THE ANGULAR SIZE AND PROPER MOTION OF THE AFTERGLOW OF GRB 030329

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Received 2004 March 29; accepted 2004 May 14; published 2004 May 19

ABSTRACT

The bright, nearby (z = 0.1685) gamma-ray burst (GRB) of 2003 March 29 has presented us with the first opportunity to directly image the expansion of a GRB. This burst reached flux density levels at centimeter wavelengths more than 50 times brighter than any previously studied event. Here we present the results of a VLBI campaign using the Very Long Baseline Array, Very Large Array, Green Bank, Effelsberg, Arecibo, and Westerbork telescopes that resolves the radio afterglow of GRB 030329 and constrains its rate of expansion. The size of the afterglow is found to be ~0.07 mas (0.2 pc) 25 days after the burst and 0.17 mas (0.5 pc) 83 days after the burst, indicating an average velocity of 3c ~ 5c. This expansion is consistent with expectations of the standard fireball model. We measure the projected proper motion of GRB 030329 in the sky to less than 0.3 mas in the 80 days following the burst. In observations taken 52 days after the burst, we detect an additional compact component at a distance from the main component of 0.28 ± 0.05 mas (0.80 pc). The presence of this component is not expected from the standard model.

Subject heading: gamma rays: bursts

Online material: color figure

1. INTRODUCTION

The fireball model has provided a remarkably successful framework in which to interpret observations of gamma-ray bursts (GRBs) and their afterglows (see Mészáros 2002 for a recent review). Among the earliest observational tests of this model was the superluminal motion inferred for GRB 970508 (Frail et al. 1997). Large fluctuations in the radio flux density on timescales of several hours were attributed to diffractive scattering of the radio waves as they propagated through the turbulent ionized gas of our Galaxy (Goodman 1997). The observed “quenching” of this scintillation pattern at t ~ 2 weeks led to a determination of a size of 3 μas, implying a mean apparent motion of 4c, which was consistent with estimates from an expanding shock (Frail et al. 1997; Waxman et al. 1998). The motion appears superluminal owing to a geometric effect first described by Rees (1966). This size measurement was independently supported by constraints derived from late-time calorimetry of GRB 970508 (Frail et al. 2000).

While interstellar scintillation can be a powerful tool to test predictions of GRB afterglow models, such observations are rare. Most GRBs are expected to remain in the strong diffractive regime for only a few days (Goodman 1997; Walker 1998), and hence there are practical difficulties obtaining well-sampled light curves. Nearby GRBs (z < 0.2), although equally rare, enable us to image the afterglow directly, measuring the expansion or proper motion of the emitting region (Waxman 1997; Sari 1999; Granot et al. 1999; Granot & Loeb 2003). Previous applications of the technique of Very Long Baseline Interferometry (VLBI) did not yield constraining limits on the angular size for distant GRBs (z ~ 1; Taylor et al. 1997, 1998). This situation changed with the detection of GRB 030329 by the HETE-2 spacecraft (Vanderspek et al. 2003). At z = 0.1685 (Greiner et al. 2003a), GRB 030329 is one of the nearest GRBs detected to date and also the brightest. At centimeter wavelengths, it reached peak flux densities of 50 mJy, motivating us to undertake a comprehensive multiepoch VLBI program.

In this Letter, we describe the results of the first five epochs covering the time between 3 and 83 days after the burst.

2. OBSERVATIONS AND RESULTS

The five epochs are summarized in Table 1. All observations employed the Very Long Baseline Array (VLBA) of the NRAO.3 Other telescopes used in one or more epochs include the Effelsberg 100 m telescope,4 the phased Very Large Array (VLA), the Green Bank Telescope (GBT), the Arecibo telescope, and the Westerbork Synthesis Radio Telescope (WSRT) tied array. The observing runs were typically 5 hr long, with 256 Mbps recording in full polarization with two-bit sampling. The nearby (15") source J1051+2119 was used for phase referencing with a 2:1 minute cycle on-source:calibrator below 15 GHz and a 1.3:1 minute cycle on-source:calibrator at 15 GHz and above. The weak calibrator J1048+2115 was observed hourly to check on the quality of the phase referencing. Self-calibration was used to further refine the calibration and remove atmospheric phase errors when the signal-to-noise ratio was sufficient.

