flares (e.g., O'Brien et al. 2005; Burrows et al. 2005, 2006), rich structure in temporal profiles of early afterglows with multiple breaks (e.g., O'Brien et al. 2005; Nousek et al. 2006), and signatures of extended internal engine activity (e.g., Falcone et al. 2006a, 2006b). These newly established features are providing powerful clues about the physics of GRB explosions, their progenitors, and the surrounding environments. It is essential to study those phenomena across a wide redshift range, as metallicity effects are likely to make distant GRBs longer, more energetic, and easier to produce (Woosley & Janka 2006; Woosley & Heger 2006).

Here we present new evidence for late-time explosive activity in high-z GRBs based on optical observations of GRB 060206 collected by the RAPTOR experiment.

2. OBSERVATIONS

On 2006 February 6, 04:46:53 UT (trigger time, hereafter $t = 0$), the Burst Alert Telescope (BAT) instrument of the *Swift* satellite (Gehrels et al. 2004) detected GRB 060206 (trigger No. 180455). The temporal profile over the interval $t = [-1, 10]$ s in the combined BAT energy range 15–350 keV is a single, bright Gaussian-like peak with duration $T_{90} = 7 \pm 2$ s (Morris et al. 2006b; Palmer et al. 2006). The 15–350 keV fluence, the peak flux, and the photon index of the time-averaged spectrum were subsequently measured to be respectively $(8.4 \pm 0.4) \times 10^{-7}$ ergs cm^{-2}, 2.8 photons cm^{-2} s^{-1}, and 1.06 ± 0.34 (Palmer et al. 2006). The onboard location (Morris et al. 2006b) was distributed in near-real time through the GRB Coordinates Network (GCN) at 04:47:07.7 UT, $t \simeq 14.7$ s.

About 1 s later, the RAPTOR-S telescope received the BAT localization, which placed the object below the altitude limit of the instrument (~19°). The RAPTOR scheduling software restarted the alert response sequence at 05:34:58 UT, $t = 48.1$ minutes, that is, immediately after the BAT position became accessible. The system collected a series of 100 30 s images covering the next hour. Despite high air mass and windy conditions, the final quality of our unfiltered images is very good (Fig. 1). RAPTOR-S is a 0.4 m, fully autonomous robotic telescope, typically operated at focal ratio f/5. It is equipped with a 1K × 1K pixel CCD camera employing a back-illuminated Marconi CCD47-10 chip with 13 μm pixels. The telescope is owned by Los Alamos National Laboratory and located at the Fenton Hill Observatory (W106°.67, N35°.88) at an altitude of ~2500 m in the Jemez Mountains of New Mexico.

The RAPTOR data processing system has capability to automatically locate optical counterparts to GRBs in real time (Woźniak et al. 2006b). About 5 minutes into the response sequence for GRB 060206, that is, after nine images, the system identified an uncataloged 17th magnitude variable object at R.A. = $13^{\rm h}31^{\rm m}43^{\rm s}.44$, decl. = $35°03'03''.2$ (J2000), a location ~1'.6 from the onboard BAT position and well inside the 3'

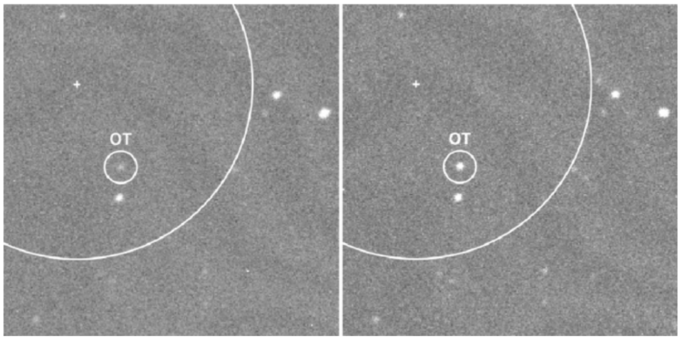

Fig. 1.—RAPTOR-S images of GRB 060206. The optical transient (OT) was an $R = 17.3$ mag object about 48.1 minutes after the trigger (*left*), and only 11 minutes later had increased its flux by almost 1 mag (*right*). The initial BAT localization is marked with a plus sign. The error radius is 3′ (*large circle*).

