

THE DISCOVERY AND BROADBAND FOLLOW-UP OF THE TRANSIENT AFTERGLOW OF GRB 980703

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Received 1998 August 28; accepted 1998 September 25; published 1998 October 21

ABSTRACT

We report on the discovery of the radio, infrared, and optical transient coincident with an X-ray transient proposed to be the afterglow of GRB 980703. At later times when the transient has faded below detection, we see an underlying galaxy with $R = 22.6$; this galaxy is the brightest host galaxy (by nearly 2 mag) of any cosmological gamma-ray burst (GRB) thus far. In keeping with an established trend, the GRB is not significantly offset from the host galaxy. Interpreting the multiwavelength data in the framework of the popular fireball model requires that the synchrotron cooling break was between the optical and X-ray bands on 1998 July 8.5 UT and that the intrinsic extinction of the transient is $A_V = 0.9$. This is somewhat higher than the extinction for the galaxy as a whole, as estimated from spectroscopy.

Subject headings: cosmology: observations — galaxies: general — gamma rays: bursts

1. INTRODUCTION

GRB 980703 of 1998 July 3.18 UT was detected by the All Sky-Monitor (ASM) of the *Rossi X-ray Timing Explorer*, *Ulysses*, BATSE, and the gamma-ray burst monitor of *BeppoSAX* (Levine, Morgan, & Muno 1998; Hurley & Kouveliotou 1998; Kippen 1998; Amati et al. 1998). The 4' radius ASM position was further refined to a 50'' radius error circle with observations using the Narrow Field Instruments (NFIs) on *BeppoSAX* (Galama et al. 1998a).

Radio observations were begun on 1998 July 4.41 UT at the Very Large Array¹³ (VLA) in Socorro, NM. A single, weak radio source was seen coincident with an optically variable source (Frail et al. 1998a). Subsequent optical¹⁴ and radio observations (Zapatero Osorio et al. 1998; Vreeswijk et al. 1998; Bloom et al. 1998a; Frail et al. 1998b) confirmed the transient nature of the source. Following a now-familiar pattern, we

identify the radio and optical transient (OT) to be the afterglow of GRB 980703.

2. OBSERVATIONS

We present a log of the optical and infrared (IR) imaging photometry in Table 1. Data were obtained using a CCD imager at the Palomar 60 inch (152 cm) telescope and the Low-Resolution Imaging Spectrograph (LRIS) (Oke et al. 1995) and Near-Infrared Camera (NIRC) (Matthews & Soifer 1994) instruments at the Keck 10 m telescopes. All nights were photometric. Flux calibration of the optical images was performed in the Johnson-Kron-Cousins magnitude system using the standard field PG 2213–006 (Landolt 1992), including a color term and an atmospheric extinction correction. The IR data were calibrated using the standards SJ 9186 and SJ 9101¹⁵. In Figure 1 we give a finding chart for the transient.

VLA monitoring of GRB 980703 was carried out at 1.43, 4.86, and 8.46 GHz. In addition, an observation was made on 1998 July 10.53 UT using the SCUBA array on the James Clerk Maxwell Telescope¹⁶ at 220 GHz. At 1.43 GHz the source has remained weak (less than 120 μ Jy). At 4.86 GHz the source exhibited a large degree of variability, consistent with interstellar scattering. At 8.46 GHz the flux has been relatively steady with a mean of 940 μ Jy during the first 11 days after the gamma-ray burst (GRB). Despite excellent conditions, no 220 GHz source was visible above a 2 σ error limit of 5.2 mJy. The observed scintillation and the broadband spectrum of GRB 980703 are similar to other well-studied radio afterglows (e.g., Shepherd et al. 1998; Taylor et al. 1998). Further discussion on the radio properties of this GRB can be found in Frail et al. (1998c).

