THE X-RAY, OPTICAL, AND INFRARED COUNTERPART TO GRB 980703


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ABSTRACT

We report on X-ray, optical, and infrared follow-up observations of GRB 980703. We detect a previously unknown X-ray source in the GRB error box; assuming a power-law decline, we find for its decay index $\alpha < -0.91$ (3 $\sigma$). We invoke host-galaxy extinction to match the observed spectral slope with the slope expected from “fireball” models. We find no evidence for a spectral break in the infrared to X-ray spectral range on 1998 July 4.4, and determine a lower limit of the cooling break frequency, $v_c > 1.3 \times 10^{17}$ Hz. For this epoch we obtain an extinction of $A_V = 1.50 \pm 0.11$. From the X-ray data we estimate the optical extinction to be $A_V = 20.2^{+12.3}_{-7.3}$, inconsistent with the former value. Our optical spectra confirm the redshift of $z = 0.966$. We compare the afterglow of GRB 980703 with that of GRB 970508 and find that the fraction of the energy in the magnetic field, $\epsilon_B < 6 \times 10^{-5}$, is much lower in the case of GRB 980703, as a consequence of the high frequency of the cooling break.

Subject headings: gamma rays: bursts — infrared: galaxies — radiation mechanisms: nonthermal — X-rays: galaxies

1. INTRODUCTION

Several properties of gamma-ray burst (GRB) afterglows can be explained well by “fireball” models, in which a relativistically expanding shock front, caused by an energetic explosion in a central compact region, sweeps up the surrounding medium and accelerates electrons in a strong synchrotron emitting shock (Mészáros & Rees 1994; Wijers, Rees, & Mészáros 1997; Sari, Piran, & Narayan 1998; Galama et al. 1998a). The emission shows a gradual softening with time, corresponding to a decrease of the Lorentz factor of the outflow. Most X-ray and optical/infrared (IR) afterglows display a power-law decay (except GRB 980425, which is most likely associated with the peculiar supernova SN 1998bw; Galama et al. 1998b).

Spectral transitions in the optical/IR have been detected for the afterglows of GRB 970508 (Galama et al. 1998a; Wijers & Galama 1998) and GRB 971214 (Ramaprakash et al. 1998). These have been explained by the passage through the optical/IR wave band of the cooling break at $v_c$ (for GRB 970508) and the peak of the spectrum at $v_m$ (for GRB 971214); see Sari, Piran, & Narayan (1998) and Wijers & Galama (1999) for their definition. For GRB 970508, the observed break is in excellent agreement with such “fireball” models, while for GRB 971214 an exponential extinction has been invoked to explain the discrepancy between the observed and expected spectral indexes.

GRB 980703 was detected on July 3.182 UT with the All-Sky Monitor (ASM) on the Rossi X-Ray Timing Explorer (RXTE; Levine et al. 1998), the Burst And Transient Source Experiment (BATSE, trigger No. 6891; Kippen et al. 1998), BeppoSAX (Amati et al. 1998), and Ulysses (Hurley et al. 1998). The burst as seen by BATSE consisted of two pulses, each lasting approximately 100 s, with a total duration of about 400 s (Kippen et al. 1998). The first pulse had significant substructure, whereas the...
The light curves of the OT are shown in Figure 2 (see Table 2 for a list of the magnitudes). In view of the flattening of the light curves after $t \approx 5$ days, we fitted a model $F_\text{OT} = F_0 + t^\alpha + F_\text{gal}$ to our own $I$- and $H$-band light curves (in these bands we have sufficient data for a free-parameter fit). Here $t$ is the time since the burst in days, and $F_\text{gal}$ is the flux of the underlying host galaxy. The values for $m_0 = -2.5 \log (F_0) + C$, the decay index $\alpha$, and $m_\text{gal} = -2.5 \log (F_\text{gal}) + C$ are listed in Table 3. The photometric calibration, which determines $C$, has been taken from Bessell (1979) for $V$, $R$, and $I$. 