error radius. This machine-generated identification of a possible optical transient (OT) associated with GRB 060206 was forwarded immediately (at 05:39:50 UT) to the RAPTOR rapid-response team using a wireless network. A quick examination of the unfolding light curve indicated that 50 minutes after the trigger, the candidate OT was undergoing a dramatic rebrightening. The initial report of a nondetection in a 72 s *V*-band frame taken by the Ultraviolet/Optical Telescope (UVOT) at $t \simeq 58$ s (Morris et al. 2006b) seemed to contradict the case for a long-lasting optical event. This unusual behavior of the OT prompted our further investigation of its association with GRB 060206 before announcing the optical counterpart.

In the meantime, Fynbo et al. (2006a) reported a candidate afterglow found using the 2.5 m Nordic Optical Telescope. The position of the proposed afterglow was consistent with that of the variable source found by RAPTOR. The afterglow hypothesis was quickly confirmed by reexamination of the UVOT data (Boyd et al. 2006) and measurement of a spectroscopic redshift of $z = 4.045$ (Fynbo et al. 2006b, 2006c). By this time, the RAPTOR light curve clearly showed that GRB 060206 displayed a spectacular rebrightening to ∼16.3 mag around $t = 1$ hr and had resumed its fading behavior (Woźniak et al. 2006a). This remarkable rebrightening was promptly confirmed by observations with the 2 m Liverpool Telescope (Guidorzi et al. 2006a; Monfardini et al. 2006).

3. PHOTOMETRY

After correction for bias, dark current, and flat-field instrumental effects, the RAPTOR real-time photometric pipeline performs source detection and centroiding using custom routines similar to those used in the SExtractor package (Bertin & Arnouts 1996). Flux peaks are detected in images smoothed with a Gaussian kernel (FWHM = 4.0 pixels). This matches the typical (largely instrumental) seeing of ∼5″ (FWHM) and 1″.2 pixel^{-1} plate scale of RAPTOR-S. Magnitudes are measured using simple aperture photometry with a 5 pixel radius. Errors are estimated by propagating the photon noise.

The flux scale, with about 3% internal consistency, was established using ∼30 high signal-to-noise ratio (S/N) objects covering the entire 24′ × 24′ field of view. Our unfiltered optical band has an effective wavelength close to that of the standard *R* band, but it has a larger width. For lack of the instrumental color information, one is forced to assume that all objects have the color of a mean star in the field. Our calibration to standard *R*-band magnitudes is based on 26

TABLE 1
RAPTOR Photometry of GRB 060206

t_{start} (minutes)	R^a (mag)	σ (mag)
48.1	17.33	0.09
48.7	17.23	0.07
49.3	17.14	0.07
49.9	17.30	0.08
50.5	17.05	0.06

Note.—Table 1 is published in its entirety in the electronic edition of the *Astrophysical Journal*. A portion is shown here for guidance regarding its form and content.

[a] Our unfiltered magnitudes were transformed to *R*-band scale (§ 3) and were not corrected for extinction [Galactic $E(B-V)$ reddening is only 0.018 mag; Schlegel et al. 1998].

sources from the USNO-B1.0 catalog. Comparison point sources were selected to have galaxy-star separation index GS ≥ 5 and R2 magnitudes brighter than 18.0 in the catalog (Monet et al. 2003).

