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INFRARED IMAGING OF GRB 970508[1]

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ABSTRACT

We have observed the field of the gamma-ray burst GRB 970508 at infrared wavelengths (2.2 μm) and have found a variable source coincident with the visible transient thought to be associated with the burst. The source was decaying in brightness with K_s magnitudes of 18.2 ± 0.1, 18.8 ± 0.1, and 19.0 ± 0.3 mag on May 13.25, 16.25, and 20.21 UT, respectively. A 1 σ upper limit of $K = 21.3$ mag was obtained for the brightness of the source on June 14.27 UT. The infrared light curve during this period is consistent with a $\sim t^{-1.2}$ power law, similar to the visible light curve. We do not find evidence for extended structure around the burst, as has been claimed for GRB 970228, and we obtain an upper limit of $0.04L_*$ for the luminosity of an underlying galaxy at the position of the infrared transient.

Subject headings: cosmology: observations — gamma rays: bursts — infrared: galaxies — radiation mechanisms: nonthermal

1. INTRODUCTION

Until last year, the search for low-energy counterparts to gamma-ray bursts (GRBs) at multiple wavelengths has been long and futile (Schaefer et al. 1987; Grindlay, Wright, & McCrosky 1974) because of a lack of rapidly available and accurate GRB positions. The launch of the Italian-Dutch X-ray satellite *BeppoSAX* has revolutionized the field (Piro, Scarci, & Butler 1995). The Wide Field Cameras (WFCs) on *BeppoSAX* enable monitoring of large regions of the sky ($40^\circ \times 40^\circ$) with a positional accuracy of 5′ in the energy range 1.8–26 keV (Jager et al. 1997). This has led to the detection of X-ray transients, as in the case of GRB 970228, which appear to be associated with the GRBs and decay on timescales much longer than the bursts themselves (Costa et al. 1997b). Follow-up observations of the WFC error circles are then solicited at longer wavelengths. The X-ray sources can then be further localized by observing with the narrow field instruments (LECS/MECS) on the satellite. These have a lower energy range from 0.1 to 10 keV but can provide spatial resolution of about an arcminute within a few hours. This has facilitated the detection of transients at visible, infrared, and radio wavelengths (van Paradijs et al. 1997; Klose et al. 1997; Frail et al. 1997) that could provide clues to the origin of the bursts.

GRB 970508 was first detected by the *BeppoSAX* Gamma-Ray Burst Monitor on May 8.904 UT (Costa et al. 1997a). The burst was rather weak, having a maximum intensity of 450 counts s^{-1} and lasting about 15 s. A visible V-band transient, lying within the 50″ radius *BeppoSAX* error circle for GRB 970508, at J2000 coordinates of $\alpha = 06^h53^m49^s.2$ and $\delta = 79^\circ16'19''$, was first reported by Bond (1997). The transient increased in brightness by ~1 mag day^{-1} during the period May 9.19–10.18 UT. A reference object that has been classified as a field star (Bond 1997) is located about 3″ west and 13″ north of the GRB.

Spectroscopic studies of the visible transient (Metzger et al. 1997a) show prominent, redshifted absorption lines. This, coupled with the absence of Lyα forest features in the spectrum, places the transient within the redshift range $2.3 \gtrsim z \geq 0.835$, which would make the burst cosmological in origin.

Many cosmological models of GRBs suggest the presence of a "host" galaxy associated with the bursts. While an overabundance of bright galaxies has been found in GRB error boxes (Larson & McLean 1997; Larson, McLean, & Becklin 1996), there is not much evidence for a rigid correlation between the two. *Hubble Space Telescope* imaging of the field of GRB 970508 (Pian et al. 1998) has not revealed any extended host system similar to that observed around GRB 970228 (van Paradijs et al. 1997; Sahu et al. 1997). From their observations, Pian et al. obtained an upper limit of $0.1L_*$ to the luminosity of a host, if it lies at $z = 0.835$. Natarajan et al. (1997) obtained a stronger limit by comparing the strength of the Mg II absorption lines in the spectrum of the visible transient with the R-band magnitudes of other galaxies in the field. They suggest that the host is most likely an unseen faint dwarf galaxy with luminosity $\lesssim 0.01L_*$. The near-infrared band is ideal to search for potential hosts since galaxies are intrinsically brightest at these wavelengths (Schmitt et al. 1997). In this Letter, we present infrared imaging of the field centered on the visible transient associated with GRB 970508.