3. RESULTS

In Table 1 we summarize the measured fluxes at the position of the transient. In Figure 2 we plot the optical and IR light

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¹³ The VLA is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

¹⁴ Some optical and infrared observations were obtained at the W. M. Keck Observatory, which is operated by the California Association for Research in Astronomy, a scientific partnership between the California Institute of Technology, the University of California, and the National Aeronautics and Space Administration.

¹⁵ S. E. Persson has made these available at http://astro.caltech.edu/mirror/keck/realpublic/inst/nirc/HST_Standards.html.

¹⁶ The James Clerk Maxwell Telescope is operated by The Joint Astronomy Centre on behalf of the Particle Physics and Astronomy Research Council of the United Kingdom, the Netherlands Organization for Scientific Research, and the National Research Council of Canada.

TABLE 1
PHOTOMETRIC OBSERVATIONS OF GRB 980703

| Date (1998 UT) | Instrument | Band | Integration (s) | Seeing (arcsec) | Magnitude ^a | Error |
|-------------------|------------|----------|--------------------|--------------------|------------------------|-------|
| Jul 4.48 | P60 | <i>R</i> | 600 | 0.85 | 21.28 | 0.18 |
| Jul 5.482 | P60 | <i>R</i> | 600 | 1.9 | 21.83 | 0.32 |
| Jul 6.607 | LRIS | <i>R</i> | 600 | 0.65 | 22.06 | 0.1 |
| | LRIS | <i>B</i> | 600 | 0.65 | 23.05 | 0.1 |
| Jul 8.576 | NIRC | <i>H</i> | 50 | 0.45 | 19.56 | 0.13 |
| Jul 8.545 | NIRC | <i>K</i> | 100 | 0.45 | 18.78 | 0.10 |
| Jul 8.597 | NIRC | <i>J</i> | 50 | 0.45 | 20.45 | 0.15 |
| Jul 10.55 | LRIS | <i>B</i> | 750 | 1.0 | 23.09 | 0.1 |
| Jul 10.56 | LRIS | <i>V</i> | 600 | 1.0 | 22.94 | 0.1 |
| Jul 10.53 | LRIS | <i>R</i> | 600 | 1.0 | 22.44 | 0.1 |
| Jul 10.57 | LRIS | <i>I</i> | 120 | 1.0 | 21.61 | 0.1 |
| Jul 18.57 | LRIS | <i>B</i> | 600 | 0.5 | 23.17 | 0.15 |
| | LRIS | <i>V</i> | 300 | 0.5 | 23.01 | 0.1 |
| Jul 18.55 | LRIS | <i>R</i> | 600 | 0.5 | 22.63 | 0.1 |
| Jul 18.58 | LRIS | <i>I</i> | 150 | 0.5 | 21.86 | 0.1 |
| Aug 7.53 | NIRC | <i>J</i> | 120 | 0.5 | 21.02 | 0.15 |
| Aug 7.52 | NIRC | <i>H</i> | 120 | 0.5 | 20.30 | 0.2 |
| Aug 7.50 | NIRC | <i>K</i> | 120 | 0.5 | 19.61 | 0.15 |

^a Optical data are reported in the Johnson-Kron-Cousins magnitude system and are uncorrected for Galactic extinction. The reported magnitudes are corrected (by less than 0.02 mag) using the standard atmospheric transmission at the respective observing sites.

curves of the transient source. It is a prediction of spherical fireball models that the late-time light curves of GRB afterglow should closely follow a power-law decline and, indeed, this has been observed (e.g., Galama et al. 1998b; Zharikov, Sokolov, & Baryshev 1998). The presence of a host galaxy will cause the light curve to flatten eventually. Following Bloom et al. (1998b), we model the light curve as $f_{\text{total}} = f_0 t^\alpha + f_{\text{host}}$, with time expressed in days, the decay constant (α), and the corresponding normalization of the transient magnitude (m_0), and the host galaxy magnitude (m_{host}). In Table 2 we give our light-curve fits to this OT + host flux model. Only the *R* and *I* bands had a sufficient number of data points to fit for the three parameters independently. The weighted average of decay constants for the *I* and *R* bands (Table 2) give $\alpha = -1.17 \pm 0.25$. For the IR bands, we assume $\alpha = -1.17$ and fit for m_{host} and m_0 . In the case of the *B* and *V* bands, we report the last observed magnitude as m_{host} .