4. RESULTS

The RAPTOR photometry of the optical afterglow of GRB 060206 is given in Table 1 and plotted in Figure 2. During the first ∼700 s after the burst position became visible (t = 48–60 minutes), the OT flux is sharply rising from $R \sim 17.3$ to a peak value of ∼16.4 mag. This peak flux was roughly maintained for the next ∼4 minutes. The subsequent decline to ∼16.75 mag at $t = 80$ minutes was followed by a secondary ∼0.1 mag brightening around $t = 95$ minutes. For the remaining 15 minutes of the response sequence, the OT was somewhat erratically fading to ∼17.0 mag. The majority of the small-scale variations in the light curve are simply statistical fluctuations due to measurement uncertainties. However, a visual inspection of the RAPTOR images indicates that some of the larger changes on timescales of a few minutes are intrinsic to the OT. We estimated the rate of flux decay after the first brightening episode (time interval 62–76 minutes) by fitting a power-law model $f(t) \propto f(t_d)[(t - t_0)/(t_d - t_0)]^{\alpha}$, where t_d is the beginning of the decline and t_0 is typically associated with the explo-

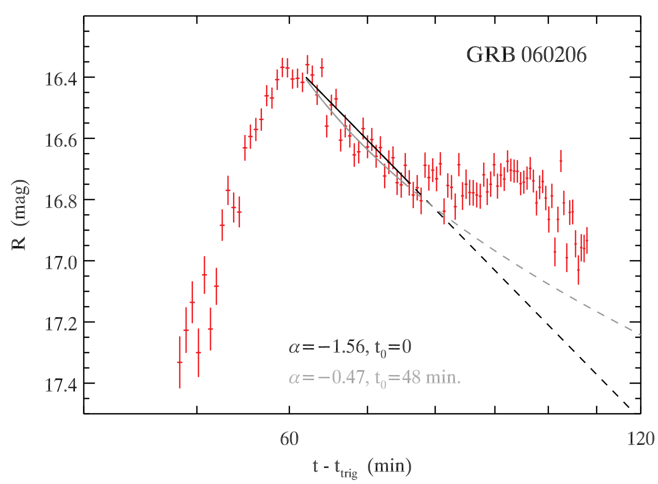

Fig. 2.—RAPTOR-S optical light curve measured for GRB 060206. The two power-law models shown have about the same goodness of fit during the time interval 62–76 minutes after the GRB trigger (§ 4). At the onset of the explosive rebrightening, the OT flux doubled on a timescale of 4 minutes. The fading behavior of the OT is consistent with a power-law flux decay of index $\alpha = -1$.

sive energy injection. The best-fit model with $t_0 = 0$ has $\alpha = -1.56 \pm 0.04$, and assuming $t_0 = 48$ minutes we find $\alpha = -0.47 \pm 0.03$ (Fig. 2). While the latter model is a better fit ($\chi^2 = 34.6$ with 21 degrees of freedom [dof], compared with $\chi^2/\mathrm{dof} = 37.7/21$), the difference is hardly significant and both models are formally unacceptable. The fading behavior of the OT is roughly consistent with a power-law flux decay of index $\alpha = -1$.

The remarkable late-time activity present in GRB 060206 has never been observed before in the optical energy range. About 1 hr into the event, we measured a peak rate of flux increase of 0.2 mag minute^{-1} (flux doubling timescale of ~4 minutes) and a lower limit of ~1 mag for the total flux increase in 12 minutes. The estimated total fluence in R-band photons received by RAPTOR-S during its ~1 hr response is 2.3×10^{-9} ergs cm^{-2}. Note, however, that for an object at $z = 4.045$, the rest-frame energies of optical photons detected by RAPTOR correspond to the far-UV regime, $\lambda \sim 130$ nm. The isotropic equivalent energy emitted by GRB 060206 around $\lambda \simeq 130 \pm 22$ nm is $E_{\mathrm{iso}} \sim 0.7 \times 10^{50}$ ergs (assuming a flat cosmology with $H_0 = 65$ km s^{-1} Mpc^{-1}, $\Omega_\Lambda = 0.7$, and $\Omega_m = 0.3$). In § 5, we discuss the broader ramifications of these observations.

5. DISCUSSION

In Figure 3, we compare the RAPTOR light curve with OT measurements from other instruments. All data were taken at face value, that is, without corrections for slight differences due to photometric filters and comparison catalogs. From the UVOT V-band measurement at $t = 58$ s (Boyd et al. 2006) and the report of fading behavior after $t = 5.23$ minutes (Guidorzi et al. 2006a), we can infer that the OT peaked at least once during the time interval preceding the RAPTOR observations. However, Figure 3 and the r' light curve from the Liverpool Telescope (Monfardini et al. 2006) suggest that during the rebrightening the OT radiated a substantial (if not dominant) part of the total energy budget in the observed R band.

