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LATE TIME OBSERVATIONS OF THE AFTERGLOW AND ENVIRONMENT OF GRB 030329

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ABSTRACT

We present Very Long Baseline Interferometry (VLBI) observations 217 days after the γ-ray burst of 2003 March 29. These observations provide further measurements of the size and position of GRB 030329 that are used to constrain the expansion rate and proper motion of this nearby GRB. The expansion rate appears to be slowing down with time, favoring expansion into a constant density interstellar medium, rather than a circumstellar wind with an r^{-2} density profile. We also present late time Arecibo observations of the redshifted H I and OH absorption spectra towards GRB 030329. No absorption (or emission) is seen allowing us to place limits on the atomic neutral hydrogen of $N_H < 8.5 \times 10^{20}$ cm^{-2}, and molecular hydrogen of $N_{H_2} < 1.4 \times 10^{22}$ cm^{-2}. Finally, we present VLA limits on the radio polarization from the afterglow of <2% at late times.

Subject headings: gamma-rays: bursts

1. INTRODUCTION

Our understanding of the origin of gamma-ray bursts (GRBs) has continued to advance rapidly in the years since the first X-ray (Costa et al. 1997), optical (van Paradijs et al. 1997) and radio (Frail *et al.* 1997) afterglows were discovered. In particular the nearby afterglow from GRB 030329 has solidified the GRB-supernova connection (Hjorth et al. 2003a; Matheson et al. 2003), and provided the first GRB with a well determined expansion rate (Taylor *et al.* 2004). This event has presented a unique opportunity to test afterglow models (Oren, Nakar, & Piran 2004; Granot, Ramirez-Ruiz & Loeb 2005), and to explore the environment around a GRB.

Afterglow models invoke gas-rich environments around at least some of the GRBs. Several basic properties of this circumburst medium are presently unknown, and need to be addressed in order to better understand the afterglow and its evolution. For example, in the simplest emission models, the density of the ambient medium is related to the afterglow flux density (Waxman 1997). Especially, if GRBs exist in both gas-poor and gas-rich environments, that could explain why afterglow is absent in some GRBs. Direct observations of the circumburst medium associated with GRBs would thus provide an important test of the fireball model.

Another issue is the density profile of the medium into which the GRB ejecta expands. Current models postulate a medium in which density is governed by the mass-loss of the progenitor star ($\rho \propto r^{-2}$). At present however, some observations instead point to a uniform density in order to explain the evolution of the afterglow lightcurve (Berger *et al.* 2003). In a few cases, strong damped Lyα absorption has been found indicating H I column densities as high as 5×10^{21} cm^{-2} (Hjorth et al. 2003b). During the expansion of the GRB ejecta, the circumburst medium is likely to go through different stages of ionization. Perna & Loeb (1998) suggest that as a consequence (optical) absorption lines will vary in their EW with time. The rate of this variation can constrain the size of the absorbing region. Similarly, in the radio the fraction of molecular and atomic gas should be governed by the effective ionization, and might therefore vary in a similar way.

One way to investigate the circumburst medium is via atomic or molecular absorption studies in the radio. Another way is to measure the deceleration of the expanding fireball. In this paper we present both late time Very Long Baseline Interferometry (VLBI) observations of the afterglow of GRB 030329 and similar epoch H I and OH absorption observations taken with the Arecibo telescope.

Assuming a Lambda cosmology with $H_0 = 71$ km/s/Mpc, $\Omega_M = 0.27$ and $\Omega_\Lambda = 0.73$, the angular-diameter distance of GRB 030329 at $z = 0.1685$ is $d_A = 589$ Mpc, and 1 milliarcsec corresponds to 2.85 pc.

2. OBSERVATIONS AND RESULTS

2.1. *Late Time VLBI Observations*

The VLBI observations were taken at 8.4 GHz on 2003 November 1, 217 days after the burst, with a global array including the Very Long Baseline Array (VLBA) of the NRAO[5]. Other telescopes used were the Effelsberg 100-m telescope[6], the phased VLA, the Green Bank Telescope (GBT), the 305 m Arecibo telescope[7], the Westerbork

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[6] The 100-m telescope at Effelsberg is operated by the Max-Planck-Institut für Radioastronomie in Bonn.
[7] The Arecibo Observatory is part of the National Astronomy and Ionosphere Center, which is operated by Cornell University under a cooperative agreement with the National Science Foundation.

