THE DISCOVERY OF THE OPTICAL AND NEAR-IR AFTERGLOWS OF THE FIRST SWIFT GAMMA-RAY BURSTS

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ABSTRACT
We present optical and near-infrared searches for afterglow emission from the first four Swift bursts with accurate positions from the X-Ray Telescope (XRT). Using telescopes at Las Campanas, Keck, and Palomar observatories, we rapidly identified and followed up afterglows for three of the four bursts and subsequently identified the redshift of GRB 050126 (z = 1.290). In three cases the burst positions were also observed with the Very Large Array, but no radio afterglow emission was detected. The optical/near-IR afterglows are fainter than about 70% of all afterglows detected to date, with GRB 050126 being the faintest, and were identified thanks to accurate and rapid positions from the XRT and rapid response with ≥1 m telescopes. This suggests that the fraction of dust-obscured bursts is small, ≤20% when combined with afterglows localized by the HETE-2 Soft X-ray Camera. The X-ray fluxes are typical of the known population, with the exception of GRB 050126, which has the faintest X-ray afterglow to date (normalized to Δt = 10 hr) and was detected thanks to a response time of only 130 s after the burst. Finally, we find that all three optical/near-IR afterglows are located ≤2″ away from the nominal XRT positions, suggesting that the XRT is capable of delivering highly accurate positions, which will revolutionize afterglow studies.

Subject heading: gamma rays: bursts

1. INTRODUCTION
The Swift gamma-ray satellite (Gehrels et al. 2004), launched on 2004, November 20, holds great promise for our understanding of gamma-ray bursts (GRBs), as well as their use for cosmological applications. This is primarily because of the positional accuracy and great sensitivility of the Burst Alert Telescope (BAT) and the on-board X-Ray Telescope (XRT) and UV/Optical Telescope (UVOT), which are capable of providing ~0″.3–5″ positions and detailed light curves within a few minutes after the burst. Starting in mid-December 2004 Swift has localized several bursts, of which a few have been followed up with the XRT, providing ~8″–30″ error circles on a timescale of several hours. The rapidity and accuracy of these localizations have enabled deep ground-based optical and near-infrared (NIR) searches.

Here we present a comprehensive investigation (optical, NIR, radio) of the first four Swift bursts with XRT detections: GRBs 041223, 050117a, 050124, and 050126. The observations were conducted at Las Campanas Observatory (LCO), Palomar Observatory, Keck Observatory, and the Very Large Array (VLA).

Even at this early stage, with the localization timescale and accuracy still an order of magnitude below the eventual capability of Swift, the combination of Swift and ≥1 m class ground-based telescopes suggests that the fraction of dust-obscured GRBs is likely low, and the afterglow recovery rate for Swift bursts may approach unity.

2. AFTERGLOW IDENTIFICATION AND FOLLOW-UP OF SWIFT GAMMA-RAY BURSTS
Properties of the prompt emission (BAT) and X-ray afterglow emission (XRT) for the four Swift bursts are summarized in Table 1. Information on our ground-based observations supercedes that given in the GRB Coordinates Network circulars.

2.1. GRB 041223
The Swift Burst BAT localized this burst on 2004, December 23.5877 UT to a 7″ radius error circle (Tueller et al. 2004; Markwardt et al. 2004). A series of XRT observations was initiated on December 23.780 UT, and a fading source was detected at R.A. = 06°40′49″, decl. = −37°04′21″ (J2000.0) with an uncertainty of about 15″ radius (Burrows et al. 2004). The spectral energy index was βx = −1.02 ± 0.13, and the temporal decay rate was about αx = −1.7 ± 0.2 (Fx ∝ tαx) with a flux of 6.5 × 10−12 ergs cm−2 s−1 (0.5–10 keV) about 6.2 hr after the burst (Table 1; Burrows et al. 2005). Following our discovery of the optical transient (Berger et al. 2004), the XRT position was revised to (Tagliaferri et al. 2004) R.A. = 06°40′47″, decl. = −37°04′22″ (J2000.0), within about 1″ of the optical afterglow position.

