THE BROADBAND AFTERGLOW OF GRB 980703

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ABSTRACT

We present radio observations of the afterglow of the bright gamma-ray burst GRB 980703 made between 1 day and 1 yr after the burst. These data are combined with published late-time radio measurements and existing optical, near-infrared, and X-ray observations to create a comprehensive broadband data set for modeling the physical parameters of the outflow. While a wind-stratified medium cannot be ruled out statistically, it requires a high fraction of the shock energy in the electrons and so is not favored on theoretical grounds. Instead, the data are consistent with a fireball model in which the ejecta are collimated and expanding into a constant-density medium. The radio data cannot be fitted with an isotropic shock but instead require a jet break at \(z \approx 3.5\), not seen at optical wavelengths because of the presence of a bright host galaxy. The addition of the full radio data set constrains the self-absorption frequency, giving an estimate of the circumburst density of \(n \approx 30\) cm\(^{-3}\), a value that differs substantially from previous estimates. This result is consistent with the growing number of GRB afterglows, for which broadband modeling yields \(n \approx 0.1–100\) cm\(^{-3}\), with a typical value of \(\sim 10\) cm\(^{-3}\).

Subject heading: gamma rays: bursts

1. INTRODUCTION

Astronomers have monitored the afterglows of gamma-ray bursts (GRBs) with considerable enthusiasm across the electromagnetic spectrum. The primary motivation in using these measurements is to infer the fundamental parameters of the explosion: the total energy release, the geometry of the explosion, and the density distribution of ambient gas (Wijers & Galama 1999; Chevalier & Li 1999; Harrison et al. 2001; Panaitescu & Kumar 2001b).

The GRB of 1998 July 3.18 UT triggered the BATSE detectors on board the Compton Gamma Ray Observatory (Kippen et al. 1998), and its afterglow was detected by the All-Sky Monitor on the Rossi X-Ray Timing Explorer (Levine, Morgan, & Muno 1998). Follow-up observations of the X-ray afterglow were obtained with the narrow-field instruments (NFIs) on the BeppoSAX satellite (see Vreeswijk et al. 1999 for a summary of NFI observations). Radio observations of this field with the Very Large Array (VLA) began 1.2 days after the burst and identified a radio source within the BeppoSAX NFI error circle. Coincident with this we discovered a fading optical source and suggested that the source was the radio and optical afterglow of GRB 980703 (Frail et al. 1998). Zapatero Osorio et al. (1998) also reported the same fading optical source, while Djorgovski et al. (1998b) discovered the host galaxy and measured its redshift \(z = 0.966\). See Bloom et al. (1998) for a summary of the early radio, optical, and near-infrared (NIR) measurements.

Unfortunately, the host galaxy of GRB 980703 is very bright, \(R \sim 22.6\) mag (Djorgovski et al. 1998a), and so while this has led to a number of interesting results regarding the physical properties of GRB host galaxies (i.e., Holland et al. 2001; Sokolov et al. 2001; Berger, Kulkarni, & Frail 2001a; Chary, Becklin, & Armus 2002), it has also meant that the optical and NIR afterglow could be tracked for only a few days before it faded below the light from the host galaxy. For this reason, the temporal decay of the optical/NIR afterglow is poorly constrained, with \(\alpha\) ranging from \(-1.17 \pm 0.25\) to \(-1.61 \pm 0.12\) (Bloom et al. 1998; Castro-Tirado et al. 1999; Vreeswijk et al. 1999; Holland et al. 2001); here, flux at time \(t\) is \(F(t) \propto t^{-\alpha}\). Furthermore, the host galaxy appears to be undergoing vigorous star formation and consequently has a large amount of dust and gas (Djorgovski et al. 1998a; Sokolov et al. 2001). Not surprisingly, the optical/NIR spectrum of the afterglow [usually characterized by a power law, \(F(\nu) \propto \nu^{\beta}\)] appears to be significantly affected by extinction within the host galaxy. The low precision with which \(\alpha\) and \(\beta\) were measured preclude constraining the fundamental explosion parameters with any reasonable precision (Bloom et al. 1998; Vreeswijk et al. 1999).