It is of interest to quantify any potential offset of the transient from its host galaxy, since the distribution of offsets may help to constrain the various progenitor models. Using the methodology outlined in Bloom et al. (1998b), we registered the Keck LRIS images taken on 1998 July 6 and 18 (see Table 1) accounting for the relative scale, rotation, translation, and second-order distortion. The rms centroid difference of the

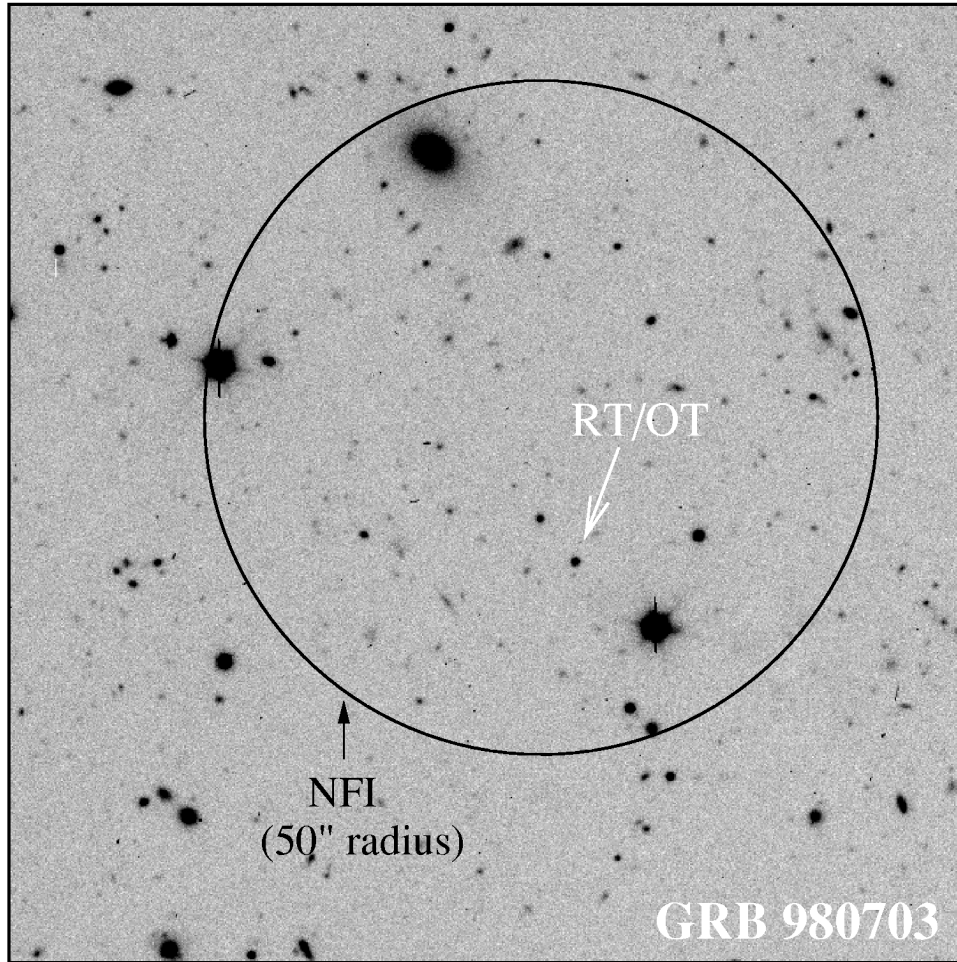


FIG. 1.—Finding chart for the transient afterglow of GRB 980703. The radio/optical transient (“RT/OT”) was discovered in the overlapping region of the ASM position (Smith, Levine, & Munro 1998), interplanetary network (IPN) annulus (Hurley & Kouveliotou 1998), and *BeppoSAX* NFI position (Galama et al. 1998a). The radio transient is located at $\alpha = 23^{\text{h}}59^{\text{m}}6.666 \pm 0.05$, $\delta = +08^{\circ}35'7.07 \pm 0.05$ (J2000). The RT/OT position is marked within the $3' \times 3'$ LRIS 600 s *R*-band image taken on July 6.6 (see Table 1).

