Discovery of the Very Red Near-Infrared and Optical Afterglow of the Short-Duration Grb 070724a

DRAFT VERSION FEBRUARY 4, 2014
Preprint typeset using LaTeX style emulateapj v. 03/07/07

DISCOVERY OF THE VERY RED NEAR-INFRARED AND OPTICAL AFTERGLOW OF THE SHORT-DURATION GRB 070724A

E. BERGER[1], S. B. CENKO[2], D. B. FOX[3] AND A. CUCCHIARA[3]

Draft version February 4, 2014

ABSTRACT

We report the discovery of the near-infrared and optical afterglow of the short-duration gamma-ray burst GRB 070724A. The afterglow is detected in $iJHK_s$ observations starting 2.3 hr after the burst with $K_s = 19.59 \pm 0.16$ mag and $i = 23.79 \pm 0.07$ mag, but is absent in images obtained 1.3 years later. Fading is also detected in the K_s-band between 2.8 and 3.7 hr at a 4σ significance level. The optical/near-IR spectral index, $\beta_{\rm O,NIR} \approx -2$, is much redder than expected in the standard afterglow model, pointing to either significant dust extinction, $A_V^{\rm host} \approx 2$ mag, or a non-afterglow origin for the near-IR emission. The case for extinction is supported by a shallow optical to X-ray spectral index, consistent with the definition for "dark bursts", and a normal near-IR to X-ray spectral index. Moreover, a comparison to the optical discovery magnitudes of all short GRBs with optical afterglows indicates that the near-IR counterpart of GRB 070724A is one of the *brightest* to date, while its observed optical emission is one of the faintest. In the context of a non-afterglow origin, the near-IR emission may be dominated by a mini-supernova, leading to an estimated ejected mass of $M \sim 10^{-4}$ $M_\odot$ and a radioactive energy release efficiency of $f \sim 5 \times 10^{-3}$ (for $v \sim 0.3$c). However, the mini-SN model predicts a spectral peak in the UV rather than near-IR, suggesting that this is either not the correct interpretation or that the mini-SN models need to be revised. Finally, the afterglow coincides with a star forming galaxy at $z = 0.457$, previously identified as the host based on its coincidence with the X-ray afterglow position ($\sim 2''$ radius). Our discovery of the optical/near-IR afterglow makes this association secure, and furthermore localizes the burst to the outskirts of the galaxy, with an offset of 4.8 ± 0.1 kpc relative to the host center. At such a large offset, the possible large extinction points to a dusty environment local to the burst and rules out a halo or intergalactic origin.

Subject headings: gamma-rays:bursts

1. INTRODUCTION

The determination of sub-arcsecond positions for short-duration gamma-ray bursts (GRBs) is of the utmost importance for our growing understanding of their redshift distribution, energy scale, host galaxies, and local environments. Such localizations require the detection of optical, near-infrared, or radio afterglows; or alternatively an X-ray detection with the *Chandra* X-ray Observatory. As of August 2009, only 15 short GRBs have been precisely localized in this manner, and all were detected in the optical band[4] (Berger et al. 2005; Fox et al. 2005; Hjorth et al. 2005b; Levan et al. 2006; de Ugarte Postigo et al. 2006; Roming et al. 2006; Soderberg et al. 2006; Perley et al. 2007; Stratta et al. 2007; Malesani et al. 2008; Piranomonte et al. 2008; Berger & Kelson 2009; Cenko et al. 2009a; D'Avanzo et al. 2009; Graham et al. 2009; Kuin & Hoversten 2009; Perley et al. 2009b).

Follow-up observations of some of these bursts have led to the detection and characterization of host galaxies, most of them star forming, and a small proportion ($\sim 20\%$) non-star forming (e.g., Berger 2009). The precise positions also allow us to study the local environment of the bursts within their hosts, and current observations point to offsets of $\sim 1-15$ kpc (e.g., Berger et al. 2005; Fox et al. 2005; Soderberg et al. 2006; D'Avanzo et al. 2009). However, since these are projected positions, and since we generally lack detailed afterglow observations that can shed light on the circumburst environment, little is known about whether the bursts originate within the inner or halo regions of their hosts (e.g., Soderberg et al. 2006; Levesque et al. 2009).

Rapid optical observations have also been used to place limits on emission from radioactive material synthesized in a putative sub-relativistic outflow associated with a compact object binary merger, a so-called Li-Paczynski mini-supernova (Li & Paczyński 1998). Such emission is theorized to have a typical peak time of ~ 1 d, and a peak luminosity of $\sim 10^{42}$ erg s^{-1}, corresponding to $m_{\rm AB} \sim 21$ mag at $z \sim 0.5$. No such emission has been detected to date (e.g., Hjorth et al. 2005a; Bloom et al. 2006). Similarly, no late-time emission from Type Ib/c supernova associations have been detected (e.g., Hjorth et al. 2005b; Bloom et al. 2006; Soderberg et al. 2006).

Most recently, near-IR and optical non-detections of GRB 070724A have been used to place limits on emission from a putative mini-SN associated with this burst (Kocevski et al. 2009). Here we report the detection of near-IR and optical counterparts of GRB 070724A about 2.3 hr after the burst, and show that the afterglow is actually one of the brightest near-IR short GRB afterglows detected to date, but is one of the faintest in the optical. We use the observed fluxes and the unusually red color to investigate the properties of the afterglow and/or mini-SN, and to precisely measure the location of the burst relative to its host galaxy. Our discovery of the afterglow of GRB 070724A suggests that recovery of a substantial fraction of short GRB optical/near-IR afterglows requires observations to $m_{\rm AB} \sim 24$ mag within about 0.5 d.