Fortunately, the radio afterglow of GRB 980703 was quite bright, and as a result we were able to mount an ambitious monitoring program at the VLA. Here we present our final results on the centimeter radio light curves of GRB 980703 and then proceed to interpret the observations in the framework of afterglow models. The primary advantage of the radio measurements is the immunity of the radio emission from the two effects discussed above (bright host and extinction). As a result, by combining the X-ray, optical/NIR, and radio data together in a single broadband data set, we are able to infer the physical parameters for the afterglow from GRB 980703 with moderate precision.

2. OBSERVATIONS AND DATA REDUCTION

The details on the initial discovery of the radio afterglow from GRB 980703 are given in Bloom et al. (1998). The
late-time data ($\Delta t > 300$ days) for this burst have been published by Berger et al. (2001a). Below we describe the VLA monitoring program and observations at other radio facilities.

**VLA.**—VLA\(^6\) observations and data reduction were carried out following standard practice. To maximize sensitivity, the full VLA continuum bandwidth (100 MHz) was recorded in two 50 MHz bands, each with both hands of circular polarization. The flux density scale was tied to 3C 48 (J0137+331), and frequent observations (every 2–5 minutes) were made of the phase calibrators J2346+095 (at 4.86 and 8.46 GHz) and J2330+110 (at 1.43 GHz). A log of the observations, giving the measured fluxes at 1.43, 4.86, and 8.46 GHz, can be found in Table 1.

One VLA observation was made at 15 GHz on 1998 July 17.56 UT employing the same methodology. No source was detected at 15 GHz above a 3\(\sigma\) limit of 1.0 mJy.

**James Clerk Maxwell Telescope (JCMT).**—An observation was made on 1998 July 10.53 UT using the SCUBA array on JCMT\(^7\) at 220 GHz. The planet Uranus was used as a primary flux calibrator. The data were reduced in the standard method (i.e., corrected for atmospheric opacity, which is estimated by extrapolating from a skydip made at 225 GHz by a radiometer operated by the Caltech Sub-millimeter Observatory) and converted to millijanskys based on the primary flux calibrator. The pointing was checked immediately before and after the observations on a nearby blazar and was found to vary by less than $\sim 2''$.

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\(^6\) The NRAO is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. NRAO operates the VLA and the VLBA.

\(^7\) The JCMT 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.