Ground-based observations commenced on December 24.185 UT (14.4 hr after the burst) using the Swope 40 inch (1.02 m) telescope at LCO (Berger et al. 2004). We imaged the entire 7′′ radius BAT error circle in the Gunn r band for a total of 20 minutes. The data were bias-subtracted, flat-fielded, and combined using standard IRAF routines. Astrometry was performed relative to the USNO-B catalog using 200 stars in common to the

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two frames. The resulting rms positional uncertainty was 0.15. A stationary source not present in the Digital Sky Survey (DSS) was detected at R.A. = 06°40′47″323, decl. = −37°04′22″777 (J2000.0) with a magnitude of $r = 20.99 \pm 0.15$. This position was 7.5″ outside of the initial XRT error circle, but only 1″ from the revised nominal XRT position. A field centered on the position of the afterglow of GRB 041223 is shown in Figure 1, and the observations are summarized in Table 2.

Additional observations with the Swope 40 inch telescope were obtained starting on December 25.15 UT in the $r$ and $i$ bands. A total of 1 hr was obtained in each filter. A comparison of the LRIS observation suggests that this object is most likely the host galaxy, although any steepening in the afterglow evolution (e.g., jet break) would mean that the emission is dominated by the host galaxy.

Late-time observations were obtained with the Near Infrared Camera (NIRC; Matthews & Soifer 1994) mounted on the Keck I Telescope in the $K_s$ band on 2005 January 25.33 UT. A total of 62 images of 50 s each were collected. The individual images were dark-subtracted, flat-fielded, and corrected for bad pixels and cosmic rays. We then created object masks, which were used to obtain 6–band observations for a total of 70 min-

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**TABLE 2**

**GROUND-BASED OPTICAL AND NEAR-INFRARED DATA**

| Date (UT) | Δ$t$ (days) | Telescope$^a$ | Filter (4) | Magnitude (5) |
|-----------|-------------|---------------|------------|---------------|
| GRB 041223 |             |               |            |               |
| 2004 Dec 24.185........... | 0.60 | LCO40 | $r$ | 20.99 ± 0.15 |
| 2004 Dec 25.204........... | 1.62 | LCO40 | $r$ | 22.19 ± 0.14 |
| 2004 Dec 25.232........... | 1.65 | LCO40 | $i$ | 21.82 ± 0.07 |
| 2005 Jan 8.339............. | 15.75 | Keck LRIS | $R$ | 24.5 ± 0.3 |
| 2005 Jan 25.333............ | 32.75 | Keck NIRC | $K_s$ | >22.0 |
| GRB 050117a |             |               |            |               |
| 2005 Jan 18.146.......... | 0.61 | P200 WIRC | $K_s$ | >18.5 |
| GRB 050124 |             |               |            |               |
| 2005 Jan 25.500.......... | 1.02 | Keck NIRC | $K_s$ | 19.66 ± 0.06 |
| 2005 Jan 25.486.......... | 1.04 | Keck NIRC | $J$ | 20.90 ± 0.05 |
| 2005 Jan 26.472.......... | 1.99 | Keck NIRC | $K_s$ | 20.63 ± 0.18 |
| 2005 Jan 26.486.......... | 2.01 | Keck NIRC | $J$ | 22.04 ± 0.17 |
| GRB 050126 |             |               |            |               |
| 2005 Jan 26.682.......... | 0.18 | Keck NIRC | $K_s$ | 19.45 ± 0.17 |
| 2005 Feb 28.526........... | 33.0 | P200 WIRC | $K_s$ | 20.9 ± 0.3$^b$ |

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**Notes.**—Ground-based optical and NIR observations of the four bursts discussed in this paper. Columns: (1) UT date of the observation; (2) time since the burst; (3) telescope/instrument; (4) filter; (5) observed magnitude (not corrected for Galactic extinction); limits are 3 $\sigma$, and uncertainties are 1 $\sigma$.