2. GRB 070724A

[1] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138
[2] Department of Astronomy, University of California, Berkeley, CA 94720
[3] Department of Astronomy and Astrophysics, Pennsylvania State University, 525 Davey Laboratory, University Park, PA 16802

[4] To date only two short GRBs have been detected in the radio (050724 and 051221a; Berger et al. 2005; Soderberg et al. 2006), and only one short GRB afterglow was discovered with *Chandra* (050709; Fox et al. 2005).

GRB 070724A was discovered by the *Swift* satellite on 2007 July 24 at 10:53:50 UT with a duration of 0.40 ± 0.04 s (Ziaeepour et al. 2007). The X-ray afterglow was detected with the on-board X-ray Telescope (XRT) beginning 72 s after the burst, while no counterpart was detected with the UV/Optical Telescope (Ziaeepour et al. 2007). The X-ray position was subsequently determined to a precision of $1.7''$ radius (90% containment). An apparently extended source was detected in coincidence with the XRT error circle in Digitized Sky Survey images, and tentatively proposed as a possible host (Bloom 2007). Subsequent near-IR and optical observations from UKIRT, Gemini-North, the Palomar 60-inch telescope, and the VLT revealed that the source was indeed an extended galaxy, but did not uncover an afterglow (Levan et al. 2007; Cenko et al. 2007; Covino et al. 2007). A recent analysis using image subtraction on UKIRT, NOT, CTIO 1.3-m, Keck, and VLT data similarly reveals no afterglow to limits of $F_{\nu,K} \lesssim 30$ μJy and $F_{\nu,i} \lesssim 0.3$ μJy at 3.2 and 22.2 hr after the burst, respectively (Kocevski et al. 2009).

Spectroscopy of the galaxy within the XRT error circle revealed that it is located at a redshift of $z = 0.4571$, is undergoing active star formation at a rate of 2.5 $M_\odot$ yr^{-1}, has a luminosity of $L_B \approx 1.4$ L*, and a metallicity of $12+\log(\mathrm{O/H}) \approx 8.9$ (Berger 2009; see also Kocevski et al. (2009) for similar results). The resulting isotropic γ-ray energy in the observed $15-150$ keV range is $E_{\gamma,\mathrm{iso}} \approx 1.6 \times 10^{49}$ erg.

3. DISCOVERY OF THE NEAR-IR AND OPTICAL AFTERGLOW

We observed the field centered on GRB 070724A with the Near Infra-Red Imager and Spectrometer (NIRI) mounted on the Gemini-North 8-m telescope in the JHK_s bands starting on 2007 July 24.566 UT (2.69 hr after the burst); see Table 1. The observations were obtained in excellent seeing conditions, $\approx 0.35''$ in the K_s-band. The data were reduced using the `gemini` package in IRAF, and individual stacks were created in each filter. Inspection of the images reveals a point source coincident with the south-east edge of the putative host galaxy; see Figure 1.

Optical observations were obtained with the Gemini Multi-Object Spectrograph (GMOS) mounted on the Gemini-North 8-m telescope in the *gi* bands starting on 2007 July 24.551 UT (2.33 hr after the burst; Table 1). The data were reduced using the `gemini` package in IRAF. The combined *i*-band image centered on the location of GRB 070724A is shown in Figure 2. An apparent extension is seen in the same location as the near-IR source.

We obtained follow-up near-IR observations of the GRB with Persson's Auxiliary Nasmyth Infrared Camera (PANIC) mounted on the Magellan/Baade 6.5-m telescope on 2008 November 18.15 UT in the K_s band (Table 1). 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 construct improved flat fields for a second round of reduction. The data were finally registered, shifted, and co-added. The resulting combined image is shown in Figure 1, and clearly reveals that the point source visible in the NIRI images has faded away.

Similarly, late-time optical *gi*-band observations were obtained with the Low Dispersion Survey Spectrograph (LDSS3) mounted on the Magellan/Clay 6.5-m telescope on 2008 December 7.14 UT (Table 1). The data were reduced using standard procedures in IRAF. The resulting *i*-band image is shown in Figure 2. As in the case of the late-time near-IR observations, the extension seen in the early GMOS observations is no longer detected.

To confirm the fading afterglow and to obtain accurate photometry and astrometry we perform digital image subtraction on the NIRI and PANIC K_s-band images and on the GMOS and LDSS3 *gi* band images with the ISIS package (Alard 2000), which accounts for variations in the stellar point-spread function (PSF). We adopt the PANIC and LDSS3 images as templates with zero afterglow contribution since they were obtained about 1.3 yr after the burst. The resulting residual K_s- and *i*-band images are shown in Figures 1 and 2, respectively, and clearly demonstrate that the point source coincident with the host galaxy has faded away. We therefore conclude that this source is the afterglow of GRB 070724A. We additionally performed image subtraction on the two NIRI K_s-band observations and find that the source has faded between mid-epochs of 2.832 and 3.696 hr after the burst at a 4σ confidence level (Figure 1). No residual is detected in the subtracted *g*-band image.