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### TABLE 1

**Radio Flux Density History of GRB 980703\(^a\)**

| Date (UT) | $\Delta t$ (days) | $F_{8.46}$ (mJy) | $\sigma_{8.46}$ (mJy) | $F_{4.86}$ (mJy) | $\sigma_{4.86}$ (mJy) | $F_{1.43}$ (mJy) | $\sigma_{1.43}$ (mJy) |
|-----------|-------------------|-------------------|----------------------|-------------------|----------------------|-------------------|----------------------|
| 1998 Jul 04.40 | 1.22              | ...               | ...                  | 146               | 25                   | ...               | ...                  |
| 1998 Jul 07.35 | 4.17              | 890               | 21                   | 912               | 26                   | ...               | ...                  |
| 1998 Jul 08.49 | 5.31              | 965               | 55                   | 635               | 49                   | 120               | 37                   |
| 1998 Jul 15.41 | 12.23             | 1050              | 35                   | 467               | 43                   | ...               | ...                  |
| 1998 Jul 16.36 | 14.38             | 840               | 72                   | 1200              | 48                   | ...               | ...                  |
| 1998 Jul 20.33 | 17.15             | 882               | 51                   | 520               | 58                   | ...               | ...                  |
| 1998 Jul 21.34 | 18.16             | 720               | 56                   | 491               | 64                   | ...               | ...                  |
| 1998 Jul 24.44 | 21.26             | 564               | 75                   | 382               | 78                   | ...               | ...                  |
| 1998 Jul 25.46 | 22.28             | 709               | 52                   | ...               | ...                  | ...               | ...                  |
| 1998 Jul 26.33 | 23.15             | 504               | 20                   | 236               | 23                   | ...               | ...                  |
| 1998 Jul 27.42 | 24.24             | 584               | 57                   | 368               | 62                   | ...               | ...                  |
| 1998 Jul 28.41 | 25.23             | 502               | 67                   | 341               | 34                   | 25                | 39                   |
| 1998 Jul 31.45 | 28.27             | 593               | 42                   | ...               | ...                  | ...               | ...                  |
| 1998 Aug 02.30 | 30.12             | 580               | 60                   | ...               | ...                  | ...               | ...                  |
| 1998 Aug 02.36 | 30.18             | 510               | 43                   | 440               | 47                   | 104               | 37                   |
| 1998 Aug 03.44 | 31.26             | 465               | 34                   | ...               | ...                  | ...               | ...                  |
| 1998 Aug 05.41 | 33.23             | 480               | 40                   | 316               | 46                   | ...               | ...                  |
| 1998 Aug 11.29 | 39.11             | 412               | 22                   | 352               | 21                   | ...               | ...                  |
| 1998 Aug 21.28 | 49.10             | 386               | 49                   | 387               | 43                   | 148               | 37                   |
| 1998 Aug 24.22 | 50.04             | 277               | 35                   | 200               | 51                   | 125               | 42                   |
| 1998 Aug 28.22 | 56.04             | 214               | 35                   | 97                | 40                   | 68                | 37                   |
| 1998 Sep 04.35 | 63.17             | 205               | 40                   | ...               | ...                  | ...               | ...                  |
| 1998 Sep 06.49 | 65.31             | 281               | 37                   | 413               | 49                   | 126               | 52                   |
| 1998 Sep 14.57 | 73.39             | 260               | 26                   | ...               | ...                  | ...               | ...                  |
| 1998 Sep 26.22 | 85.04             | 131               | 33                   | 193               | 43                   | 18                | 46                   |
| 1998 Sep 30.32 | 89.14             | 167               | 26                   | ...               | ...                  | ...               | ...                  |
| 1998 Oct 06.32 | 95.14             | 143               | 33                   | 84                | 32                   | 36                | 42                   |
| 1998 Oct 18.31 | 107.13            | ...               | ...                  | 106               | 19                   | ...               | ...                  |
| 1998 Oct 30.24 | 119.06            | ...               | ...                  | ...               | 108                  | 52                | ...                  |
| 1998 Nov 10.08 | 129.90            | 80                | 18                   | 90                | 39                   | ...               | ...                  |
| 1998 Nov 15.03 | 134.85            | ...               | ...                  | ...               | 99                   | 25                | ...                  |
| 1998 Nov 23.97 | 143.79            | 110               | 20                   | 146               | 24                   | ...               | ...                  |
| 1998 Dec 27.04 | 176.86            | 103               | 16                   | 125               | 27                   | ...               | ...                  |
| 1999 Jan 29.89 | 210.71            | 70                | 17                   | 93                | 18                   | ...               | ...                  |

**Note.**—Each row lists the starting UT date of the observation, the time elapsed (in days) since the GRB, the flux density ($F$), and the rms noise ($\sigma$) at 8.46, 4.86, and 1.43 GHz.

\(^a\) On 1998 July 7 we searched for a polarized signal from the radio, obtaining 3\(\sigma\) limits on the linear and circular polarization at 4.86 and 8.46 GHz of $\sim 8\%$.

\(^b\) This is a VLBA measurement. All other measurements were made with the VLA. See § 2 for details.
Despite excellent photometric conditions, no 220 GHz source was visible at the position of GRB 980703 above a 2 σ limit of 5.2 mJy. Similar upper limits from JCMT are reported by Smith et al. (1999).

**Very Long Baseline Array (VLBA).**—Very long baseline interferometry observations were performed on 1998 August 2 at 8.42 GHz, using the 10-element VLBA for 5.6 hr. Both right- and left-circular polarizations were recorded using 2 bit sampling across a bandwidth of 32 MHz. The VLBA correlator produced 16 frequency channels across each 8 MHz channel during every 2 s integration. Amplitude calibration for each antenna was derived from measurements of the antenna gain and system temperatures. Global fringe fitting was performed on the strong nearby calibrator J2346+0930, and the resulting delays, rates, and phases were transferred to GRB 980703 before averaging in frequency or time. The time for a complete cycle on the phase calibrator and target source was 3 minutes.

The data for all sources were edited, averaged over 30 s intervals, and then imaged using DIFMAP (Shepherd 1997). We detected GRB 980703 with the VLBA at a level of 0.58 ± 0.06 mJy, consistent with VLA measurements at this same time. At the time of the VLBA observation, we place a limit on the angular size of the radio afterglow of GRB 980703 of less than 0.3 mas. We also derive a position of α(J2000) = 23:59:06:8661, δ(J2000) = 8°35′07′′0939, with an uncertainty of 0′′0007 in each coordinate.