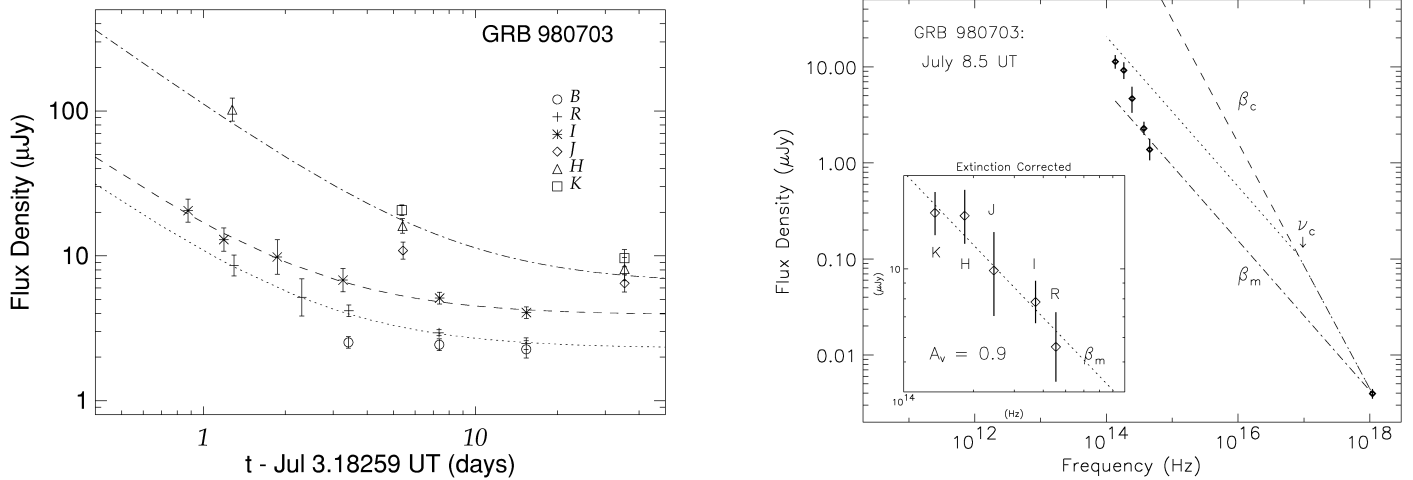


FIG. 2.—*Left*: Optical and infrared light curve of the transient of GRB 980703. The fit to the *R*-, *I*-, and *H*-band light curves are shown (see Table 2). The first four *I*-band points are from Vreeswijk et al. (1998), and the first *H*-band point is from Henden et al. (1998). The plotted fluxes have not been corrected for Galactic extinction. We did not fit a model to the *B*-band light curve, since the OT had faded away at *B* band by the time of our first observation. *Right*: Inferred broadband spectrum of the transient afterglow of GRB 980703 on July 8.5. The fluxes plotted above have been corrected for Galactic extinction (see Table 2). We show the predicted spectra of the IR/optical/X-ray if these frequencies were below ($F_\nu \propto \nu^{\beta_m}$; dot-dashed line) or above ($F_\nu \propto \nu^{\beta_c}$; dashed line) the synchrotron cooling regime.

transformed star positions (including both axes) was $\sigma = 36$ mas. We find the angular separation of the OT and the host galaxy to be 63 mas, which includes the error of the transformation and centering errors of the objects themselves. However, the transient contributed only 30% of the total OT + host flux on the first epoch. Thus, we conclude that the transient is offset by 210 ± 120 mas; this angular separation is consistent with no offset from the host galaxy at the 1.8σ level.