The X-ray light curve is shown in Figure 1. We checked for the presence of the 6.4 keV K line at the redshifted energy of 3.26 keV, but did not detect it. The upper limit on its flux is $8.3 \times 10^{-6}$ photons cm$^{-2}$ s$^{-1}$ (90% confidence level), corresponding to an equivalent width of 532 eV in the observer’s frame.

3. OPTICAL AND INFRARED OBSERVATIONS

We observed the field of GRB 980703 with the Wise Observatory 1 m telescope ($I$); the 3.5 m New Technology Telescope (NTT; in $V$, $I$, and $H$), 2.2 m (in $H$ and $K_s$), and Dutch 90 cm (in Gunn $i$) telescopes of ESO (La Silla); the CTIO 0.9 m telescope (in $R$); and UKIRT (in $H$, $J$, and $K$).

The optical images were bias-subtracted and flat-fielded in the standard fashion. The infrared frames were reduced by first removing bad pixels and combining about five frames around each object image to obtain a sky image. This sky image was then subtracted after scaling it to the object image level, and the resulting image was flat-fielded.

Four reference stars were used to obtain the differential magnitude of the optical transient (OT) in each frame. These stars were calibrated by observing the standard stars PG 2331+055 (in $V$ and $I$; Landolt 1992), FS 2, and FS 32 (in $J$, $H$, and $K$; Casali & Hawarden 1992). We used the $R$-band calibration of Rhoads et al. (1998). The offsets in right ascension and declination from the OT and the apparent standard magnitudes outside the Earth’s atmosphere of the reference stars are listed in Table 1.
and from Bessell & Brett (1988) for $J$, $H$, and $K$. The weighted mean value of $\alpha$ for the $I$ and $H$ bands is $-1.61 \pm 0.12$, while an $I$- and $H$-band joint fit, with a single power-law decay index, gives $\alpha = -1.63 \pm 0.12$ ($\chi = 15.4/16$). For the $V$, $R$, $J$, and $K$ bands, we fixed $\alpha$ at $-1.61$, included data from the literature, and fitted $m_0$ and $m_{gal}$. The fits are shown as solid lines in Figure 2. We note that when we fit all three parameters to the $R$-band data (mainly data from the literature), we obtain a temporal slope of $\frac{-1.94 \pm 0.22}{t}$, consistent with the adopted value of $-1.61 \pm 0.12$. However, we do not include this value in the average, since the $R$-band magnitudes are taken from the literature and thus not consistently measured.

For four epochs we have reconstructed the spectral flux distribution of the OT (times $t_1$, $t_2$, $t_3$, and $t_4$ in Fig. 2, corresponding to 1998 July 4, 6, 7, and 8, respectively). The host-galaxy flux, obtained from the fits to the light curves, was subtracted. We corrected the OT fluxes for Galactic foreground absorption ($A_V = 0.19$). If more than one value per filter was available around the central time of the epoch, we took their weighted average. All values were brought to the same epoch by applying a correction using the slope of the fitted light curve. For the first epoch ($t_1$) we fitted the resulting spectral flux distribution with a power law, $F_\nu \propto \nu^p$, and find $\beta = -2.71 \pm 0.12$.

We took three 1800 s spectra of the OT with the NTT, around July 8.38 UT. The No. 3 grism that was used has a blaze wavelength of 4600 Å and a dispersion of 2.3 Å pixel$^{-1}$. The slit width was set at 1". The three spectra were bias-subtracted and flat-fielded in the usual way. The coadded spectrum was then extracted the same way as the standard star Feige 110. We wavelength calibrated the spectrum with a Helium/Argon lamp spectrum, with a residual error of 0.03 Å. The spectrum was flux calibrated with the standard star Feige 110 (Massey et al. 1988). We estimate the accuracy of the flux calibration to be 10%. The wavelength- and flux-calibrated spectrum shows one clear emission line at $7330.43 \pm 0.14$ Å with a flux of $3.6 \pm 0.4 \times 10^{-16}$ ergs cm$^{-2}$ s$^{-1}$. At the redshift $z = 0.966$ determined by Djorgovski et al. (1998) this is the $\lambda 3727$ line of [O II]: our wavelength measurement corresponds to $z = 0.9665 \pm 0.0005$.