### 3. BROADBAND DATA

Before undertaking any detailed model fits, it is worthwhile to review the general characteristics of the entire broadband data set for this afterglow. In addition to the radio data summarized in § 2 and Table 1, there exist a large amount of published data in the X-ray (Vreeswijk et al. 1999), optical/NIR (Bloom et al. 1998; Castro-Tirado et al. 1999; Vreeswijk et al. 1999; Holland et al. 2001; Sokolov et al. 2001), and radio (Berger et al. 2001a) bands. Light curves of these data are plotted in Figures 1–3. The X-ray measurements were converted to flux density with the spectrally weighted factor (using the observed photon index) that 1 Jy = 2.4 × 10^{-11} ergs cm^{-2} s^{-1}. We corrected the optical data for absorption in our Galaxy (Schlegel, Finkbeiner, & Davis 1998) before converting to flux densities using the factors in Bessell (1979) for the optical and Bessell & Brett (1988) for the NIR bands. An additional 1% error was added in quadrature to all the measured flux densities to account for any cross-calibration systematic uncertainties.

In Figure 1 we display the radio light curves at the frequencies of 1.43, 4.86, and 8.46 GHz. The 8.46 GHz light curve has a well-defined peak above 1 mJy between 5 and 12 days after the burst, followed by a power-law decay. As noted previously by Berger et al. (2001a), the flux density at centimeter wavelengths undergoes a flattening about 1 yr after the burst, which is attributed to synchrotron emission from an underlying host galaxy. After subtracting this component (F_{host} = 39 mJy) from the 8.46 GHz light curve, we derive a temporal decay index \( \alpha_R = -1.05 \pm 0.03 \) (where \( F_R \propto t^{-\alpha_R} \)) between 12 and 1000 days after the burst.

The 4.86 GHz light curve shows a similar rise and decay to that at 8.46 GHz. However, superposed on this long-term secular behavior, there are significant changes in the flux density from one point to the next. These erratic fluctuations are not confined to day to day variations, but there is
also evidence for short-term variability (50%) on timescales of a few hours. Narrowband, short-timescale flux variations are a hallmark of interstellar scattering (ISS; Goodman 1997; Frail et al. 1997). Although we make rough approximations for the ISS-induced fluctuations in § 4, a more detailed treatment of ISS for GRB 980703 is postponed for a later paper.

In contrast to the flux variations seen at 8.46 and 4.86 GHz, the 1.43 GHz light curve is notable for its relative constancy. Most of the emission at this frequency is dominated by the host galaxy, with $F_{\text{host}} \sim 68 \mu$Jy (Berger et al. 2001a). After allowing for some variation due to ISS, the peak flux of 0.15 mJy reached ~50 days after the burst is well below the peak at 8.46 GHz (~1 mJy) and at 4.86 GHz (~0.3 mJy). This apparent drop in the peak flux density with decreasing frequency (i.e., “peak flux cascade”) has been noted for other well-studied bursts (Frail, Waxman, & Kulkarni 2000; Yost et al. 2002) and poses an important constraint on possible models (see § 4).

The optical/NIR data shown in Figure 2 exhibit the familiar power-law decay of the afterglow. GRB 980703 occurred in a bright GRB host galaxy (Djorgovski et al. 1998a), and so the optical/NIR afterglow could only be followed for a few days before the host dominated the light curve. The $B$, $V$, $R$, $I$, $J$, $H$, and $K$-band light curves can be characterized by a power-law afterglow component (in time and frequency) plus a frequency-dependent host component. There is also a small excess in the flux density between the $R$ and $K$ bands near day 20. As noted by Holland et al. (2001), this could be due to a supernova component in the late-time light curve, but its significance is not strong enough to warrant its inclusion in the fitting.

A noise-weighted least-squares fit of the form $F(\nu, t) = F_0(\nu^3) + F_{\text{host}}(\nu)$ was carried out on the entire optical/NIR data set and yielded $\alpha_{\nu} = -1.67 \pm 0.08$ and $\beta_{\nu} = -2.67 \pm 0.08$ with $\chi^2/\text{dof} = 64.7/66$. The steep spectral slope $\beta_{\nu}$ relative to the X-ray ($\beta_X = -1.51 \pm 0.32$) has been noted before and attributed to dust extinction from the host galaxy (Vreeswijk et al. 1999). Our more accurate value of $\alpha_{\nu}$ is consistent with earlier derivations (Bloom et al. 1998; Castro-Tirado et al. 1999; Vreeswijk et al. 1999), but it is considerably steeper than the radio ($\alpha_R = -1.05$) and X-ray ($\alpha_X < -0.91$) light curves in Figures 1 and 3.