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TABLE 1
Observational Summary

Date	Δt (days)	Frequency (GHz)	Integ. Time (min)	BW (MHz)	Polar.	Instrument
20 Jun 2003	83	8.409	138	50	2	Y27
1 Nov 2003	217	8.409	138	50	2	Y27
1 Nov 2003	217	8.409	165	32	2	VLBA+EB+Y27+WB+AR+MC+NT
30 Nov 2003	247	1.216	30	12	2	AR
30 Nov 2003	247	1.428	50	12	2	AR
30 Nov 2003	247	1.473	30	12	2	AR

*NOTE - EB = 100m Effelsberg telescope; Y27 = phased VLA; GBT = 105m Green Bank Telescope; WB = phased Westerbork array; AR = 305m Arecibo telescope; MC = Medecina 32m telescope; NT = Noto 32m telescope.

(WSRT) tied array, and the Noto and Medecina telescopes of the Consiglio Nazionale delle Ricerche. In all some 56 individual and combined antennas each of 25m or more in diameter were employed with a combined collecting area of 0.12 km^2. Most antennas were on-source for a period of 5.5 hours. All stations recorded with 256 Mbps with 2 bit sampling in dual circular polarization with the exception of Noto which had only a right-circular polarization receiver available. The observations were correlated at the Joint Institute for VLBI in Europe (JIVE).

The nearby (1.5°) source J1051+2119 was used for phase-referencing with a 2:1 minute cycle on source:calibrator. The weak calibrator J1048+2115 was observed hourly to check on the quality of the phase referencing. Self-calibration with a 1 hour solution interval was used to further refine the calibration and remove some slow-changing atmospheric phase errors. The final image has an rms noise of 24 μJy/beam. This is substantially higher than the expected thermal noise of 8μJy/beam, in part because of partial loss of signals from Arecibo and Westerbork for reasons not completely understood.

We fit a symmetric, two-dimensional Gaussian to the measured visibilities on GRB 030329 and find a size of 0.176 ± 0.08 mas. As in Taylor *et al.* (2004) the error of the size is estimated from signal-to-noise ratios and from Monte-Carlo simulations of the data using identical (u,v) coverage, similar noise properties, and a Gaussian component of known size added. The standard deviation of the recovered sizes, modelfitted in the same way as we treat the observations, was found to be 0.053 mas.

We also obtain a position for GRB 030329 of R.A. $10^h44^m49.95955^s$ and Dec. 21°31'17.4377" with an uncertainty of 0.2 mas in each coordinate. Solving for proper motion using all the high frequency VLBI observations to date, we derive $\mu_{\rm r.a.} = -0.05 \pm 0.41$ mas yr^{-1} and $\mu_{\rm dec.} = -0.24 \pm 0.41$ mas yr^{-1}, or an angular displacement over the first 217 days of 0.14±0.35 mas (Fig. 1). These observations are consistent with those reported by Taylor *et al.* (2004), and impose an even stronger limit on the proper motion. This limit argues against the cannonball model for GRBs proposed by Dado, Dar & De Rujula (2004).

2.2. *Single Dish Arecibo Observations*

Single dish observations of GRB 030329 were carried out with the L-band Wide receiver of the 305 m Arecibo Radio Telescope on 2003 November 30, for a total of 2 hr. The simple position-switched observations utilized all four interim correlator boards to observe various L-band frequencies. The bandwidth of each board was 12.5 MHz. While the first two boards were set to observe the frequency of the redshifted λ21 cm H I line, recording each linear polarization with 2048 spectral channels, the other two boards were set to observe simultaneously the orthogonal polarizations at the frequencies of the redshifted λ18 cm mainline OH transitions (1665 & 1667 MHz) and the 1720 MHz satellite OH transition with 1024 spectral channels per polarization.

Following the editing out of data suffering from radio frequency interference, the total on-source integration time for the redshifted λ21 cm H I and the 1720 MHz satellite OH transitions was 30 min each. For the redshifted λ18 cm mainline OH transitions, the on-source integration time was 50 min.