3.1. *Absolute and Differential Astrometry*

We determine the absolute position of the afterglow from the NIRI and GMOS residual images using the `SExtractor` software package[5]. Since our NIRI images do not contain any 2MASS stars, we first perform an astrometric tie of the GMOS *i*-band image relative to USNO-B (using 13 common objects with a resulting rms of $0.15''$) and then tie the NIRI astrometry to the *i*-band image (using 20 common objects with a combined total rms of $0.18''$). The optical afterglow is located at $\alpha = 01^{\mathrm{h}}51^{\mathrm{m}}14.071^{\mathrm{s}}$, $\delta = -18^\circ 35' 39.33''$, while the near-IR afterglow position is $\alpha = 01^{\mathrm{h}}51^{\mathrm{m}}14.066^{\mathrm{s}}$, $\delta = -18^\circ 35' 39.34''$ (J2000). These positions are consistent within the uncertainty of the astrometric tie. The optical/near-IR afterglow is offset by about $0.5''$ and $0.9''$ relative to the X-ray positions from Evans et al. (2009) and Butler (2007), which have 90% containment errors of $1.6''$ and $1.7''$, respectively.

The detection of the optical/near-IR afterglow makes the association of GRB 070724A with the previously-proposed host galaxy secure (Berger 2009), and allows us to precisely measure the offset between the GRB and host center. We perform differential astrometry on the NIRI images and find that the offset is $0.34 \pm 0.01''$ east and $0.75 \pm 0.01''$ south of the host center, corresponding to a radial offset of $0.82 \pm 0.01''$. The uncertainty reflects the centroiding accuracy of both the afterglow and host, which we determine using `SExtractor`. At a redshift of $z = 0.4571$ the scale[6] is 5.785 kpc arcsec^{-1}, and the offset is therefore 4.76 ± 0.06 kpc. This is similar to the offsets measured for previous short GRBs with optical afterglows (Berger et al. 2005; Fox et al. 2005; Soderberg et al. 2006; D'Avanzo et al. 2009). The location of the burst in the late-time PANIC and LDSS3 images does not exhibit any excess emission; see Figure 3.

3.2. *Photometry*

Photometry of the afterglow was performed on all residual images using photometric standard stars that were observed in conjunction with the PANIC and LDSS3 observations. We find that the afterglow had $K_s = 19.59 \pm 0.16$ mag and $K_s = 19.64 \pm 0.17$ mag in the first and second NIRI epochs, respectively, and $i = 23.79 \pm 0.07$ mag in the GMOS observation. The 3σ limit on the *g*-band magnitude is $g \gtrsim 23.5$ mag,

[5] `http://sextractor.sourceforge.net/`

[6] We use the standard cosmological parameters, $H_0 = 71$ km s^{-1} Mpc^{-1}, $\Omega_m = 0.27$, and $\Omega_\Lambda = 0.73$.

determined by placing $\sim 10^3$ random apertures on the residual image and using the width of the resulting Gaussian flux distribution as 1σ. The near-IR magnitudes are quoted in the Vega system, while the optical magnitudes are given in the AB system. Since the *g*-band limit is shallower than the detected *i*-band magnitude, it provides no meaningful constraints on the properties of the afterglow.

The observed K_s- and *i*-band magnitudes correspond to fluxes of 9.3 ± 1.5 μJy, 8.9 ± 1.5 μJy, and 1.1 ± 0.1 μJy, respectively. We stress that the uncertainty in the flux of the near-IR afterglow is dominated by the convolution with the PANIC image, which was obtained under worse seeing conditions than the NIRI images. To assess the statistical uncertainty in the afterglow flux we note that a stellar point source with $K_s = 19.62$ mag, identical to the afterglow brightness, located near the afterglow position has a 1σ uncertainty of 0.03 mag in the NIRI images. This greater depth in the NIRI data allows us to detect a significant fading between the two NIRI observations despite an uncertainty of 0.16 mag relative to the PANIC observation.

We note that the afterglow is also clearly detected in the *J*- and *H*-band images from NIRI. However, due to the lack of late-time template images we cannot robustly measure its brightness in these bands. Still, a color-composite image reveals that the afterglow is redder in the near-IR bands than the rest of the host galaxy; see Figure 4.

4. AFTERGLOW/MINI-SUPERNOVA PROPERTIES

A comparison of our afterglow near-IR flux measurements to contemporaneous limits from UKIRT observations by Kocevski et al. (2009) reveals that the afterglow is about a factor of three times fainter than the UKIRT upper limits. These authors also find a limit on the optical emission at 0.93 d after the burst of $F_{\nu,i} \lesssim 0.3$ μJy. A comparison to our detected *i*-band flux at 0.12 d indicates that the afterglow temporal decay index is $\alpha < -0.6$ ($F_\nu \propto t^\alpha$), typical of GRB afterglows.

On the other hand, a comparison of our contemporaneous K_s- and *i*-band fluxes reveals an unusually steep spectral index, $\beta = -2.0 \pm 0.2$ ($F_\nu \propto \nu^\beta$). Typically we expect $\beta \approx -0.6$ to -1.2 for a wide range of electron power law indices and values of the synchrotron cooling frequency (Sari et al. 1998).

The unusually red afterglow can be explained in two ways. First, the optical emission may be suppressed by extinction within the host galaxy. To reconcile the observed fluxes with a typical spectral index of $\beta \approx -0.6$ requires $E(i-K_s)_{\rm obs} \approx 1$ mag, or a rest-frame $A_V^{\rm host} \approx 2$ mag for a Milky Way extinction curve. Such a large extinction seems unlikely given the location of the afterglow at the edge of the host galaxy. However, a large average value of $E(B-V) \approx 1.2$ mag (i.e., $A_V \approx 4$ mag) has been inferred for the host galaxy based on its ratio of Hγ and Hβ emission lines (Kocevski et al. 2009), indicating that extinction may indeed play a role in suppressing the optical emission.