4. BROADBAND MODELING

We interpret the observations summarized in §§ 2 and 3 within the framework of the standard relativistic blast wave model (see Mészáros 2002 for a review). In this model an impulsive release of energy from the GRB event drives an ultrarelativistic outflow into the surrounding medium. Particle acceleration occurring within this forward-propagating shock produces the afterglow emission via synchrotron and/or the inverse Compton (IC) processes. Since the evolution of the blast wave is sensitive to the energy and geometry of the explosion, as well as the density structure of the circumburst medium, the modeling of the afterglow emission can be used, in principle, to extract valuable information on GRB progenitors and their environments, as well as details on the microphysics of the shock (e.g., Panaitescu & Kumar 2001a).

The particular approach we have taken to model broadband afterglow emission has been described in some detail in two recent papers (Harrison et al. 2001; Yost et al. 2002). In brief, we characterize the broadband spectrum by several break frequencies, including both synchrotron and IC components, one of which usually dominates depending on the circumstances. The microphysics of the shock, such as the electron energy index $p$, the fraction of shock energy in electrons $\epsilon_e$, and the fraction of shock energy in the magnetic field $\epsilon_B$, are taken to be invariant with time. The temporal evolution of the break frequencies is governed by the energy of the shock (which can be radiative), the geometry of the shock (which can be isotropic or jetlike), and the density structure of the surrounding medium (which can be constant or vary as the inverse square of the radius). In addition to the basic physics, the model also accounts for several complicating effects such as ISS at radio wavelengths, dust extinction in the optical/NIR bands, and a possible panchromatic contribution to the emission from a host galaxy.

The solution that best describes all the afterglow data for GRB 980703 is a collimated outflow expanding into a constant-density medium. Under the heading “ISM,” Table 2 summarizes the best-fit parameters that were derived using a least-squares approach. In addition to the shock parameters $p$, $\epsilon_e$, and $\epsilon_B$, the model solves for the jet opening angle $\theta_{\text{jett}}$, the circumburst density $n$, the isotropic-equivalent fireball energy at the time when the fireball evolution becomes largely adiabatic $E_{\text{iso}}(t_{\nu_{\text{iso}}})$, the rest-frame extinction $A(V)$, and the host flux density at several wavelengths. Perhaps the most striking feature of this model is that it requires a jet break at ~3.5 days after the burst. The expected steepening of the optical/NIR light curves at $t_{\nu_{\text{iso}}}$ is not obvious because of the brightness of the host galaxy.
Although the steep value of $\alpha_p$ relative to $\alpha_R$ and $\alpha_X$ is suggestive (see §3; Holland et al. 2001), the case for a jet in GRB 980703 is based primarily on the peak flux cascade observed at radio wavelengths (see §3 and Fig. 1). It is this same behavior that makes it impossible to model the afterglow of GRB 980703 as an adiabatic expansion of an isotropic shock. In general, since radio afterglows exhibit a different observational signature from that of either optical or X-ray afterglows, they have proven useful in revealing other cases of “hidden jets” (Berger et al. 2001b).