Pronounced rebrightenings in GRB afterglows may arise as a result of a strongly nonuniform density profile of the material in the path of the blast wave (e.g., Tam et al. 2005). Some of the "bumps" in the combined light curve (Stanek et al. 2006; Monfardini et al. 2006) are probably of that nature. Alternatively, the complexity of the pulse train may be due to the internal engine itself. The energy could be injected at a variable rate over a time interval comparable to the response timescale of the shocked medium (see recent discussion by Proga & Zhang 2005). The refreshed-shock scenario involves energetic shells of material traveling at lower Lorentz factors (Rees & Mészáros 1998; Ramirez-Ruiz et al. 2001). In that scenario, rebrightening occurs when a trailing outflow collides with decelerating outer shocks, as proposed for GRB 060206 by Monfardini et al. (2006) based on modeling of the joined multicolor optical and X-ray data. For the best-observed GRB afterglows, we are on the verge of performing a proper reverberation mapping (Vestrand et al. 2005, 2006) using the prompt emission as a tracer of the input energy and shock development models as a fiducial response function (e.g., Mészáros & Rees 1997; Sari & Piran 1999). Panchromatic light curves can then constrain the models because the derived density profile should be independent of the observed energy range.

5.1. *Comparison with GRB 050904*

The most distant γ-ray burst known today, GRB 050904 ($z = 6.295$), was well observed. Therefore, we can make a

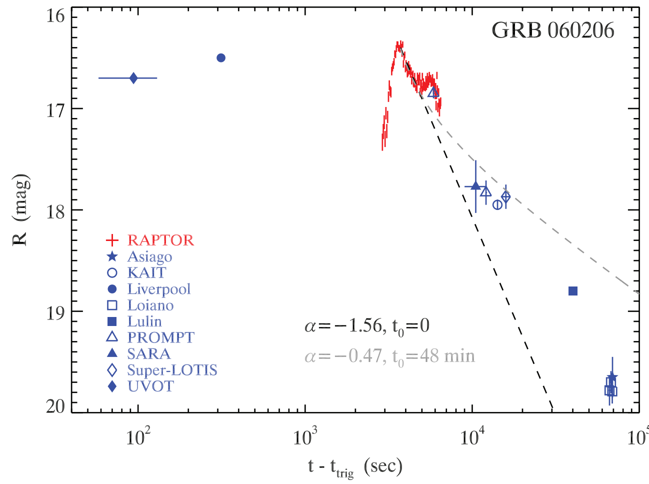

FIG. 3.—RAPTOR optical light curve of GRB 060206 compared with measurements from other instruments: Asiago (Malesani et al. 2006), KAIT (Li 2006), Liverpool (Guidorzi et al. 2006a), Loiano (Greco et al. 2006), Lulin (Lin et al. 2006), PROMPT (Haislip et al. 2006), SARA (Homewood et al. 2006), and Super-LOTIS (Milne & Williams 2006). All measurements were reported as R magnitudes except for PROMPT (r') and UVOT (V). The lines are model fits described in § 4.

number of interesting comparisons between the multiwavelength properties of GRB 060206 and the current record holder for the distance. The duration of GRB 050904 in γ-rays was $T_{90} \simeq 225$ s, compared with $T_{90} \simeq 7$ s for GRB 060206.[1] The difference is large even when transformed to the rest frame of the burst. GRB 050904 was an average-size event, with γ-ray fluence $S_\gamma = (5.1 \pm 0.2) \times 10^{-6}$ ergs cm^{-2} and $E_{\gamma,\mathrm{iso}} = 3.8 \times 10^{53}$ ergs (Sakamoto et al. 2005). In contrast, GRB 060206 produced roughly an order of magnitude less energy: $S_\gamma = (8.4 \pm 0.4) \times 10^{-7}$ ergs cm^{-2} and $E_{\gamma,\mathrm{iso}} = 3.1 \times 10^{52}$ ergs (Palmer et al. 2006).