4. DISCUSSION AND CONCLUSIONS

The small offset of the afterglow from the underlying galaxy suggests, like most other well-studied GRBs (e.g., Sahu et al. 1997; Odewahn et al. 1998), that GRB 980703 is closely connected to its host galaxy. If indeed the galaxy is the host, then at $R = 22.6$ it is the brightest (apparent) host galaxy of any cosmological GRB thus far (see Hogg & Fruchter 1998 for a review). In a companion paper, Djorgovski et al. (1998) derive a redshift for the OT + host of $z = 0.966$. Assuming $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $\Omega = 0.2$, the luminosity distance to the host is $d_L = 1.92 \times 10^{28} \text{ cm}$. A cubic-spline fit to the host spectrum (Table 2) gives a flux density of $4.6 \mu\text{Jy}$ at 8745 \AA , the redshifted effective wavelength of the *B* band. This corresponds to an absolute magnitude of $M_B \approx -21.2$. The host

is thus a typical galaxy at the knee of the *B*-band luminosity function at the epoch of $z \approx 1$ (e.g., Lilly et al. 1995). In the July 18 LRIS images, the galaxy appears marginally extended with a FWHM of $0''.74$ in $0''.65$ seeing.

In discussing the interpretation of the specific features of the optical-IR spectrum, we will assume an adiabatic hydrodynamical evolution of the afterglow and that the cooling frequency (ν_c) is blueward of the peak frequency (ν_m) (see Sari, Piran, & Narayan 1998 for details).

The optical and IR transient fluxes at day 5.3 (July 8.5 UT) are fit by a spectral slope of ≈ -2 with some indication of a break near $1 \mu\text{m}$ (Fig. 2). In the case of GRB 971214, where the behavior was quite similar, the IR/optical data required an additional extinction correction (presumably dust extinction local to the GRB) to fit the expectations of the fireball model (Ramaprakash et al. 1998; Wijers & Galama 1998). Indeed, without an extinction correction, an extrapolation of the IR/optical spectrum would underpredict the X-ray point (Galama et al. 1998a) by several orders of magnitude. If the IR/optical/X-ray behaviors were simultaneously in the cooling regime, the spectral slope expected from our derived α would be $\beta_c = -1.1$. No value of extinction can correct the observed IR/optical spectral slope without *underpredicting* the X-ray point by more than a factor of 10. We therefore exclude the possibility that the IR/optical/X-ray were simultaneously in the cooling regime on July 8.5. The other possibility is that ν_c had not yet moved into the IR/optical bands; in this case we expect a spectral index of $\beta_m = -0.78$. Indeed, fitting the IR/optical data with a galactic extinction curve to this expected power-law slope, we find that with an extinction correction of $A_V = 0.9 \pm 0.2$ (Castro-Tirado et al. 1998 found $A_V \approx 1.6$), the IR/optical data can be made consistent with $\beta_m = -0.78$. Nevertheless, extrapolating the extinction-corrected spectrum *overpredicts* the X-ray flux by a factor of 10 (see Fig. 2).

To this end, we suggest that there must be a cooling break ($\nu_c \approx 9 \times 10^{16} \text{ Hz}$) between the IR/optical and X-ray bands on July 8.5 UT. This observation leads immediately to the value for electron energy spectral index $p = 2.6$, consistent with other afterglows (e.g., Yoshida et al. 1998; Sokolov, Zharikov, &

TABLE 2
BROADBAND SPECTRUM FITS

| Band | α | m_0 | m_{host} |
|----------------|------------------|-------------------------|-------------------------|
| <i>B</i> | ... | ... | 22.92 ± 0.2 |
| <i>V</i> | ... | ... | 22.83 ± 0.1 |
| <i>R</i> | -1.22 ± 0.35 | $21.14^{+0.23}_{-0.29}$ | $22.62^{+0.18}_{-0.22}$ |
| <i>I</i> | -1.12 ± 0.35 | $20.51^{+0.15}_{-0.17}$ | $21.92^{+0.22}_{-0.28}$ |
| <i>J</i> | (-1.17) | $19.16^{+0.34}_{-0.50}$ | $21.11^{+0.16}_{-0.19}$ |
| <i>H</i> | (-1.17) | $17.72^{+0.17}_{-0.20}$ | $20.66^{+0.24}_{-0.31}$ |
| <i>K</i> | (-1.17) | $17.20^{+0.19}_{-0.23}$ | $19.78^{+0.17}_{-0.20}$ |