2. OBSERVATIONS AND REDUCTIONS

The region associated with GRB 970508 was observed on the nights of 1997 UTC May 13, 16, and June 14 with the Near Infrared Camera at the f/25 focus of the 10 m Keck I telescope (Matthews & Soifer 1994). The detector is a Hughes–Santa Barbara Research Corporation InSb photovoltaic array of size 256 × 256 pixels. The plate scale is 0″.15 $pixel^{-1}$ at the f/25 focus. A K_s filter centered at $\lambda = 2.16$ μm and having width $\Delta\lambda = 0.3$ μm was used for the May observations. The June observation was performed using a K filter centered at $\lambda = 2.21$ μm and $\Delta\lambda = 0.4$ μm. The GRB field was observed at an air mass of ~2.4 in May and ~3.3 in June. We adopted a dithered observing scheme with a 30 s integration at each position on May 13 and a 60 s integration on May 16 and June 14. The resultant on-source time after rejecting some of the bad frames was about 8 minutes for each night in May and 25 minutes in June.

On May 20, observations were made with the Hale 5 m

[1] Primarily based on observations at the W. M. Keck Observatory.

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TABLE 1
Summary of Observations

UT Date	Air Mass	K_s Magnitude[a]	Flux Density[b] (μJy)
May 13.25 ……	2.41	18.2 ± 0.1	33 ± 4
May 16.25 ……	2.43	18.8 ± 0.1	20 ± 2
May 20.21 ……	1.69	19.0 ± 0.3	16 ± 5
Jun 14.27 …….	3.32	>21.3[c]	<2

[a] Within a beam that has a diameter that is twice the seeing FWHM and using the reference object in the field as a secondary calibrator. Error bars reflect only the statistical uncertainty in the relative photometry. There is an additional uncertainty in the absolute photometry of the reference object that would uniformly affect all the observations (see text for details).
[b] Zero points obtained from Tokunaga 1998.
[c] 1 σ upper limit at the K band.

telescope at the Palomar Observatory. Near-infrared images in the K_s band were obtained with the Cassegrain near-infrared camera, which contains a 256 × 256 InSb array detector. The pixel scale is 0″.125 pixel^{-1}, so the full array subtends 32″ × 32″. The total exposure time was 67 minutes, and the position of the telescope was dithered by a few arcseconds every 160 s. Our observations are summarized in Table 1.

The nights of May 13 and 20 were plagued by variable, thin clouds, while the nights of May 16 and June 14 were photometrically clear. The seeing, as determined from the reference object located 3″ west and 13″ north of the visible transient position, was ∼1″ FWHM on May 13, ∼0″.9 on May 16, ∼1″.2 on May 20, and ∼1″.3 on June 14.

The reduction procedure involved subtracting the bias and dark current from the source frames. The resultant frames were flat-fielded by using a normalized sky flat, and an appropriate sky frame was used to remove the background. Bad pixels were corrected using linear interpolation of neighboring pixels. The sky-subtracted images were then aligned on the reference object, and one average image was produced for each individual night.

The data from May 16 and June 14 were calibrated by observing standards from S. E. Persson (1997, private communication) and Casali & Hawarden (1992). Since the GRB field was at a much higher air mass than the standards, appropriate air-mass corrections were performed.

The reference object in the field was clearly detected on all the nights. To within our resolution of ∼1″, the reference object appears to be a point source at infrared wavelengths. The observed K_s magnitude of the object on May 16.25 UT was 17.1 ± 0.1 mag. The June 14.27 UT observations provided a K magnitude of 16.96 ± 0.09 mag. We estimate that the K and K_s magnitudes should differ by only about 0.05 mag. Hence, we adopt a K_s magnitude of 17.0 mag and a K magnitude of 16.95 mag for the reference object. We assumed that this object is constant in brightness and calibrated the GRB relative to it. The use of the reference object as a secondary calibrator made it possible to obtain relative photometry of the GRB, in spite of the poor photometric quality of two of the nights.

We adopted a uniform procedure for the relative photometry that would not be substantially affected by the range of seeing values. The diameter of the beam for each of the nights was set at twice the seeing FWHM. The brightness of the transient was then estimated as the flux density within the beam, assuming that the reference object had the adopted magnitude within a similar beam. Curves of growth were then determined within beams centered on 30 quasi-random points on the final frame for each night. The uncertainty in the photometry was taken as the standard deviation of the curve-of-growth values.