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**FIG. 1.**—Field centered on the position of the optical afterglow of GRB 041223 (crosshairs) imaged in the $r$ band with the LCO 40 inch (1.02 m) telescope on December 24.185 UT (14.4 hr after the burst). Also shown are the initial (XRT-1) and revised (XRT-2) 15″ radius error circles from *Swift* XRT.
to construct improved flat fields for a second round of reduction. The data were finally registered, shifted, and co-added. Photometry was performed relative to three Two Micron All Sky Survey (2MASS) sources in the field, and no object was detected at the position of the afterglow to a $3\sigma$ limit of $K_s = 22.0$ mag.

Finally, we obtained spectroscopic observations using LRIS with a 400 line grating on the red side (dispersion of 1.86 Å pixel$^{-1}$) and a 600 line grism on the blue side (dispersion of 0.63 Å pixel$^{-1}$). Two 2400 s exposures were obtained with a 1.5" slit in 1''1 seeing. The data were bias-subtracted and flat-fielded using IRAF. Rectification and sky subtraction were performed using the method and software described in Kelson (2003). We detect weak continuum emission, but no obvious emission lines in the range $\approx$3500–9500 Å.

2.2. GRB 050117a

This burst was localized by the BAT on 2005 January 17.5365 UT to a 4′′ radius error circle (Sakamoto et al. 2005; Barthelmy et al. 2005). XRT observations revealed a fading source at R.A. = $23^h53^m53^s0$, decl. = $+65^\circ56'20''$ (J2000.0) with an uncertainty of 15′′ radius (Hill et al. 2005). We note that the location of GRB 050117a less than 4′′ away from the Galactic plane results in large extinction, $E(B-V) = 1.75$ mag (Schlegel et al. 1998), which severely hampered optical searches.

We observed the XRT position of GRB 050117a with the Wide Field Infra-red Camera (WIRC) mounted on the Palomar Hale 200 inch (5.08 m) telescope on January 18.146 UT (14.6 hr after the burst; Fox et al. 2005). A total of 32 minutes were obtained in the $K_s$ band. Several 2MASS and DSS sources were detected within and near the XRT position. A field centered on the XRT error circle of GRB 050117a is shown in Figure 2. At the present no afterglow candidate is identified.

We observed the field with the VLA$^{12}$ on 2005 January 19.08 and 24.14 UT (1.54 and 6.60 days after the burst, respectively) at a frequency of 8.46 GHz (Frail 2005; Soderberg & Frail 2005a). No source was detected within the error circle to a $3\sigma$ limit of 98 (January 19.08) and 84 (January 24.14) μJy.

2.3. GRB 050124

This burst was localized by the BAT on 2005 January 24.4792 UT to a 6′′ radius error circle (Markwardt et al. 2005; Cummings et al. 2005). An XRT observation was initiated on January 24.607 UT (3.1 hr after the burst), and ground analysis revealed a source at R.A. = $12^h51^m30^s4$, decl. = $+13^\circ02'39''0$ (J2000.0), with an uncertainty of 8′′ (Pagani et al. 2005; Osborne et al. 2005). The flux of the source was $2 \times 10^{-12}$ ergs cm$^{-2}$ s$^{-1}$ (2–10 keV; see Table 1).

We observed the XRT 8′′ error circle with NIRC in the $J$ and $K_s$ bands starting on January 25.501 (24.5 hr after the burst; Berger & Kulkarni 2005a). A total of 15 minutes were obtained in each band, and the data were reduced in the manner described in § 2.1. Within the XRT error circle we detected a single point source, located at R.A. = $12^h51^m30^s5$, decl. = $+13^\circ02'41''3$ (J2000.0). The astrometry was performed relative to an image of the field from the Palomar 60 inch (1.52 m) telescope with a rms positional uncertainty of 0′′2. The NIR afterglow position is only 2′4 away from the nominal XRT position. Follow-up observations with NIRC on January 26.471 (47.8 hr after the burst) in the $J$ (13.3 minutes) and $K_s$ (14.2 minutes) bands revealed a clear fading of the point source, confirming its identification as the afterglow of GRB 050124 (Berger & Kulkarni 2005b). The brightness of the source was $K_s = 19.66 \pm 0.06$ mag in the first observation, with a decay rate $\alpha_o = -1.45 \pm 0.25$. The observations are summarized in Table 2 and the first epoch NIRC image is shown in Figure 3.