Now that the true geometry is known (i.e., $\theta_{\text{jet}} \sim 13^\circ$), the energy released in the GRB phase $E_{\text{iso}}(\gamma)$ and the afterglow phase $E_{\text{iso}}(\nu_{\text{iso}})$ can be determined and compared. For a two-sided jet, these isotropic values are reduced by the factor $\theta_{\text{jet}}^2/2$. Thus, the geometry-corrected gamma-ray energy $E(\gamma) = 1.7 \times 10^{51}$ ergs, and the kinetic energy in the blast wave $E_k = 3.2 \times 10^{51}$ ergs. The value of $E(\gamma)$ differs from the compilation of Frail et al. (2001) because here we have used the circumburst density derived from the broadband modeling rather than some assumed value. Note also that $E_k$ is only a lower limit on the true initial energy of the blast wave since $E_{\text{iso}}(\nu_{\text{iso}})$ is derived at a time $\nu_{\text{iso}} = 1.4$ days. After this time the blast wave evolution is predominantly adiabatic, and the energy dissipation is less than a factor of 2 up to 100 days after the burst. We estimate that prior to this time (when radiative losses decrease the blast wave energy), the energy drops by about a factor of 3. Another important quantity that can be estimated is $\eta_\gamma$, the efficiency of the fireball in converting the energy in the ejecta into gamma rays. A number of recent papers (Beloborodov 2000; Guetta, Spada, & Waxman 2001; Kobayashi & Sari 2001) have argued that internal shocks under certain conditions are very efficient at producing gamma rays (i.e., $\eta_\gamma \sim 0.2$). From $E_k$ and $E(\gamma)$ we derive $\eta_\gamma \sim E(\gamma)/[E_k + E(\gamma)]$ between 15% and 35%, comparable to previous estimates of this and other well-studied events (e.g., Panaitescu & Kumar 2001a).

While this interstellar medium (ISM) model provides satisfactory agreement with the broadband data set (§3), it is not a unique solution. An explosion into a wind-blown circumburst medium (Chevalier & Li 1999) also yields an equally good fit (see Table 2, Figs. 4 and 5). The ejecta are also collimated in this model with $\theta_{\text{jet}} \sim 18^\circ$. The density is parameterized by $A_\text{w}$, which characterizes the wind density, with $\rho(R) = 5 \times 10^{12} A_\text{w} R_\text{cm}^{-2}$ g cm$^{-3}$ and with $R_\text{cm}$ the wind radius in centimeters. The most troubling feature of this model is that it requires about 70% of the shock energy going into the electrons. Likewise, the geometry-corrected gamma-ray energy of $E(\gamma) = 3 \times 10^{51}$ ergs is a factor of 10 larger than the kinetic energy in the blast wave, $E_k$. This suggests an unusually high $\eta_\gamma \sim 90\%$, which, as noted above, is contrary to theoretical expectations, since little of the initial shock energy in the fireball is left to power the afterglow. Thus, while a wind-blown solution formally fits the data and cannot be ruled out, we prefer the ISM model since it does not require such extreme physical conditions.

Regardless of which afterglow model is preferred, the host magnitudes are comparable to those derived by Sokolov et al. (2001) and Berger et al. (2001a) at optical and radio wavelengths, respectively. Likewise, the steep spectral slope $\beta_\nu$ (see §3) requires modest rest-frame $V$-band extinction $A(V) \sim 1$, in accordance with earlier estimates (Bloom et al. 1998; Castro-Tirado et al. 1999; Vreeswijk et al. 1999).

**TABLE 2**

| Parameter | ISM | Wind |
|-----------|-----|------|
| $\chi^2$ for 162 data points | 170.4 | 171.4 |
| $t_{\text{jet}}$ (days) | 3.43 | 5.11 |
| $t_{\text{nonet}}$ (days) | 49.6 | 26.4 |
| $t_{\nu_{\text{iso}}}$(days) | 1.41 | 5.17 |
| $E_{\text{iso}}(\nu_{\text{iso}})$ (10$^{52}$ ergs)$^*$ | 11.8 | 0.66 |
| $n/A^*$ | 27.6 | 1.42 |
| $p$ | 2.54 | 2.11 |
| $e_\gamma$(fraction of E) | 0.27 | 0.69 |
| $E(\gamma)$(10$^{52}$ ergs)$^*$ | $1.8 \times 10^{-3}$ | $2.8 \times 10^{-2}$ |
| $\theta_{\text{jet}}$(rad) | 0.234 | 0.310 |
| Host $A(V)$ | 1.15 | 1.33 |
| Host at $B$(Jy) | 2.93 | 2.94 |
| Host at $V$(Jy) | 3.07 | 3.07 |
| Host at $R$(Jy) | 3.61 | 3.64 |
| Host at $I$(Jy) | 4.84 | 4.81 |
| Host at $J$(Jy) | 8.77 | 8.67 |
| Host at $H$(Jy) | 9.15 | 9.00 |
| Host at X(Jy) | 10.1 | 10.0 |
| Host at 1.4 GHz (Jy) | 53 | 58 |
| $E_{\text{iso}}(\nu_{\text{iso}})$ (10$^{52}$ ergs)$^*$ | 6.01 | 6.01 |
| $E(\gamma)$(10$^{50}$ ergs) | 16.5 | 28.9 |

$^a$ Isotropic-equivalent blast wave energy (not corrected for collimation).