From our 8.4 GHz observations on April 6, we derive a 3σ limit on the linear polarization of 0.16 mJy beam−1, which corresponds to a limit on the fractional polarization of less than 1.0%. In a contemporaneous optical observation, Greiner et al. (2003b) measure a polarization of 2.2% ± 0.3%. The decrease in polarization at lower frequencies could be explained as the result of the source being optically thick at 8.4 GHz at these early times.

For each observation listed in Table 1, we fit a circular Gaussian to the measured visibilities to derive angular diameters (or limits). For components that are slightly resolved, a Gaussian, uniform disk, and ring all have a similar quadratic dependence on baseline length for the short baselines (Pearson 1999). There are some differences in scaling in that a Gaussian with size 1 mas FWHM is equivalent to a uniform disk with...
TABLE 1

| Date          | \( \Delta \tau \) (days) | Frequency (GHz) | Integration Time (minutes) | Bandwidth (MHz) | Polarization | Instrument       |
|---------------|--------------------------|-----------------|-----------------------------|-----------------|--------------|-----------------|
| 2003 Apr 01   | 2.73                     | 4.617           | 108                         | 16              | 2            | VLBA            |
| 2003 Apr 06   | 2.73                     | 4.995           | 108                         | 16              | 2            | VLBA            |
| 2003 Apr 22   | 7.71                     | 4.617           | 100                         | 16              | 2            | VLBA            |
| 2003 May 19   | 51.3                     | 15.354          | 96                           | 32              | 2            | VLBA + EB       |
| 2003 Jun 20   | 83.3                     | 8.409           | 138                         | 32              | 2            | VLBA + EB + Y27 + WB + AR |

Notes.—EB = 100 m Effelsberg telescope. Y27 = phased VLA. GBT = 105 m GBT. WB = phased Westerbork array. AR = 305 m Arecibo telescope.

TABLE 2

| Epoch         | Frequency (GHz) | S (mJy) | rms (mJy) | Beam (mas) | R.A._offset (mas) | Decl._offset (mas) | Size (mas) | Self-Calibration? |
|---------------|-----------------|---------|-----------|------------|-------------------|-------------------|------------|-------------------|
| 2003 Apr 01   | 4.8             | 3.0     | 0.10      | 2.17 x 0.99 | -0.66 ± 0.56     | 0.12 ± 0.56       | <0.59      | No                |
| 2003 Apr 06   | 8.6             | 8.3     | 0.16      | 1.24 x 0.57 | 0.0 ± 0.22       | 0.0 ± 0.30        | <0.19      | No                |
| 2003 Apr 22   | 15.4            | 26.8    | 0.39      | 1.16 x 0.39 | 0.24 ± 0.2       | -0.06 ± 0.2       | <0.12      | Yes               |
| 2003 May 19   | 22.2            | 36.0    | 0.80      | 1.00 x 0.47 | 0.29 ± 0.2       | -0.26 ± 0.2       | <0.18      | Yes               |
| 2003 Jun 20   | 16.2            | 14.1    | 0.12      | 0.74 x 0.26 | 0.25 ± 0.2       | -0.35 ± 0.2       | 0.065 ± 0.022 | Yes               |
| 2003 Apr 01   | 22.2            | 11.1    | 0.22      | 0.52 x 0.18 | 0.26 ± 0.2       | -0.25 ± 0.2       | 0.077 ± 0.036 | Yes               |
| 2003 May 19   | 15.4            | 4.0     | 0.08      | 0.67 x 0.24 | 0.11 ± 0.2       | -0.40 ± 0.2       | <0.10      | Yes               |
| 2003 Jun 20   | 22.2            | 4.0     | 0.14      | 0.57 x 0.19 | 0.31 ± 0.2       | -0.03 ± 0.2       | <0.14      | Yes               |
| 2003 Jun 20   | 8.4             | 3.0     | 0.03      | 0.97 x 0.53 | 0.03 ± 0.2       | -0.24 ± 0.2       | 0.172 ± 0.043 | Yes               |