Observations were conducted with the VLA at 4.86 and 8.46 GHz on 2005 January 29.41 UT (4.93 days after the burst;}

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$^{12}$ The VLA is operated by the National Radio Astronomy Observatory, a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.
Soderberg & Frail 2005b). No source was detected at the position of the NIR afterglow or within the XRT position, to a 3σ limit of 130 (4.86 GHz) and 100 (8.46 GHz) μJy.

2.4. GRB 050126

This burst was localized with the BAT on 2005 January 26.5001 UT to a 4σ radius error circle (Sato et al. 2005). The XRT observation started 129 s after the burst and revealed a source that was localized to a 3σ error circle (Kennea et al. 2005). Ground analysis based on data from four orbits resulted in a refined position of 8σ accuracy (Campana et al. 2005) centered on R.A. = 18h32m27s, decl. = +42°22′13.5″ (J2000.0).

We observed the XRT 30″ error circle with NIRC in the Ks band starting on 2005 January 26.6682 UT (4.4 hr after the burst; Berger & Kulkarni 2005c; Berger 2005) for a total of 8.3 minutes. The data were reduced in the manner outlined above, and astrometry was performed relative to the DSS using six stars in common between the two images. The resulting rms positional uncertainty was 0.12. Within the revised XRT error circle we detect one object not visible in the DSS at R.A. = 18h32m27.18s, decl. = +42°22′13.6″ (J2000.0). This position is only 2″ away from the nominal XRT position. The source has $K_s = 19.45 \pm 0.17$ mag. The NIRC image is shown in Figure 4. Observations of the afterglow candidate on 2005, February 28.53 UT using the WIRC camera on the Palomar 200 inch telescope reveal that the afterglow has faded by at least 1.36 mag, indicating that $\alpha_v < -0.3$. A faint source is detected at the same position which we consider to be the host galaxy. We note that the afterglow of GRB 050126 is the faintest detected to date (see Fig. 6 and Klose et al. 2003).

We obtained spectra of the host galaxy using the Echelle Spectrograph and Imager (ESI) mounted on the Keck II 10 m telescope on 2005 March 6 and 7 UT. A total of four 2700 s exposures were obtained with a 1″ slit in 0″9 seeing. The data were bias-subtracted and flat-fielded using IRAF. Rectification and sky subtraction were performed using the method and software described in Kelson (2003). Wavelength calibration was performed using a combination of Cu/Ar and Xe/Hg/Ne arc lamps, and air-to-vacuum and heliocentric corrections were applied. We detect a single emission at an observed wavelength of 8532.74 ± 0.07 Å, which we interpret as [O ii] $\lambda 3726.05$. Given a fluence of $2 \times 10^{-6}$ ergs cm$^{-2}$ (Table 1), we conclude that the isotropic-equivalent gamma-ray energy of the burst was $8.7 \times 10^{51}$ ergs.

We observed the position of GRB 050126 with the VLA at 8.46 GHz on 2005 January 26.67 and 28.59 UT (4.1 hr and 2.09 days after the burst, respectively). No object was detected at the position of the NIR candidate or within the revised XRT error circle to a limit of about 100 μJy (Frail & Soderbergs 2005).