$^b$ Isotropic-equivalent energy emitted in gamma rays, taken from Bloom, Frail, & Sari 2001.
wave model. Although our specific methodology does differ somewhat, in at least one case when fits were made using the same data for GRB 000926, the results were in good agreement (Harrison et al. 2001; Panaitescu & Kumar 2002). The most serious limitation of the Panaitescu & Kumar (2001b) analysis of this burst is that it relies on data taken over a limited frequency range and a limited temporal range. The optical data were restricted effectively to 1–5 days because of host-galaxy contamination, and the early radio data (especially at 5 GHz) were of limited use because of ISS. With the addition of a complete set of centimeter radio light curves for GRB 980703, much of this difficulty can be resolved. The most significant area of improvement is in the determination of the synchrotron self-absorption frequency $\nu_s$. This important break frequency is largely unconstrained in the Panaitescu & Kumar (2001b) model and is likely the origin of our discrepant density estimates.

An alternate way to view the difficulties in the afterglow model of Panaitescu & Kumar (2001b) is to use the "C-parameter," introduced by Sari & Esin (2001), which places a constraint on the combination of synchrotron break frequencies and the peak flux density. From Figure 1 of Panaitescu & Kumar (2001b), we find the following values for the synchrotron parameters: $\nu_m(t = 1.2\,\text{days}) \approx 7 \times 10^{15}\,\text{Hz}$, $\nu_c(t = 1.2\,\text{days}) \approx 3 \times 10^{18}\,\text{Hz}$, and $F_m(t = 1.2\,\text{days}) \approx 2\,\text{mJy}$. In order not to violate the theoretical limit of $C < 0.25$, it requires a self-absorption break $\nu_a(t = 1.2\,\text{days}) \approx 1\,\text{GHz}$. It is this upper limit on $\nu_a$ that leads to the low value of $n^{PK} = 7.8 \times 10^{-4}\,\text{cm}^{-3}$. A broadband spectrum of the GRB 980703 afterglow on day 4.5 (see Fig. 6) shows this to be a significant underestimate of $\nu_a$. If we use a more appropriate value of $\nu_a = 14\,\text{GHz}$ at this time, then the additional synchrotron parameters of Panaitescu & Kumar (2001b) give an unphysical solution with $C > 1$ unless the cooling frequency $\nu_c$ is significantly reduced.

5. COMPARISON WITH OTHER MODELS

There have been several attempts to derive the fireball parameters for GRB 980703 by constructing single-epoch spectra from the early afterglow data (Bloom et al. 1998; Castro-Tirado et al. 1999; Vreeswijk et al. 1999). The estimates for these parameters have varied widely among these papers because of slightly different data sets and a high degree of correlation between the parameters. For example, there is a degeneracy between the electron energy index $p$, the extinction $A(V)$, and the host brightness that makes it difficult to extract the underlying spectral slope of the afterglow and therefore the location of two important break frequencies $\nu_m$ and $\nu_c$. This leads to large uncertainties in the parameters $E_{\text{iso}}$, $n$, $p$, $\epsilon_e$, and $\epsilon_B$.

The limitations of this spectral snapshot method can be overcome by globally fitting all the afterglow data using a hydrodynamic model of the blast wave. This is the approach that we have adopted in this paper, but the first application of this method to GRB 980703 was made by Panaitescu & Kumar (2001b). Their basic model is similar to our own. They find that a collimated outflow in a constant-density medium provides a good description of the data, and they also find acceptable fits to a stellar-wind model. However, the differences between our models show up most clearly in the derived fireball parameters with $E_{\text{iso}}^{PK} = 2.9 \times 10^{54}\,\text{ergs}$, $n^{PK} = 7.8 \times 10^{-4}\,\text{cm}^{-3}$, $p^{PK} = 3.08$, $\epsilon_e^{PK} = 0.075$, $\epsilon_B^{PK} = 4.6 \times 10^{-4}$, and $\theta_{\text{jet}}^{PK} > 0.047\,\text{rad}$. Radiative losses are small in their model, and IC emission is negligible, while $\epsilon_e = 0.27$ in our model and IC is important for flattening the X-ray light curve around day 1. The most severe difference, however, is that the density derived by Panaitescu & Kumar (2001b) is $3.5 \times 10^4$ times smaller than our estimate in Table 2.