Notes.—Col. (1): Epoch of observation. Col. (2): Observing frequency formed from the average of all intermediate frequencies. Col. (3): Flux density derived from a Gaussian model fit. Col. (4): Naturally weighted image rms. Col. (5): Uniform weighted beam size. Col. (6): Offset in right ascension and declination from the April 1 8.6 GHz position at R.A. = 10°44'40"959550, decl. = 21°31'17"347881 (J2000.0). Col. (7): 2 \( r \) size limit or actual FWHM of a circular Gaussian fit to the main component. Col. (8): Indication if phase self-calibration was applied.
the bulk Lorentz factor of the fireball. A more precise description of the dynamics is given by the Blandford & McKee (1976) solution. The apparent radius $R_\text{a}$ of the relativistic blast wave as seen by a distant observer viewing a GRB close to face-on is approximately $R_\text{a} \sim R_\gamma$. A calculation by Galama et al. (2003) for constant density gives

$$R_\text{a}(\text{ISM}) = 3.9 \times 10^{16} \left( \frac{E_{52}}{n_0} \right)^{1/8} \left( \frac{t_j}{1 + z} \right)^{5/8} \text{ cm},$$

where $E_{52}$ is the isotropic energy normalized to $10^{52}$ ergs and $t_j$ is the time in days in the observer’s frame. The coefficient in equation (1) is the same as in Granot et al. (1999), but it is 6% larger than the estimate by Waxman et al. (1998). A circumburst medium shaped by mass loss from a massive progenitor star is expected to have a density that falls off with radius as $\rho = A R^{-2}$, where $A = M_*/4\pi V_*$ is a constant, typically normalized to $A = 5 \times 10^{13} A_*$ g cm$^{-1}$ (i.e., values for the mass-loss rate $M_*$ and wind velocity $V_*$ of a typical W-R star). Chevalier & Li (2000) give estimates for the line-of-sight radius $R$ and Lorentz factor in a wind-blown medium, but for consistency we use Galama et al. (2003):

$$R_\text{a}(\text{wind}) = 2.4 \times 10^{16} \left( \frac{E_{52}}{A_*} \right)^{1/4} \left( \frac{t_j}{1 + z} \right)^{3/4} \text{ cm}.$$  

Assuming a $\Lambda$ cosmology with $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.27$, and $\Omega_\Lambda = 0.73$, the angular diameter distance of GRB 030329 at $z = 0.1685$ is $d_\text{a} = 589$ Mpc. Thus, the angular diameters corresponding to the radii in equations (1) and (2) are $8.9(E_{52}/n_0)^{1/8} t_j/(1 + z)^{5/8}$ and $5.5(E_{52}/A_*)^{1/4} [t_j/(1 + z)]^{3/4}$ μas for the interstellar medium (ISM) and wind models, respectively.

The measured sizes 24 and 83 days after the burst give average apparent perpendicular expansion velocities of 5$c$ and 3$c$, respectively. Based on energetics and breaks in the light curves, typical GRBs appear to be collimated into a cone of angle $\theta \sim 0.1$ radians (Berger et al. 2003a), which we must be within to see the gamma rays. Since the apparent expansion, $\beta_a$ is given by $\beta_a = \beta \sin \theta(1 - \beta \cos \theta)$, then to get an apparent superluminal expansion of 5$c$ requires Lorentz factors of $\sim 1$ and values of $\beta$ close to unity. These values for $\beta$ are much larger than $\sim 0.1$, found in simulations by Cannizzo et al. (2004).

In Figure 2, we show the evolution of the expected angular size of GRB 030329 for the ISM and wind models for some representative values of $E_{52}/n_0$ (or $E_{52}/A_*$) and jet break times. There is good agreement from the predictions of the isotropic models with our measurements (Table 2). The size estimates in the ISM model are more robust than the wind model in the sense that they are relatively insensitive to the ratio of $E_{52}/n_0$, yielding values of 60 and 130 μas for $E_{52}/n_0 \sim 1$ at $\Delta t = 25$ days and $\Delta t = 83$ days, respectively.

The introduction of a jet raises the energy requirements substantially. Part of this increase may be due to our limited understanding of how to describe the lateral expansion of a GRB jet. However, for $t_j \sim 10$ days, an acceptable fit is obtained for $E_{52}/n_0 = 10$ (or $E_{52}/A_* \approx 7$) and a best fit for $E_{52}/n_0 = 30$. For $t_j \sim 0.5$ days, acceptable fits for either the ISM or wind model require $E_{52}/n_0 \gtrsim 100$.