3. AFTERGLOW PROPERTIES

We now provide a simple analysis of the afterglow emission from the individual bursts. For GRB 041223 we combine the data presented in this paper with measurements in the J and K bands from Burrows et al. (2005). Correcting for Galactic extinction ($A_R = 0.32, A_J = 0.23, A_K = 0.11$, and $A_K = 0.04$ mag; Schlegel et al. 1998), we find that the best-fit spectral index using all the available optical/NIR observations is $\beta_v = -0.6 \pm 0.1$, while the best-fit temporal decay rate is $\alpha_v = -1.1 \pm 0.1$. In the absence of significant extinction within the host galaxy, we can use these values, along with the synchrotron closure relations (e.g., Berger et al. 2002), to determine the value of the electron distribution power-law index, $p [N(\gamma) \propto \gamma^{-p}]$, the geometry of the circumburst environment (interstellar medium [ISM] or wind), and the location of the synchrotron cooling frequency.
relative to the optical/NIR band. Three possibilities exist, namely, \( \alpha - 3/2 = 0 \) (ISM\textsubscript{blue}), \( \alpha - 3/2 = -1/2 = 0 \) (ISM\textsubscript{red} and wind\textsubscript{red}), and \( \alpha - 3/2 + 1/2 = 0 \) (wind\textsubscript{blue}); the subscript designates whether the cooling frequency is blueward or redward of the optical/NIR band. The ISM\textsubscript{blue} closure relation provides the best result, \( -0.2 \pm 0.25 \), indicating that \( P = 2.2 \pm 0.2 \), and the cooling frequency is located blueward of the optical/NIR band. This conclusion is supported by the X-ray spectral index, \( \beta_X = -1.0 \pm 0.1 \), which implies \( P = 2.0 \pm 0.2 \) if \( \nu_c \) is located redward of the X-ray band.

A comparison of the optical/NIR flux and the X-ray flux, extrapolated to a common time of 19.6 hr using \( \alpha_X = -1.7 \), indicates that the spectral index between the two bands is \( \beta_\odot \approx -0.65 \). Taken in conjunction with the individual optical/NIR and X-ray spectral indices, this indicates that the cooling frequency is \( \nu_c \approx 1.1 \times 10^{17} \) Hz or about 0.45 keV. We note, however, that in the context of this model, the X-ray temporal decay is expected to be \( \alpha_X = -1.1 \pm 0.1 \), which is about 2.7 \sigma away from the measured value, \( \alpha_X = -1.7 \pm 0.2 \). The steeper decay may be due to a contribution from inverse Compton emission (Sari & Esin 2001). We note that Burrows et al. (2005) suggest that the optical/NIR and X-ray afterglows are dominated by two different physical components.

We perform a similar analysis for GRB 050124. Based on the pair of \( J \)- and \( K_s \)-band observations taken on the first and second nights after the burst, we find a spectral index, \( \beta_\odot \approx -0.4 \pm 0.2 \), and a temporal decay index \( \alpha_\odot \approx -1.45 \pm 0.25 \). These values satisfy the closure relation for the wind\textsubscript{blue} case, \( -0.35 \pm 0.55 \), indicating that \( P = 2.1 \pm 0.3 \) and the cooling frequency is located blueward of the NIR bands. A comparison of the X-ray flux at 7.1 hr after the burst to the NIR flux, extrapolated to the epoch of the X-ray observations using the measured value of \( \alpha \), indicates an optical/X-ray spectral index, \( \beta_{ox} \approx -0.5 \), in good agreement with the optical/NIR spectral index. This suggests that the cooling break is most likely located near the X-ray band.

Finally, for GRB 050126 we simply note that the decay rate of the NIR afterglow is steeper than \( \alpha_\odot \approx -0.3 \). Both the NIR and X-ray afterglows are fainter than any other afterglow detected to date. For the purpose of this comparison we extrapolate the NIR flux to the optical \( R \) band using a typical spectral index of \( \alpha_X \approx -0.6 \), and the X-ray flux from 200 s to 10 hr using \( \alpha_X \approx -1.3 \), which is typical for X-ray afterglows (Berger et al. 2003).