We further investigate this possibility by comparison to the X-ray afterglow brightness at the time of the optical observations, $F_{\nu,X}(1\,{\rm keV}) \approx 0.04$ μJy (Ziaeepour et al. 2007). This leads to an optical to X-ray spectral index of $\beta_{\rm O,X} \approx -0.5$, which marginally qualifies GRB 070724A as a "dark burst" (Jakobsson et al. 2004; Cenko et al. 2009b). On the other hand, the near-IR to X-ray spectral index, $\beta_{\rm NIR,X} \approx -0.7$, is consistent with a typical afterglow. Thus, the comparison of the optical/near-IR and X-ray afterglow emission is consistent with a standard afterglow origin and significant dust extinction. We note that Kocevski et al. (2009) find excess absorption in the early X-ray data, but attribute this result to rapid variations in the X-ray flux and spectral hardness. In light of the possible significant dust extinction, the excess photoelectric absorption may indeed be real.

An alternative explanation is that the near-IR flux is dominated by a different source of emission than the afterglow. In particular, in the context of a compact object merger, the emission may be due to the decay of radioactive material synthesized in a sub-relativistic outflow, the so-called Li-Paczynski mini-supernova (Li & Paczyński 1998; Rosswog & Ramirez-Ruiz 2002; see also Kocevski et al. 2009). In the formulation of Li & Paczyński (1998), the emission from such a mini-SN is described by a peak luminosity (L_p):

$$L_p \approx 2 \times 10^{44}\, f_{-3} M_{-2}^{1/2} (3\beta)^{1/2} (\kappa/\kappa_e)^{-1/2}\ \ {\rm erg\ s^{-1}}, \quad (1)$$

a peak effective temperature ($T_{{\rm eff},p}$):

$$T_{{\rm eff},p} \approx 2.5 \times 10^4\, f_{-3}^{1/4} M_{-2}^{-1/8} (3\beta)^{-1/8} (\kappa/\kappa_e)^{-3/8}\ \ {\rm K}, \quad (2)$$

and a peak time (t_p):

$$t_p \approx 1\, M_{-2}^{1/2} (3\beta)^{-1/2} (\kappa/\kappa_e)^{1/2}\ \ {\rm d} \quad (3)$$

where f is the fraction of rest mass energy released by the radioactivity, M is the ejecta mass in units of M$_\odot$, $\beta \equiv v/c$ is the ejecta velocity, κ is the average opacity, $\kappa_e \approx 0.2$ cm^2 g^{-1} is the electron scattering opacity, and we use the notation $X \equiv 10^n X_n$.

For our detected source we use the near-IR luminosity and observed time as proxies for L_p and t_p, respectively, leading to $L_p \approx 10^{43}$ erg s^{-1} and $t_p \approx 0.1$ d. Using the constraint that $3\beta \lesssim 1$ and assuming that $\kappa = \kappa_e$, we find from Equation 3 that $M_{-2} \lesssim 10^{-2}$ (i.e., $M \lesssim 10^{-4}$ M$_\odot$). In conjunction with Equation 1 this provides a lower limit of $f_{-3} \gtrsim 5$. The resulting lower limit on the effective temperature is $T_{{\rm eff},p} \gtrsim 7 \times 10^4$ K, corresponding to a peak in the UV rather than in the near-IR. The apparent discrepancy in the spectral peak may be viewed as an indication that the observed emission is not due to a mini-SN. However, we note that Equations 1-3 correspond to the case of a power law decay model with an assumed contribution from elements with a wide range of decay timescales. An exponential decay model, in which a single element dominates the release of energy, may lead to distinctly different luminosity and evolution (Li & Paczyński 1998).

To summarize, the unusually red optical/near-IR counterpart of GRB 070724A, can be explained as a typical afterglow with significant dust extinction, $A_V^{\rm host} \approx 2$ mag. The alternative explanation of a mini-SN leads to an expected peak in the UV, but this may suggest that the mini-SN models should be revised.

5. DISCUSSION AND CONCLUSIONS

Optical afterglow emission has now been detected from 16 short GRBs, including GRB 070724A. In Figure 5 we plot the flux of each optical afterglow at the time of its discovery. For GRB 070724A we show both the optical and near-IR fluxes, as well as the expected *i*-band flux extrapolated from the K_s-band using a typical spectral index of $\beta = -0.6$. While the observed *i*-band flux is one of the faintest to date, the near-IR flux indicates that the afterglow of GRB 070724A is actually one of the brightest at the time of its discovery. Indeed, only the optical afterglows of GRBs 050724, 060313, 070714, and 090510 were brighter, and of these only the afterglow of GRB 050724 was discovered on a comparable timescale;

the optical afterglows of GRBs 060313, 070714, and 090510 were all discovered $\lesssim 20$ min after the burst. On a timescale of 1 hr to 1 d after the burst, the optical afterglows of short GRBs generally have fluxes of $\sim 1-10$ μJy, about two orders of magnitude lower than the typical brightness of long GRB afterglows (e.g, Kann et al. 2008; Cenko et al. 2009b). From the existing distribution we conclude that the detection of a substantial fraction of short GRB afterglows requires optical/near-IR observations to $m_{\rm AB} \sim 24$ mag within ~ 0.5 d.