There exists a wide range of energy estimates for GRB 030329 in the literature. Vanderspek et al. (2004) estimate an isotropic gamma-ray energy release $E_{\gamma, \text{iso}} = (1.80 \pm 0.07) \times 10^{52}$ ergs. Allowing for a reasonable radiative efficiency $\eta = 0.2$ (Pannatiscu & Kumar 2001), $E_{52} = E_{\gamma, \text{iso}}/\eta = 9$. A jet break seen at ~0.5 days in the X-ray and optical light curves (Price et al. 2003; Tiengo et al. 2003) reduces this energy by a factor of about 400. However, Granot et al. (2003), in explaining the unusual fluctuations in the optical light curve, increase the energy by a
factor of 10 by having the afterglow shock "refreshed" by slower moving ejecta shells.

3.2. Proper-Motion Limits

In the relativistic fireball model, a shift in the flux centroid is expected owing to the spreading of the jet ejecta (Sari 1999). For a jet viewed away from the main axis, the shift can be substantial (Granot & Loeb 2003). However, since gamma rays were detected from GRB 030329 it is likely that we are viewing the jet largely on-axis. The predicted displacement in this case is expected to be small (0.02 mas) and well below our measured limit over 80 days of 0.10 ± 0.14 mas (see § 2).

Proper motion in the cannonball model originates from the superluminal motion of plasmoids ejected during a supernova explosion with $\Gamma_2 \sim 1000$ (Dado et al. 2003). Dar & De Rújula (2003) predicted a displacement of 2 mas over the 80 days of our VLBI experiment assuming plasmoids propagating in a constant density medium. This estimate was revised downward to 0.55 mas by incorporating plasmoid interactions with density inhomogeneities at a distance of ∼100 pc within a wind-blown medium (Dado et al. 2004). Neither variant of this model is consistent with our proper-motion limits. A more general problem for the cannonball model is the absence of rapid fluctuations in the radio light curves of GRB 030329 (Berger et al. 2003b). Strong diffractive scintillation is expected between 1 and 5 GHz with a modulation index of order unity and a timescale of a few hours, because the size of the plasmoids (∼0.01 μas) always remains below the Fresnel scale (∼5 μas) of the turbulent ionized medium (Taylor & Cordes 1993; Walker 1998). Strong and persistent intensity variations in centimeter radio light curves for all GRBs are expected in the cannonball model. Strong intensity variations are not seen for GRB 030329, nor are they expected for the relativistic blast wave model. Our angular size measurements in § 3.1 and Figure 2 suggest that the expanding fireball is too large after the first few days to exhibit diffractive scintillation. There are moderate variations seen in the radio light curves of GRB 030329 (25% at 4.9 GHz, 15% at 8.5 GHz, and 8% at 15 GHz) that decrease by a factor of 3 from ∼3 to 40 days after the burst. Berger et al. (2003b) have attributed this behavior to an expanding fireball undergoing weak interstellar scintillation and derive a size for GRB 030329 of 20 μas at Δt = 15 days. However, the details of the change in modulation index depend on knowing the distance of the screen, the transition frequency between weak and strong interstellar scintillation, and the geometry of the scattering region.

4. CONCLUSIONS

We present the first images directly resolving a GRB afterglow 25 and 83 days after the explosion. The observed expansion velocity of 3c–5c can be fitted with standard fireball models. We estimate the energetics of the burst to have an isotropic equivalent energy, $E_{\text{iso}}$, divided by the ambient density of $E_{\text{iso}}/n_0 \sim 30$ assuming a jet break at 10 days, and expansion into a constant density circumburst medium. Our measurements also place stringent upper limits on the proper motion of the fireball to less than 0.3 mas over the 80 days covered, or less than 1.4 mas yr⁻¹. These limits are also consistent with the standard fireball model. Much less easy to explain is the single observation 52 days after the burst of an additional radio component 0.28 mas northeast of the main afterglow. This component requires a high average velocity of 19c and cannot be readily explained by any of the standard models. Since it is only seen at a single frequency, it is remotely possible that this image is an artifact of the calibration. Other nearby GRBs would benefit from more frequent time sampling to search for the presence of similar high-velocity components.

We are particularly grateful to the schedulers of the VLBA, GBT, Effelsberg, WSRT, and Arecibo telescopes for their heroic efforts on behalf of this program. D. A. F. thanks J. Granot for useful discussions on the expansion of relativistic jets, and we thank W. Brisken and S. Chatterjee for checking the results of the proper-motion fits.

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