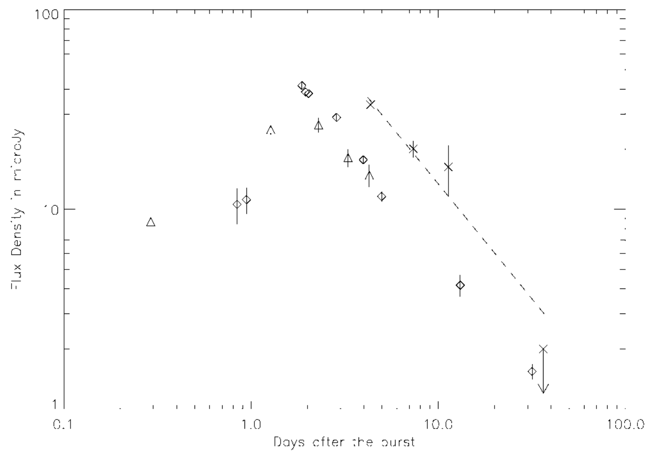

Fig. 1.—K_s- and R-band light curves of GRB 970508. The diamonds are the R_C-band points from Sokolov et al. (1997) and Mignoli et al. (1997), the triangles are the r-band points from Djorgovski et al. (1997) converted using a zero point of $F_{r,0}$ = 3010 Jy, while the crosses are the infrared points. The dashed line illustrates a $t^{-1.2}$ power-law fit to the infrared data. The figure also shows the 1 σ upper limit obtained 36 days after the burst.

3. RESULTS

We detected an infrared source in the 50″ *BeppoSAX* error circle for the nights in May. The K_s magnitude of the source was 18.2 ± 0.1 mag on May 13.25, 18.8 ± 0.1 mag on May 16.25, and 19.0 ± 0.3 mag on May 20.21 UT.[4] The source was undetected in the June 14.27 UT observations, and a 1 σ upper limit of K = 21.3 mag in a 2″.6 diameter beam was obtained. The corresponding flux densities are listed in Table 1. The infrared transient is 12″.7 south and 3″ east of the reference object, which agrees very well with the published separation between the visible transient and the reference object (Bond 1997). The infrared light curve is plotted in Figure 1 relative to the R-band light curve.

Spectroscopic observations of the visible transient led to the detection of absorption lines that have been attributed to the presence of absorption systems along the line of sight at redshifts of $z = 0.835$ and $z = 0.767$ (Metzger et al. 1997a). The limits from the June 14.27 UT observations provide an upper limit of $0.04L_*$ for the luminosity of such an absorption-line system centered at the position of the infrared transient. This is assuming $H_0 = 50$ km s^{-1} Mpc^{-1}, $q_0 = 0$, and $z = 0.835$ and after accounting for the k- and evolutionary corrections (Bruzual 1983). L_* is the “knee” of the Schechter luminosity function and corresponds (for $H_0 = 50$ km s^{-1} Mpc^{-1}) to absolute magnitude $M_K = -25.1$ mag (Mobasher, Sharples, & Ellis 1993).

We do not detect the two galaxies (called G1 and G2 in Pian et al. 1998) located about 5″ away from the position of the visible/infrared transient, at least one of which has been thought to be associated with the burst (Djorgovski et al. 1997; Natarajan et al. 1997). This is consistent with the upper limits

[4] The error bars reflect only the statistical uncertainty in the relative photometry and not the systematic uncertainty associated with the calibration of the reference object that would uniformly affect all the observations. We expect the systematic error to be less than 0.1 mag. The numbers are slightly revised from those in Morris et al. (1997), but the sense of the light curve remains the same.

from our June 14.27 UT observations and the H magnitudes of the galaxies obtained from the Near-Infrared Camera and Multiobject Spectrometer observations (Pian et al. 1998).

4. DISCUSSION

The agreement between the positions of the infrared and visible transients leads us to infer that they have a common source associated with the GRB. Fireball models of GRBs predict that after the peak, the light curves of the transients follow a $t^{-\beta}$ power law in time t (Mészarós & Rees 1997). The r-band data (Djorgovski et al. 1997) from the days immediately following the burst suggest $\beta = 1.0 \pm 0.1$, while observations on timescales of months show a $\beta = 1.18 \pm 0.02$ (Sokolov et al. 1997). A minimized χ^2 fitted to the infrared data yields $\beta = 1.2 \pm 0.1$ with $\chi^2 = 3.81$ and 2 degrees of freedom.[5] We conclude that within the errors, the infrared and visible light curves show the same rate of decline. Of the different GRB remnant models, this value of β points toward the piston model, in which the energy input is impulsive and dissipation occurs through forward shocks with the external medium (Mészarós, Rees, & Papathanassiou 1994).