4. DISCUSSION

From the optical/IR light curves presented in § 3 we have obtained an average power-law decay constant $\alpha = -1.61 \pm 0.12$. This value is consistent with those derived by Bloom et al. (1998) ($\alpha_R = -1.22 \pm 0.35$ and $\alpha_I = -1.12 \pm 0.35$) and Castro-Tirado et al. (1999) ($\alpha_R = -1.39 \pm 0.3$ and $\alpha_H = -1.43 \pm 0.11$).

If we make the assumption that the OT emission is due to synchrotron radiation from electrons with a power-law energy distribution (with index $p$), we would expect a relation between $p$, the spectral slope $\beta$, and the decay constant $\alpha$ (Sari, Piran, & Narayan 1998). We assume that our observations are situated in the slow-cooling, low-frequency regime (e.g., for GRB 970508 this was already the case after 500 s; Galama et al. 1998a). One must distinguish two cases:

1. Both the peak frequency $\nu_m$ and the cooling frequency $\nu_c$ are below the optical/IR wave band. Then $p = -(4\alpha + 2)/3 = 2.81 \pm 0.16$ and $\beta = -p/2 = -1.41 \pm 0.08$.

2. The peak frequency $\nu_m$ has passed the optical/IR wave band, but $\nu_c$ has not yet. In that case, $p = -(4\alpha + 3)/3 = 3.15 \pm 0.16$ and $\beta = -(p-1)/2 = -1.07 \pm 0.08$.

In both cases, the expected value of $\beta$ is inconsistent with the observed $\beta = -2.71 \pm 0.12$. Following Ramaparaksh
determine the host-galaxy absorption, we first blueshifted the OT fluxes for Galactic foreground absorption). To et al. (1998), we assume that the discrepancy is caused by the Galactic extinction curve of Cardelli, Clayton, & Mathis (1989) to obtain the expected spectral slope $\beta$. For epoch $t_1$ (July 4.4 UT), we obtain $A_V = 1.15 \pm 0.13$ and $A_V = 1.45 \pm 0.13$ for cases 1 and 2, respectively (see Fig. 3).

In case 1, we find that an extrapolation of the optical flux distribution to higher frequencies predicts an X-ray flux that is significantly below the observed value, whereas in case 2 the extrapolated and observed values are in excellent agreement. The mismatch in case 1 is in a direction that cannot be interpreted in terms of the presence of a cooling break between the optical and X-ray wave bands. When we include the X-ray data point in the fit to obtain a more accurate determination of $A_V$, we find $A_V = 1.50 \pm 0.11$ and $\beta = -1.013 \pm 0.016$. We conclude that the optical/IR range is not yet in the cooling regime, and so

<table>
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<th>Filter</th>
<th>Exposure Time (s)</th>
<th>Seeing (arcsec)</th>
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<td>$K$</td>
<td>2160</td>
<td></td>
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Note.—Instruments and CCDs used: NTT EMMI: red arm with TEK 2k x 2k CCD (No. 36), 0.27 pixel$^{-1}$; NTT SUSI2: EEV 4k x 2k CCD (No. 45 and 46), 0.08 pixel$^{-1}$; NTT SOFI: Hawaii 1k x 1k HgCdTe array, 0.29 pixel$^{-1}$; ESO Dutch: CCD Camera with TEK 512 x 512 CCD (No. 33), 0.47 pixel$^{-1}$; Wise 1.36 m: CTIO 0.9 m: ESO 2k x 2k CCD, 0.38 pixel$^{-1}$; UKIRT: IRCAM3 with FPA2 256 x 256 detector, 0.29 pixel$^{-1}$; 2.2 m (IRAC2b): NICMOS-3 256 x 256 array, 0.507 pixel$^{-1}$. Note that we do not list an estimate of the seeing in the case of infrared observations, since the real seeing is overestimated as a result the process of coadding the individual frames.

et al. (1998), we assume that the discrepancy is caused by host-galaxy extinction (note that we have already corrected the OT fluxes for Galactic foreground absorption). To determine the host-galaxy absorption, we first blueshifted the OT flux distribution to the host-galaxy rest frame (using $z = 0.966$), and then applied an extinction correction using the Galactic extinction curve of Cardelli, Clayton, & Mathis (1989) to obtain the expected spectral slope $\beta$. For epoch $t_1$ (July 4.4 UT), we obtain $A_V = 1.15 \pm 0.13$ and $A_V = 1.45 \pm 0.13$ for cases 1 and 2, respectively (see Fig. 3).