The unusually red afterglow of GRB 070724A can be explained with a substantial rest-frame dust extinction, $A_V^{\rm host} \approx 2$ mag. This value is larger than the typical extinction inferred for most long-duration GRBs, $A_V \sim 0.1-1$ mag (e.g., Perley et al. 2009a), and indeed the optical to X-ray spectral index, $\beta_{\rm OX} \approx -0.5$, marginally qualifies GRB 070724A as a dark burst (Jakobsson et al. 2004; Cenko et al. 2009b). Since the GRB is located on the edge of its host galaxy, it is likely that the extinction arises in the local environment of the burst. This implies that the progenitor system was not ejected from the host galaxy into the halo or intergalactic medium. Instead, the large extinction may point to an explosion site within a star forming region, or alternatively that the progenitor system itself produced the dust (for example, a binary system with an evolved AGB star). The possibility that some short GRBs are obscured by dust has important ramifications for the nature of the progenitors, and can also serve to localize the bursts to the galactic disk environments. Thus, rapid and deep near-IR observations are of crucial importance.

Alternatively, in the context of a compact object merger model, the near-IR emission may arise from radioactive decay in a sub-relativistic outflow produced during the merger process – a mini-SN. In this scenario, we find that the required ejected mass is $M \lesssim 10^{-4}$ M$_\odot$, with a radioactive energy release efficiency of $f \gtrsim 5\times10^{-3}$. We note, however, that in the standard formulation the spectral peak at this time is expected to be in the UV rather than in the near-IR. This may indicate that the detected source is completely due to afterglow emission, or that the mini-SN models need to be revised.

We thank Alicia Soderberg for assistance with the digital image subtraction. This paper includes data gathered with the 6.5 meter Magellan Telescopes located at Las Campanas Observatory, Chile. Observations were also obtained at the Gemini Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the NSF on behalf of the Gemini partnership: the National Science Foundation (United States), the Particle Physics and Astronomy Research Council (United Kingdom), the National Research Council (Canada), CONICYT (Chile), the Australian Research Council (Australia), CNPq (Brazil) and CONICET (Argentina)

REFERENCES

Alard, C. 2000, A&AS, 144, 363
Berger, E. 2009, ApJ, 690, 231
Berger, E., & Kelson, D. 2009, GRB Coordinates Network, 8934, 1
Berger, E., et al. 2005, Nature, 438, 988
Bloom, J. S. 2007, GRB Coordinates Network, 6658, 1
Bloom, J. S., et al. 2006, ApJ, 638, 354
Butler, N. R. 2007, AJ, 133, 1027
Cenko, S. B., Cobb, B. E., Perley, D. A., & Bloom, J. S. 2009a, GRB Coordinates Network, 8933, 1
Cenko, S. B., et al. 2009b, ApJ, 693, 1484
Cenko, S. B., Rau, A., Berger, E., Price, P. A., & Cucchiara, A. 2007, GRB Coordinates Network, 6664, 1
Covino, S., Piranomonte, S., Vergani, S. D., D'Avanzo, P., & Stella, L. 2007, GRB Coordinates Network, 6666, 1
D'Avanzo, P., et al. 2009, A&A, 498, 711
de Ugarte Postigo, A., et al. 2006, ApJ, 648, L83
Evans, P. A., et al. 2009, MNRAS, 397, 1177
Fox, D. B., et al. 2005, Nature, 437, 845
Graham, J. F., et al. 2009, ApJ, 698, 1620
Hjorth, J., et al. 2005a, ApJ, 630, L117
Hjorth, J., et al. 2005b, Nature, 437, 859
Jakobsson, P., Hjorth, J., Fynbo, J. P. U., Watson, D., Pedersen, K., Björnsson, G., & Gorosabel, J. 2004, ApJ, 617, L21
Kann, D. A., et al. 2008, ArXiv e-prints
Kocevski, D., et al. 2009, ArXiv e-prints
Kuin, N. P. M., & Hoversten, E. A. 2009, GRB Coordinates Network, 9342, 1
Levan, A. J., Tanvir, N. R., & Davis, C. 2007, GRB Coordinates Network, 6662, 1
Levan, A. J., et al. 2006, ApJ, 648, L9
Levesque, E. M., et al. 2009, ArXiv e-prints
Li, L.-X., & Paczyński, B. 1998, ApJ, 507, L59
Malesani, D., et al. 2008, GRB Coordinates Network, 8190, 1
Perley, D. A., et al. 2009a, ArXiv e-prints
Perley, D. A., et al. 2009b, ApJ, 696, 1871
Perley, D. A., Thoene, C. C., Cooke, J., Bloom, J. S., & Barton, E. 2007, GRB Coordinates Network, 6739, 1
Piranomonte, S., et al. 2008, A&A, 491, 183
Roming, P. W. A., et al. 2006, ApJ, 651, 985
Rosswog, S., & Ramirez-Ruiz, E. 2002, MNRAS, 336, L7
Sari, R., Piran, T., & Narayan, R. 1998, ApJ, 497, L17
Soderberg, A. M., et al. 2006, ApJ, 650, 261
Stratta, G., et al. 2007, A&A, 474, 827
Ziaeepour, H., Barthelmy, S. D., Parsons, A., Page, K. L., de Pasquale, M., & Schady, P. 2007, GCN Report, 74, 2