The origin of this discrepancy is not likely the result of differences in the implementation of the relativistic blast...
and an IC component is added. This has the effect of increasing the density of the circumburst medium.

6. DISCUSSION AND CONCLUSIONS

A high-quality panchromatic data set, resulting from a multiwavelength observing campaign of GRB 980703, has enabled us to apply the relativistic blast wave model in order to determine the geometry and energetics of the explosion and the density of the medium immediately surrounding the progenitor, as well as the properties of the interstellar medium within the host galaxy. All of the afterglow data for GRB 980703 are consistent with a model in which the ejecta are collimated and expanding into a constant-density medium. Although it is not a unique solution, it yields reasonable estimates for the physical parameters that are in agreement with other well-studied events.

Perhaps the most interesting result from this work is what has been learned about the properties of the GRB environment. A proper understanding of the density structure of the circumburst medium remains an important goal, since it is invariably tied to the GRB progenitor question. To the degree that the underlying assumptions behind the fireball model of GRB afterglows are correct, broadband modeling gives us the only direct determination of this density. Optical extinction, host-galaxy properties, X-ray lines, late-time optical bumps, or the attenuation of low-energy X-ray photons are all indirect or line-of-sight measures of the GRB environment. In a recent compilation of 10 well-studied afterglows, Panaitescu & Kumar (2002) showed that broadband modeling yielded densities in the range of 0.1–100 cm$^{-3}$. Their result is in good accord with our own extensive modeling of afterglows (e.g., Frail et al. 2000; Berger et al. 2000, 2001b; Harrison et al. 2001; Yost et al. 2002).

For two events, GRB 990123 and GRB 980703, Panaitescu & Kumar (2001b) showed that broadband modeling yielded densities in the range of 0.1–100 cm$^{-3}$. Their result is in good accord with our own extensive modeling of afterglows (e.g., Frail et al. 2000; Berger et al. 2000, 2001b; Harrison et al. 2001; Yost et al. 2002).

For two events, GRB 990123 and GRB 980703, Panaitescu & Kumar (2001b) showed that the derived densities (i.e., $n \approx 10^{-3}$ cm$^{-3}$) are much lower than the values given above. These low estimates prompted the suggestion that some GRBs are massive stars that explode in the preexisting cavities of superbubbles created by a previous generation of supernovae (Scalo & Wheeler 2001). The circumburst density for GRB 980703 derived from our model, $n \approx 28$ cm$^{-3}$, is much higher because the synchrotron self-absorption frequency $\nu_{\text{abs}}$ was not well constrained by the early observations. On the timescale of interest, $\nu_{\text{abs}}$ lies within the radio band and is a sensitive indicator of the ambient density; i.e., $\nu_{\text{abs}} \propto n^{3/2} C_0^{-1} B_0 E_{50}$. A similar problem likely explains results from GRB 990123, but it is further complicated by the evidence that the early radio emission was dominated by a reverse shock component (Kulkarni et al. 1999). Likewise, it can be shown that the claims of high circumburst densities (i.e., $n \approx 10^{4}$ cm$^{-3}$) based solely on X-ray and optical observations (Piro et al. 2001; in’t Zand et al. 2001) cannot be supported once radio data are included (Harrison et al. 2001). Thus, radio observations, which help to constrain the low-energy part of the synchrotron spectrum, are essential for deriving accurate physical parameters of the blast wave.

In summary, for all well-studied GRB afterglows to date, there is little evidence for an extreme of either high, $n \approx 10^{4}$ cm$^{-3}$, or low, $n \approx 10^{-3}$ cm$^{-3}$, circumburst densities. Instead, GRB 980703 is the latest of a growing number of events whose density lies within a narrow range of 0.1–100 cm$^{-3}$ with a canonical value of the order of $n \approx 10$ cm$^{-3}$. Such densities are found in diffuse interstellar clouds of our Galaxy, commonly associated with star-forming regions. A density of the order of 5–30 cm$^{-3}$ is also characteristic of the interclump medium of molecular clouds, as inferred from observations of supernova remnants in our Galaxy (e.g., Chevalier 1999 and references therein).

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