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\[ p = 3.15 \pm 0.16. \]

Where would the cooling frequency, \( \nu_c \), be located? The X-ray photon index, \( \Gamma = 2.51 \pm 0.32 \), corresponding to a spectral slope of \( \beta = -1.51 \pm 0.32 \), suggests that perhaps the X-ray wave band is just in the cooling regime, in which case the expected local X-ray slope would be \( \beta = -p/2 = -1.57 \pm 0.08 \), while if not in the cooling regime it would be \( \beta = -(p-1)/2 = -1.07 \pm 0.08 \). However, the large error on the measured X-ray spectral slope would also allow the cooling break to be above 2–10 keV. We estimate the (2 \( \sigma \)) lower limit to the cooling frequency to be \( \nu_c > 1.3 \times 10^{17} \) Hz (\( \nu_c > 0.5 \) keV).

We performed the same analysis for the other epoch (\( t_4 \)) with X-ray data (see Fig. 3). At this epoch, the X-ray upper limit does not allow us to discriminate between the two cases. However, we can still estimate a lower limit to the cooling break from its time dependence: \( \nu_c \propto t^{-1/2} \), which would allow the break to drop to \( \nu_c > 6.3 \times 10^{16} \) Hz only, between epochs \( t_1 \) and \( t_4 \).

On the basis of our analysis, we conclude that there is no strong evidence for a cooling break between the optical/IR and the 2–10 keV passband before 1998 July 8.4 UT. This conclusion is at variance with Bloom et al. (1998), who infer from their fits that there is a cooling break at about \( 10^{17} \) Hz. However, upon closer inspection, there is no real disagreement; Bloom et al. found a slightly shallower temporal decay, and therefore a bluer spectrum of the afterglow, which causes their extrapolated optical spectrum to fall above the X-ray point. However, their error of 0.35 on the temporal decay leads to an error of 0.24 on their predicted spectral slope, and this means that a 1 \( \sigma \) steeper slope in their Fig. 2 would be consistent with no detected cooling break.

Assuming that the spectral slope \( (\beta = -1.013 \pm 0.016) \) did not change during the time spanned by the four epochs \( t_1 - t_4 \) (as suggested by the lack of evidence for a break in the light curve during this time span), we have derived the \( V \)-band extinction \( A_V \) as a function of time: \( A_V = 1.50 \pm 0.11, 1.38 \pm 0.35, 0.84 \pm 0.29, \) and \( 0.90 \pm 0.25 \) for the epochs 1–4, respectively. Fitting a straight line through these, we obtain a slope of \(-0.16 \pm 0.06\), i.e., not consistent with zero at the 98.8% confidence level. Such a decrease of the optical extinction, \( A_V \), might be caused by ionization of the surrounding medium (Perna & Loeb 1997).

The \( V \)-band extinction \( A_V = 20.2^{+12.3}_{-7.3} \) derived from the host galaxy \( N_H \) fit to the MECS and LECS data (July 4–5 UT) is not in agreement with the \( A_V = 1.50 \pm 0.11 \) derived from the fit to the optical spectral flux distribution. This may be due to a different dust-to-gas ratio for the host galaxy of GRB 980703 or to a higher abundance than normal of the elements that cause the X-ray absorption.