The X-Ray Telescope (XRT) spectrum of the early X-ray afterglow in GRB 050904 is harder than that of GRB 060206, with $\Gamma_{\mathrm{ph}} \sim 1.2$ (Watson et al. 2006) and $\Gamma_{\mathrm{ph}} \sim 2.0$ (Morris et al. 2006a), respectively. GRB 050904 displayed high-amplitude flaring activity lasting several hours in the X-ray band (Watson et al. 2006; Cusumano et al. 2006) with features not unlike the optical/UV flare in GRB 060206. While the burst-frame peak optical/UV flux of GRB 060206 appears fainter by ~2 mag when compared with GRB 050904, the latter event emitted less energy in optical/UV photons during the afterglow phase relative to the γ-ray output (Boër et al. 2006).

5.2. *Intergalactic and Circumburst Medium at $z = 4$*

GRBs have X-ray and optical spectra with featureless continua that are easy to model. They are also sufficiently long-lived and bright enough to be used in studies of the intergalactic medium at high redshifts. Watson et al. (2006) conclude that GRB afterglows are more promising X-ray beacons than active galactic nuclei. The number of bright optical flashes from high-z GRBs detected so far suggests that this is also true for high-resolution optical spectroscopy.

From modeling of the XRT spectra (0.3–20 keV), Watson et al. (2006) found evidence for low-energy absorption toward GRB 050904 with column densities $N_{\mathrm{H}} \sim 8 \times 10^{20}$ cm^{-2} in

[1] At redshift $z = 1$, GRB 060206 would qualify as a short burst ($T_{90} < 2$ s), although this could be an artifact of the low S/N.

excess of the Galactic value. An excess absorption of $\sim 3 \times 10^{20}$ cm^{-2} (with a large uncertainty) was reported for GRB 060206 (Morris et al. 2006a). The H I column density inferred from the soft X-ray attenuation is very sensitive to the assumed redshift for the absorber [$N_{\rm H} \sim (1+z)^{2.6}$]. For GRB 050904, Watson et al. (2006) found $N_{\rm H} \sim 3 \times 10^{22}$ cm^{-2}, and in GRB 060206, $N_{\rm H} \sim 10^{22}$ cm^{-2} is implied, assuming a circumburst absorber. With the Galactic A_V-$N_{\rm H}$ relation (Predehl & Schmitt 1995), we would naively expect 5–15 mag of visual extinction A_V for GRBs 050904 and 060206—enough to bury the optical/UV emission. The issue of little optical reddening accompanying high X-ray columns in GRBs has been raised before (e.g., Galama & Wijers 2001). Watson et al. (2005) concluded that in GRB 050401 the discrepancy is likely a result of the low dust-to-metals ratio in the absorber. Future X-ray, UV, and optical absorption studies will provide sensitive diagnostics of the element composition and state of the medium surrounding GRB progenitors.

5.3. *Implications for Orphan GRB Searches*

GRB 060206 was an "optically rich" burst. An interesting possibility is that the optical/UV radiation emitted during the rebrightening of the afterglow originates in jet material traveling at a relatively low Lorentz factor, $10 < \Gamma < 100$, and producing little γ-ray emission. This situation could arise in any of the scenarios involving a highly structured or patchy jet viewed slightly off-axis (Nakar & Piran 2003), a "dirty fireball" with strong baryon loading (e.g., Rhoads 2003; Huang et al. 2002), or variations in the Lorentz factor of the ejecta (e.g., Rees & Mészáros 1998; Panaitescu 2005). Therefore, observations of GRB 060206 support the case for the existence of events in which the optical/UV emission would completely dominate or perhaps precede the actual γ-ray burst. In any case, it is a fact that optical emission lasting tens of minutes can be detected with a modest wide-field telescope in GRBs occurring over a large volume of the universe. A well-designed untriggered search using small optical telescopes is likely to be successful and could significantly expand the range of GRB parameters covered by observations.

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