TABLE 1
LOG OF NEAR-IR AND OPTICAL OBSERVATIONS OF GRB 070724A

Date (UT)	Δt (d)	Telescope	Instrument	Filter	Exposures (s)	$\theta_{\rm FWHM}$ ($''$)	mag	F_ν (μJy)
2007 July 24.549	0.094	Gemini-N	GMOS	g	2×180	0.71	$\gtrsim 23.5$	$\lesssim 1.5$
2007 July 24.551	0.097	Gemini-N	GMOS	i	2×180	0.53	23.79 ± 0.07	1.1 ± 0.1
2007 July 24.572	0.118	Gemini-N	NIRI	K_s	15×60	0.35	19.59 ± 0.16	9.3 ± 1.5
2007 July 24.585	0.131	Gemini-N	NIRI	J	15×60	0.45	... [a]	... [a]
2007 July 24.596	0.142	Gemini-N	NIRI	H	15×30	0.46	... [a]	... [a]
2007 July 24.608	0.154	Gemini-N	NIRI	K_s	15×60	0.35	19.64 ± 0.17	8.9 ± 1.5
2008 Nov 18.17	481.6	Magellan	PANIC	K_s	54×20	0.47	... [b]	... [b]
2008 Dec 7.13	500.6	Magellan	LDSS3	g	2×240	0.94	... [b]	... [b]
2008 Dec 7.14	500.6	Magellan	LDSS3	i	3×120	0.58	... [b]	... [b]

NOTE. — [a] No templates are available in the *J* and *H* bands and as a result we cannot measure the flux of the afterglow.
[b] The flux of the afterglow in the PANIC and LDSS3 images is assumed to be zero.

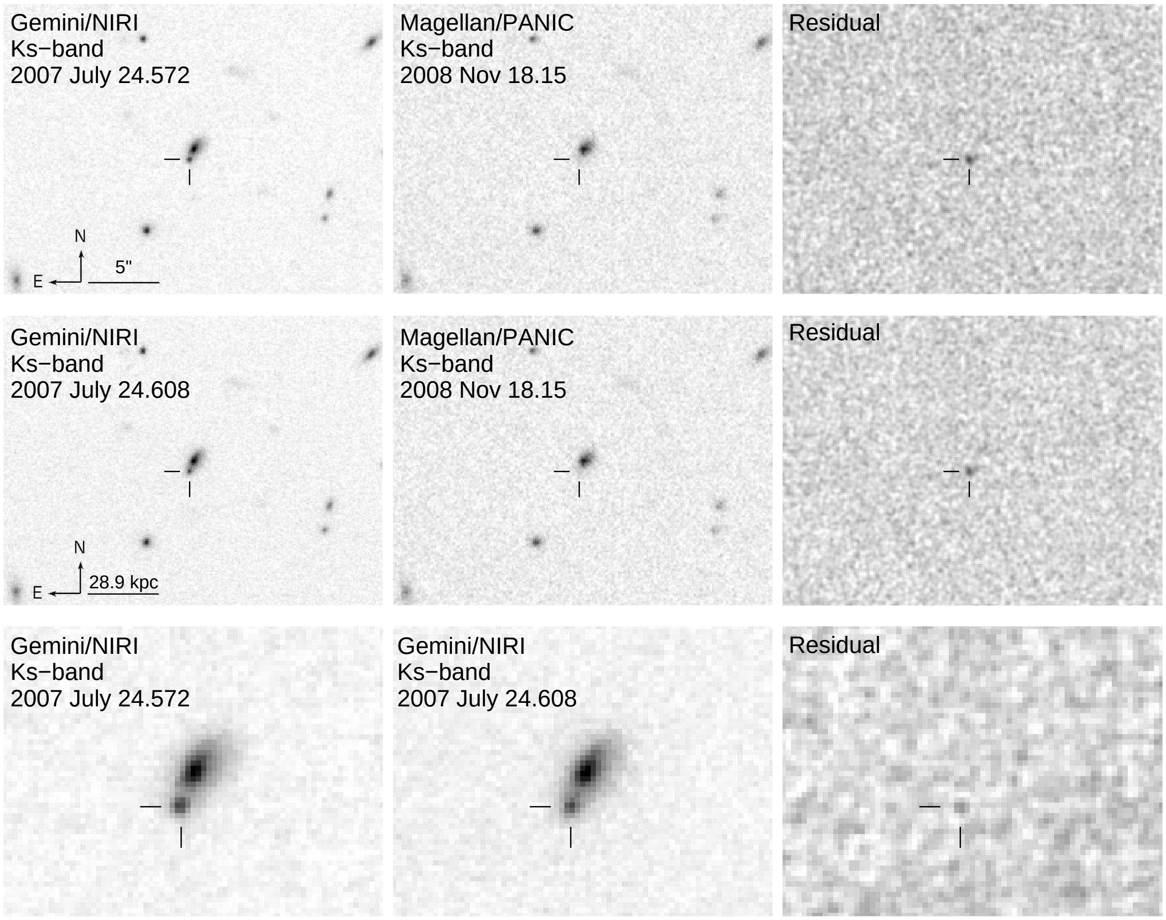

FIG. 1.— Near-IR K_s-band images of GRB 070724A. In each row we display the afterglow image, corresponding template image, and residual image from ISIS. The near-IR afterglow is clearly visible in the residual images relative to the final PANIC epoch, as well as in the subtraction of the two NIRI epochs.