3. CONSTRAINTS ON THE ATOMIC AND MOLECULAR GAS

3.1. *Limits on Absorption*

Figures 2, 3, and 4 show pairs of total-intensity spectra of the GRB 030329 centered at the optical heliocentric velocity that corresponds to the frequency of the redshifted λ21 cm H I line, the redshifted λ18 cm OH mainlines, and the redshifted λ18 cm OH satellite line at 1720 MHz, respectively.

The top spectra in Figs. 2, 3, and 4, are Hanning-smoothed with spectral resolutions of 3.52 km s^{-1} (12.2 kHz), 5.99 km s^{-1} (24.4 kHz), and 5.80 km s^{-1} (24.4 kHz), respectively. The rms noise level in each of these spectra is 1.02, 0.32, and 0.57 mJy beam^{-1}, respectively. The bottom plot in each figure is a five-channel smoothed version of the respective top spectra. The velocity resolution in these spectra is 8.80, 14.98, and 14.50 km s^{-1}, and the rms noise level of each spectrum is 0.482, 0.224, and 0.282 mJy beam^{-1}, respectively.

No emission or absorption is seen in any of the Arecibo spectra. We can derive a 3σ limit on the H I opacity of $\tau < 0.53$ with a velocity resolution of 8.8 km s^{-1}. This corresponds to a H I column density limit of $N_H < 8.5 \times 10^{20}$ cm^{-2} assuming a spin temperature of 100 K, and uniform coverage. If the spin temperature is higher or the line is shallow and wide, then this limit could be higher. Given the extreme energies involved in the GRB, enough to cause a sudden ionospheric disturbance in the Earth's atmosphere (Schnoor *et al.* 2003) some 740 Mpc

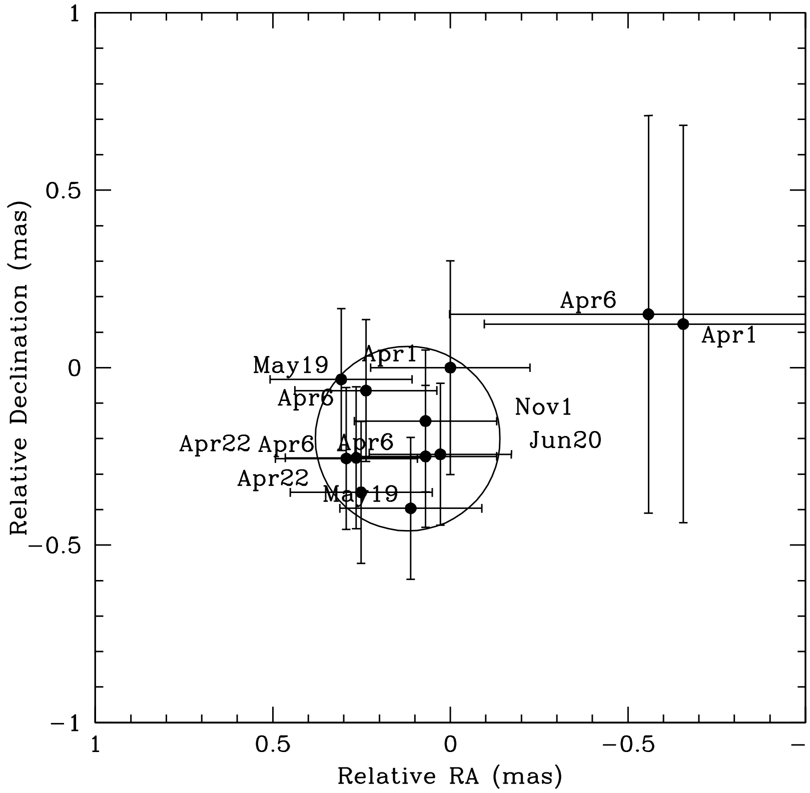

FIG. 1.— The positions derived from the observations in six epochs relative to the first determination on April 1st at 8.4 GHz. Observations at multiple frequencies at a given epoch have been plotted separately since they are independent measurements. A circle with a radius of 0.26 mas (2σ) is shown to encompass all measurements except those taken at 5 GHz, which suffer from systematic errors (Taylor *et al.* 2004). Taken together these observations provide a constraint on the proper motion of 0.14 ± 0.35 mas over 217 days.

away, it could well be that nearly all the H I along the line-of-sight in the host galaxy has been ionized and not yet recombined. Further research in this area is needed.