4. DISCUSSION AND CONCLUSIONS

One of the main promises of Swift is rapid localization and follow-up with the XRT and UVOT. The X-ray fluxes from XRT (Burrows et al. 2005; J. E. Hill et al., in preparation; J. P. Osborne et al., in preparation; G. Tagliaferri et al. 2005, in preparation) are summarized in § 2 and Table 1. In Figure 6 we plot the X-ray fluxes normalized to 10 hr after the burst in comparison to the sample of Berger et al. (2003). We find that three of the four XRT afterglows are typical of the general population, but the X-ray afterglow of GRB 050126 is the faintest detected to date. For the purpose of this comparison we extrapolate the X-ray fluxes at 7.1 hr after the burst to the NIR flux, extrapolated to the epoch of the X-ray observations using the measured value of \( \alpha \), indicates an optical/X-ray spectral index, \( \beta_{ox} \approx -0.5 \), in good agreement with the optical/NIR spectral index. This suggests that the cooling break is most likely located near the X-ray band.

Similarly, we plot the \( R \)-band magnitudes of the Swift afterglows, measured directly or extrapolated from the NIR (using the measured spectral indices or a typical \( F_\nu \propto \nu^{-0.6} \)), in comparison to a compilation of optical light curves collected in the past 7 yr. We find that the afterglows are fainter than about 70% of the population on a similar timescale (Fig. 6). In particular, the afterglow of GRB 050126 is the faintest detected to date. We note that the subsequent detection of the NIR afterglow of GRB 050126 is fainter than about 70% of the known afterglows detected prior to 2005. The Swift optical/NIR afterglows are fainter than about 70% of the known afterglow population. Their detection was due to the small error circles from XRT and searches with large telescopes. The inset shows the distribution of X-ray fluxes at 10 hr after the burst for the XRT bursts (using measured temporal decay indices or assuming the typical \( \alpha_X = -1.3 \) compared to the sample of Berger et al. 2005). Three of the four afterglows are typical of the general population, but the afterglow of GRB 050126 is the faintest detected to date, in agreement with the faintness of the NIR afterglow. We note that the X-ray emission for GRB 050117a is contaminated by the prompt emission and should be considered as an upper limit.

Several conclusions can already be drawn from this early work. First, nearly every XRT localization has resulted in the identification of an optical or NIR afterglow; the single exception (GRB 050117a) is likely due to large Galactic extinction. The optical/NIR afterglow recovery rate for XRT (9/13 as of GRB 050319) and the High Energy Transient Explorer 2 SXC (11/13) is about 80%. The brightness of the XRT+SXC sample normalized to \( t = 12 \) hr compared to all other optical afterglows is shown in Figure 7. The afterglows of the XRT bursts appear to be fainter than about 70% of all afterglows detected prior to

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\[ \text{Fig. 6.—} \text{Optical light curves of the Swift bursts discussed in this paper (and upper limit on GRB 050117a) compared to the sample of afterglows detected and studied in the past 7 yr. We transformed the NIR flux of GRB 05124 to the R band using the measured spectral index, and that of GRB 050126 assuming a typical index of } \beta = -0.6. \text{ The dotted line indicates the minimum decay rate for GRB 050126 (} \alpha_x \approx -0.3 \text{ given the nondetection in the second epoch (Table 2). The Swift optical/NIR afterglows are fainter than about 70% of the known afterglow population. Their detection was due to the small error circles from XRT and searches with large telescopes. The inset shows the distribution of X-ray fluxes at } t = 10 \text{ hr after the burst for the XRT bursts (using measured temporal decay indices or assuming the typical } \alpha_X = -1.3 \text{ compared to the sample of Berger et al. (2005). Three of the four afterglows are typical of the general population, but the afterglow of GRB 050126 is the faintest detected to date, in agreement with the faintness of the NIR afterglow. We note that the X-ray emission for GRB 050117a is contaminated by the prompt emission and should be considered as an upper limit.} \]
Swift, suggesting that past nondetections were mainly the result of large error regions and/or shallow searches. This indicates that the fraction of "dark" (dust-obscured) GRBs is low, although we note that two of the XRT bursts were localized in the NIR and the fraction of "dark" (dust-obscured) GRBs is small. The inset shows the cumulative distribution for all afterglows discovered prior to Swift along with the three afterglows discussed in this paper. The Swift XRT bursts are fainter than about 70% of all afterglows localized to date. In the past, these may have been designated as dark.

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