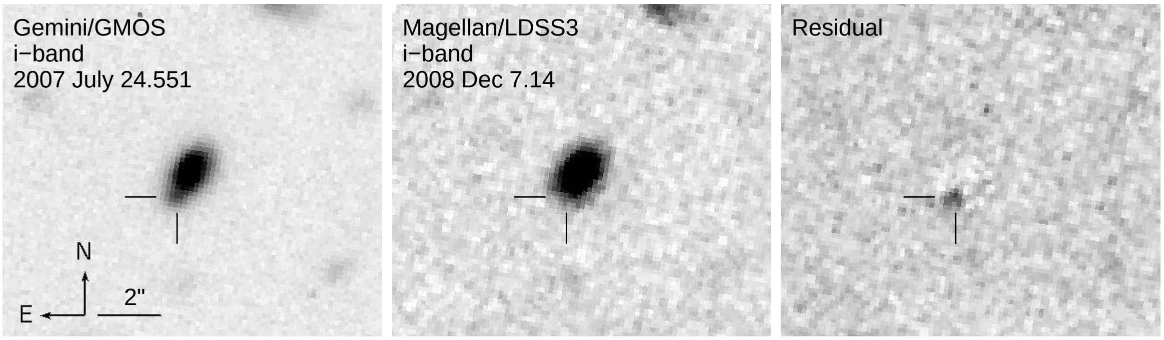

FIG. 2.— Optical *i*-band images of GRB 070724A. We display the afterglow image, template image, and residual image from ISIS. The afterglow is clearly visible in the residual image.

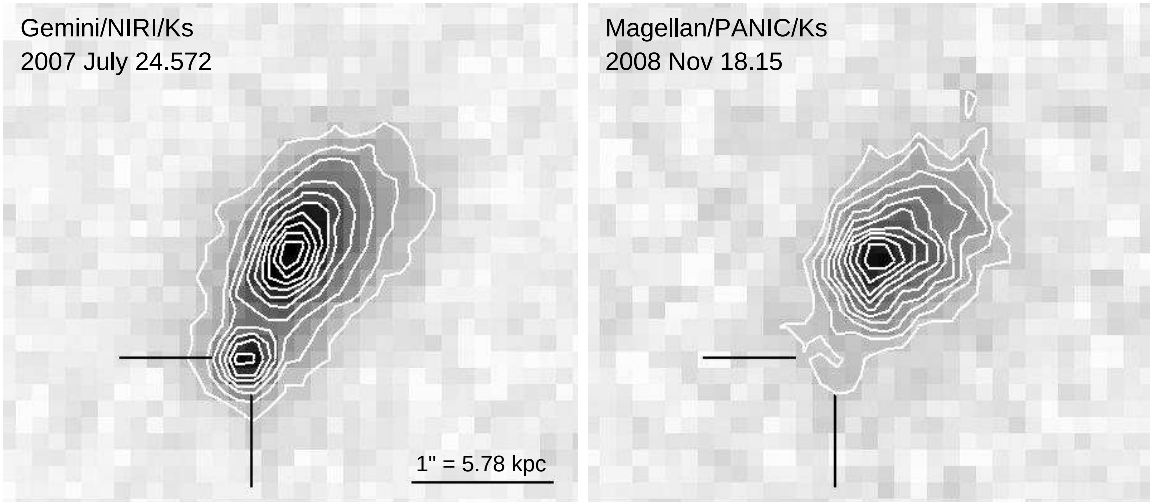

FIG. 3.— Near-IR K_s-band images from NIRI and PANIC of the host and afterglow of GRB 070724A. The cross-hairs on the PANIC image mark the location of the afterglow and indicates that GRB 070724A occurred on the outskirts of the host galaxy. The offset measured from the NIRI image is 4.76 ± 0.06 kpc.