NOTE.—Magnitudes are corrected assuming a Galactic extinction of $E(B - V) = 0.0607$ (Schlegel, Finkbeiner, & Davis 1998) and the extinction curve from Cardelli, Clayton, & Mathis (1989). The uncertainties on a given parameter are formal errors of the fit and include the uncertainties in the other parameters.

Panthenko 1998). Furthermore, the measured decay constants are consistent with this picture. Since the X-ray transient was observed while in the cooling regime, its time decay ($\alpha_X = -1.33 \pm 0.25$; Galama et al. 1998a) is *expected* to be steeper than that measured from the IR/optical ($\alpha = -1.17 \pm 0.25$). The late-time radio decay appears to be somewhat slower than the IR/optical decay (Frail et al. 1998c), which could indicate the evolution of the fireball to a nonrelativistic regime. The location of the cooling break between the X-ray and optical bands at this time suggests that the electrons are not cooling efficiently, and thus our assumption of adiabatic hydrodynamical evolution is a correct one.

Our model fits to early-time observations allow us to constrain additional properties of the afterglow. Assuming the standard bandpass shapes and zero-magnitude calibration (Fukugita, Shimasaku, & Ichikawa 1995; Bessel & Brett 1988), our fit (Table 2) to the transient light curve, and an extinction of $A_V = 0.9$, we find a total integrated fluence over R , I , J , H , and K bands from day 1 onward of $S_{\text{IR/opt}} \approx 8 \times 10^{-8}$ ergs cm^{-2} . For comparison, the fluence above 20 keV in the GRB itself was $S_\gamma \approx 4.6 \times 10^{-5}$ ergs cm^{-2} (Kippen 1998). We estimate the total X-ray fluence (1.3–10 keV) from day 1 onward of $S_X \approx 6 \times 10^{-7}$ ergs cm^{-2} using the data reported in Galama et al. (1998a). The fluence ratio is then $S_{\text{IR/opt}} : S_X : S_\gamma = 1:8:575$. The associated total energy release [$\approx 4\pi S d_L^2/(1+z)$] is $E_\gamma = 10^{53}$, $E_X = 10^{51}$, and $E_{\text{IR/opt}} = 2 \times 10^{50}$ ergs.

In conclusion, the broadband spectrum and the light curves demonstrate the general consistency of the afterglow spectrum and the expectations of an adiabatic relativistic blast wave. Correction of the intrinsic extinction suggests that the synchrotron cooling break frequency was somewhere between the optical and X-ray bands on July 8.5 UT. Since the inferred intrinsic extinction is ≈ 0.6 mag greater than the extinction inferred toward the host's H II regions (Djorgovski et al. 1998), this suggests that the GRB could have occurred in a dusty environment.

We thank F. Chaffee, the Director of the W. M. Keck Observatory, for allocation of service time for observations. The staff of WMKO and of the Palomar Observatory are thanked for their continued effort on the GRB project. We thank W. Wack, T. Williams, E. Morris, M. Pierce, and A. Conrad for service observations at Keck and P. Groot for assistance during our latest Keck run. In addition, we are indebted to the *BeppoSAX* team and the *RXTE*-ASM team for their X-ray work. The GRB community, as a whole, has greatly benefited from the information disseminated by the GRB Coordinates Network (GCN), and we thank in particular S. Barthelmy for his efforts. The research of S. R. K. and J. S. B. is supported by NSF and NASA. S. G. D. acknowledges partial support from the Bressler Foundation.

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