To determine the spectrum of the transient, we interpolated the R_C-band light curve of Sokolov et al. (1997) to May 13.25 UT, the date of the first infrared observation. We obtain an R_C magnitude of 20.8 ± 0.1 mag that corresponds to an $R_C - K_s$ color of ~2.6 mag. Using the R_C zero points in Hayes (1985) and assuming a single power-law spectrum $F_\nu \propto \nu^\alpha$ from the visible to the infrared, we derive an $\alpha \sim -0.6 \pm 0.2$. This agrees reasonably well with the spectral index of ~ -1 derived by Sokolov et al. (1997). If we do the same analysis for the observations on June 14.27 UT, we find that the transient has become bluer, with an $R_C - K_s < 2.2$ mag. This is consistent with the spectroscopic observations of the visible transient that shows [O II] in emission at $z = 0.835$ (Metzger et al. 1997b), suggesting a blue, star-forming region along the line of sight.

[5] To fit the upper limit from June 14.27, we chose a data value of 0 since the signal in the beam was in the negative direction. The noise in the beam was determined from the curves-of-growth technique described previously.

To calculate the fluence at infrared wavelengths, we integrated the $t^{-1.2}$ light curve in νF_ν over the time span of our data. We obtain a lower limit of 3.5×10^{-8} ergs cm^{-2} in the wavelength range 1.2–3.5 μm. This can be compared with the estimated total fluence of $(3.1 \pm 0.2) \times 10^{-6}$ ergs cm^{-2} in the energy range 20–1000 keV (Kouveliotou et al. 1997). The infrared value is $\gtrsim$1% of the fluence in the GRB itself and is comparable to the 3% observed in the visible bands (Djorgovski et al. 1997).

5. CONCLUSIONS

We report the second detection of an infrared transient associated with a gamma-ray burst (Klose et al. 1997; Soifer et al. 1997). The infrared light curve over the first month after the burst is consistent with a $\sim t^{-1.2}$ profile, which agrees well with the GRB model based on an expanding fireball with an initial impulsive burst of energy input into the system. We do not find evidence for any extended source of emission around the transient position and obtain an upper limit of $\sim 0.04 L_*$ to the luminosity of a galaxy that might be responsible for the observed absorption lines at $z = 0.835$.

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REFERENCES

Bond, H. E. 1997, IAU Circ. 6654
Bruzual A., G. 1983, Rev. Mexicana Astron. Astrofis., 8, 63
Casali, M. M., & Hawarden, T. G. 1992, JCMT-UKIRT Newsl., 3, 33
Costa, E., et al. 1997a, IAU Circ. 6649
———. 1997b, Nature, 387, 783
Djorgovski, S. G., et al. 1997, Nature, 387, 876
Frail, D. A., et al. 1997, Nature, 389, 261
Grindlay, J. E., Wright, E. L., & McCrosky, R. E. 1974, ApJ, 192, L113
Hayes, D. S. 1985, in IAU Symp. 111, Calibration of Fundamental Stellar Quantities, ed. D. S. Hayes et al. (Dordrecht: Reidel), 225
Jager, R., et al. 1997, A&AS, 125, 557
Klose, S., et al. 1997, IAU Circ. 6611
Kouveliotou, C., et al. 1997, IAU Circ. 6660
Larson, S. B., & McLean, I. S. 1997, ApJ, 491, L86
Larson, S. B., McLean, I. S., & Becklin, E. E. 1996, ApJ, 460, L95
Matthews, K., & Soifer, B. T. 1994, Exp. Astron., 3, 77
Mészarós, P., & Rees, M. J. 1997, ApJ, 476, 232
Mészarós, P., Rees, M. J., & Papathanassiou, H. 1994, ApJ, 432, 181
Metzger, M. R., et al. 1997a, Nature, 387, 879
Metzger, M. R., et al. 1997b, IAU Circ. 6676
Mignoli, M., et al. 1997, IAU Circ. 6661
Mobasher, B., Sharples, R. M., & Ellis, R. S. 1993, MNRAS, 263, 560
Morris, M., et al. 1997, IAU Circ. 6666
Natarajan, P., et al. 1997, NewA, 2, 471
Pian, E., et al. 1998, ApJ, 492, L103
Piro, L., Scarci, L., & Butler, R. C. 1995, Proc. SPIE, 2517, 169
Sahu, K. C., et al. 1997, Nature, 387, 476
Schaefer, B. E., et al. 1987, ApJ, 313, 226
Schmitt, H. R., Kinney, A. L., Calzetti, D., & Storchi Bergmann, T. 1997, AJ, 114, 592
Soifer, B., et al. 1997, IAU Circ. 6619
Sokolov, V. V., et al. 1997, in Proc. Fourth Huntsville Gamma-Ray Burst Symp., ed. C. Meegan, R. Preece, & T. Koshut (New York: AIP), in press (Poster Paper)
Tokunaga, A. T. 1998, in Astrophysical Quantities, ed. A. Cox (4th ed.; New York: AIP), in press
van Paradijs, J., et al. 1997, Nature, 386, 686