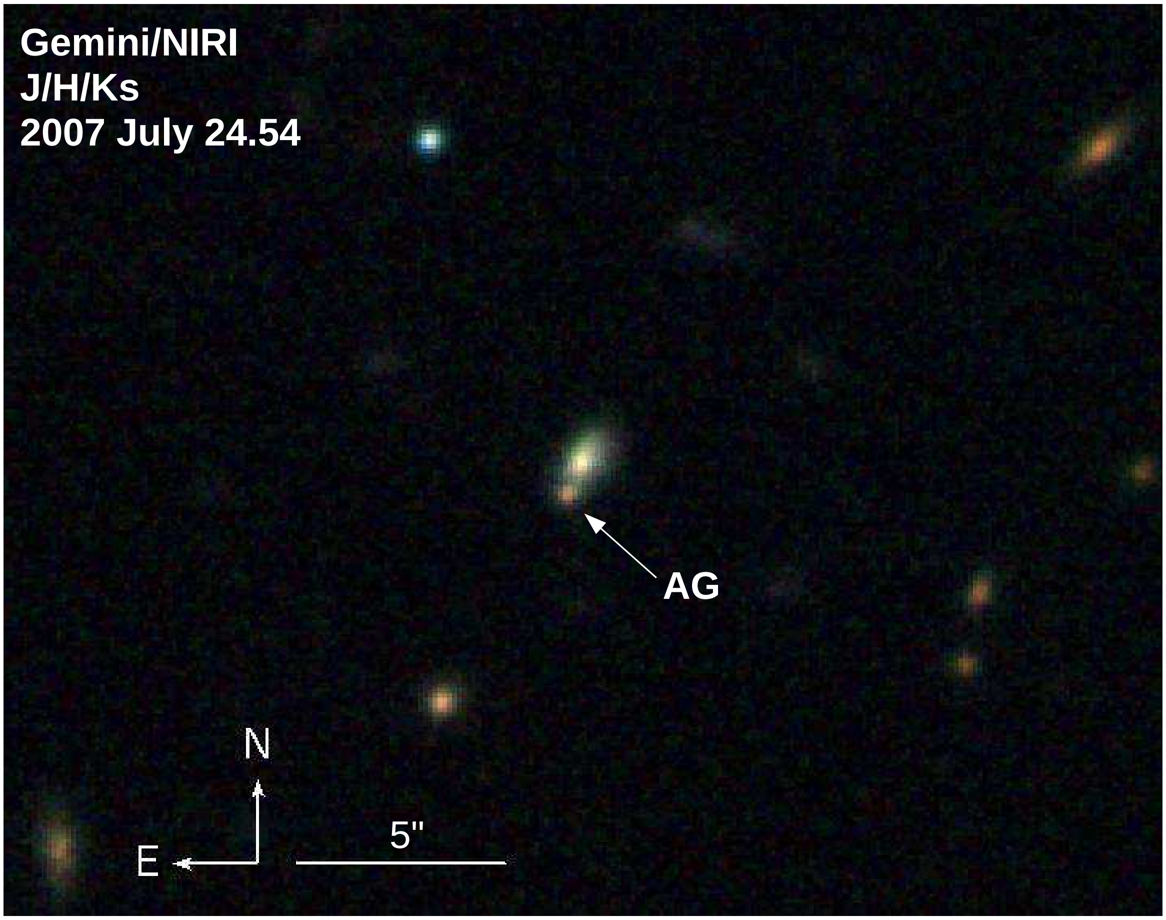

FIG. 4.— Color composite image of the field of GRB 070724A using J (blue), H (green) and K_s (red) images from NIRI. Although we cannot clearly measure the afterglow flux in the J and H bands due to the lack of late-time template images, we find that the afterglow is clearly redder than the host galaxy.

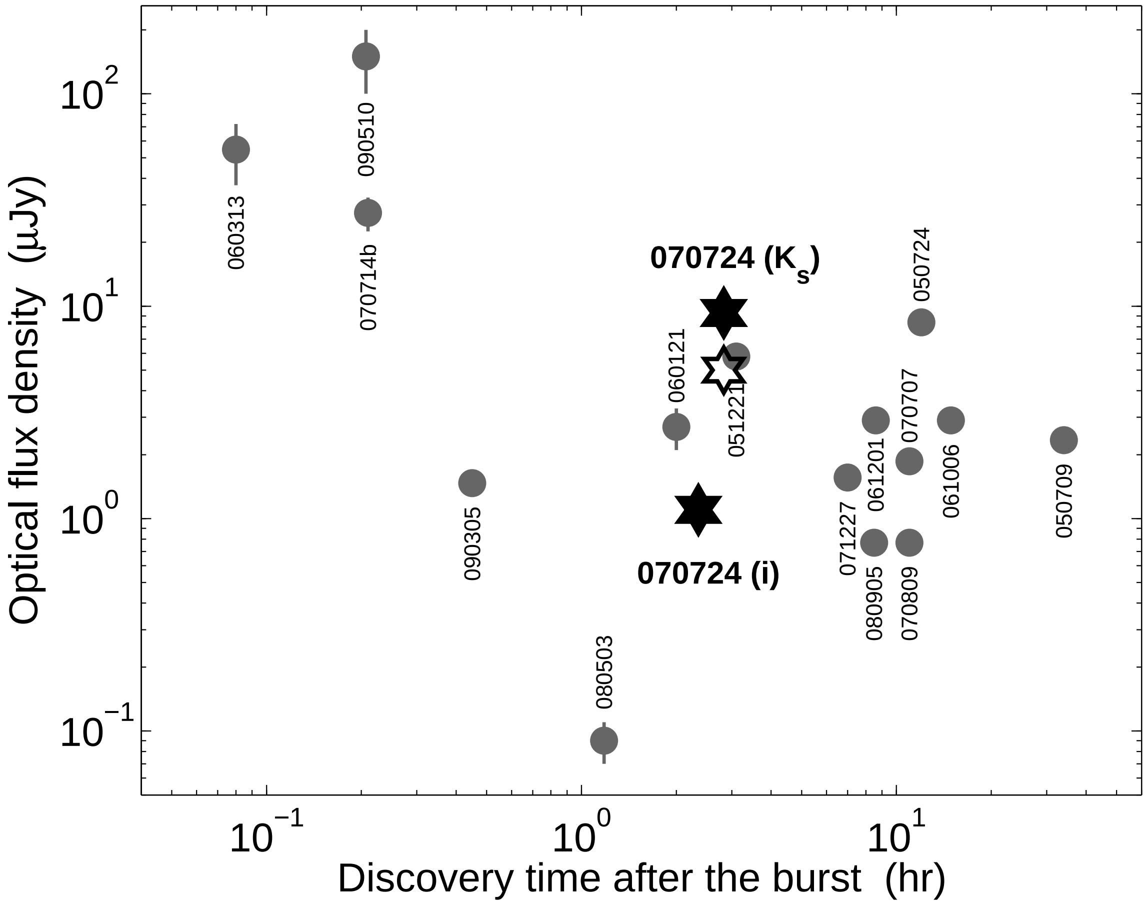

FIG. 5.— Optical flux at the time of discovery for all 16 short GRBs with optical and near-IR afterglows (including GRB 070724A). The solid stars mark the *i*- and K_s-band fluxes of the afterglow of GRB 070724A, while the open star is the optical flux in the *i*-band extrapolated from the near-IR with a spectrum of $F_\nu \propto \nu^{-0.6}$, typical of GRB afterglows. Data for other short GRBs are taken from the literature (Hjorth et al. 2005b; Berger et al. 2005; Soderberg et al. 2006; de Ugarte Postigo et al. 2006; Levan et al. 2006; Roming et al. 2006; D'Avanzo et al. 2009; Stratta et al. 2007; Piranomonte et al. 2008; Graham et al. 2009; Perley et al. 2007, 2009b; Malesani et al. 2008; Cenko et al. 2009a; Berger & Kelson 2009; Kuin & Hoversten 2009).