With the constraint on \( \nu_c \) derived above, we can partially reconstruct the broadband flux distribution of the afterglow of GRB 980703; from the radio observations of Frail et al. (1998b) at 1.4, 4.86, and 8.46 GHz, we determine the self-absorption frequency, and its flux, \( F_{\nu} \), from the fit \( F_{\nu} = F_{\nu_0} (\nu/\nu_0)^{p} \left[ 1 - \exp \left( -\nu/\nu_0 \right) \right] \) to the low-energy part of the spectrum (e.g., Granot, Piran, & Sari 1998). We have

- **Fig. 3.** Left: Broadband spectrum of GRB 980703 at July 4.4 UT (i.e., at \( t_1 \) shown in Fig. 2). The open symbols show the \( R, I, \) and \( H \) OT fluxes (interpolated to July 4.4 and corrected for Galactic foreground absorption and the host-galaxy flux) and the MECS (2–10 keV) deabsorbed flux (the absorption correction is 7%). Filled symbols are obtained by invoking an interstellar extinction, \( A_V \), to force the slope of the data points to take on the two possible theoretical spectral slopes. The two slopes \( \beta \) and their 1 \( \sigma \) errors are indicated by the solid and dotted lines, respectively. Right: Broadband spectrum of GRB 980703 at July 8.4 UT (i.e., at \( t_4 \) shown in Fig. 2). The open symbols show the \( V, R, I, J, H, \) and \( K \) OT fluxes and the MECS (2–10 keV) deabsorbed 3 \( \sigma \) upper limit.

- **Fig. 4.** Radio to X-ray spectrum of GRB 980703 at July 4.4 UT (i.e., at \( t_1 \) shown in Fig. 2). Shown are data from Fig. 3 as well as 1.4, 4.86, and 8.46 GHz observations from Frail et al. (1998b). The fit \( F_{\nu} = F_{\nu_0} (\nu/\nu_0)^{p} \left[ 1 - \exp \left( -\nu/\nu_0 \right) \right] \) to the low-energy part of the spectrum with \( \nu_0 = 3.68 \pm 0.33 \) GHz and \( F_{\nu_0} = 789 \pm 42 \) \( \mu Jy \) is shown by the dotted line. The best fit to the optical/IR and X-ray data is also shown.
used averages of the 1.4 and 4.86 GHz observations to obtain best estimates of the radio flux densities, since those frequencies in particular suffer from large fluctuations due to interstellar scintillation (Frail et al. 1998b). We find $v_{\text{m}} = 3.68 \pm 0.33$ GHz and $F_{v_{\text{m}}} = 789 \pm 42 \mu$Jy. (The fit is shown in Fig. 4.) The intersection of the extrapolation from the low-frequency to the high-frequency fit gives a rough estimate of the peak frequency, $v_{\text{p}} \approx 4 \times 10^{12}$ Hz, and of the peak flux, $F_{v_{\text{p}}} \approx 8$ mJy (see Fig. 4). By assuming such a simple broken power law spectrum, the peak flux density will likely be overestimated (realistic spectra are rounder at the peak); it is clear from Figure 4 that $1 < F_{v_{\text{m}}} < 8$ mJy.

Following the analysis of Wijers & Galama (1999), we have determined the following intrinsic fireball properties:

1. the energy of the blast wave per unit solid angle, $\epsilon > 5 \times 10^{52}$ ergs per $4\pi$ sr;
2. the ambient density, $n > 1.1$ nucleons cm$^{-3}$;
3. the percentage of the nucleon energy density in electrons, $\epsilon_e > 0.13$; and
4. the percentage in the magnetic field, $\epsilon_B < 6 \times 10^{-5}$. The very low energy in the magnetic field, $\epsilon_B$, is a natural reflection of the high frequency of the cooling break, $v_{\text{c}}$.

We have compared this afterglow spectrum with that of GRB 970508. Scaling the latter in time according to $v_{\text{p}} \propto t^0$,

$v_{\text{m}} \propto t^{-3/2}$, and $v_{\text{c}} \propto t^{-1/2}$, the results of GRB 970508 (Galama et al. 1998a; see also Granot, Piran, & Sari 1998) would correspond to $v_{\text{p}} \approx 2.3$ GHz, $v_{\text{m}} = 2.8 \times 10^{12}$ Hz, $v_{\text{c}} = 4.8 \times 10^{14}$ Hz, and $F_{v_{\text{m}}} = 1.3$ mJy. In this calculation we have corrected for the effect of redshift (see Wijers & Galama 1999) such that the values represent GRB 970508, were it at the redshift of GRB 980703 and observed 1.2 days after the event. The greatest difference between the two bursts is in the location of the cooling frequency, $v_{\text{c}}$.

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