In a similar manner we can place a 3σ upper limit on the 1667 MHz OH mainline opacity of $\tau < 0.11$ with a velocity resolution of 15.0 km s^{-1}. This corresponds to an OH column density limit of $N_{OH} < 1.4 \times 10^{15}$ cm^{-2} assuming a uniform covering factor, and an excitation temperature of 10 K. We can further deduce a limit on molecular hydrogen using the relation $N_{H_2} \sim 10^7 \ N_{OH}$ (Kanekar & Chengalur 2002), of $N_{H_2} < 1.4 \times 10^{22}$ cm^{-2}.

The continuum flux density of the GRB 030329 at 1.4 GHz at the time of these observations was ~ 3.5 mJy. The various spectra reported here show a higher continuum flux density, because of a 15 mJy continuum source located at an angular distance of about 3 arcmin from the GRB 030329, i.e., within the primary beam of the Arecibo radio telescope.

3.2. *Angular Size Measurements*

Our measured size of 0.176 ± 0.08 mas is quite close to the size of 0.172 ± 0.043 found by Taylor *et al.* (2004), indicating a possible slowing of the burst at late times. This trend was already apparent from the average expansion velocities derived from the angular size measurements on April 22 and June 20. The entire history of expansion for GRB 030329 is shown in Fig. 5. The first measurement at 15 days comes from a model-dependent estimate of the quenching of the scintillation (Berger *et al.* 2003). The late time curvature may indicate that between 83 and 217 days, GRB 030329 has transitioned into a non-relativistic expansion. Alternatively, it is possible (but somewhat contrived) that the intrinsic surface brightness profile has changed in a way to compensate for the expansion. For all epochs we fit

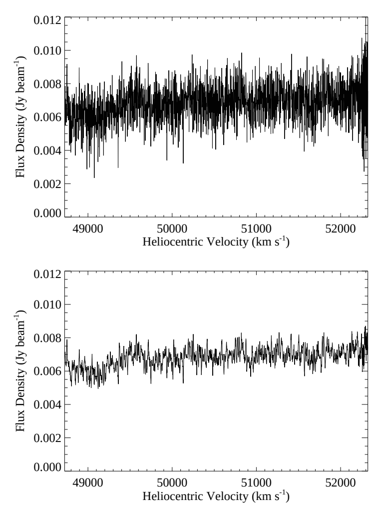

FIG. 2.— Redshifted λ21 cm H I spectra toward the GRB 030329. The top spectrum is Hanning-smoothed with 3.52 km s^{-1} (12.2 kHz) spectral resolution. The bottom plot is a five-channel smoothed version of the top plot, with a velocity resolution of 8.80 km s^{-1} and an rms noise level of 0.482 mJy beam^{-1}.

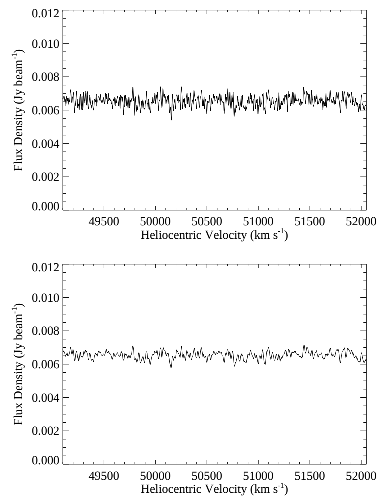

FIG. 3.— Redshifted $\lambda 18$ cm OH mainline spectra toward the GRB 030329. The top spectrum is Hanning-smoothed with 5.99 km s^{-1} (24.4 kHz) spectral resolution. The bottom plot is a five-channel smoothed version of the top plot, with a velocity resolution of 14.98 km s^{-1} and an rms noise level of 0.224 mJy $beam^{-1}$.

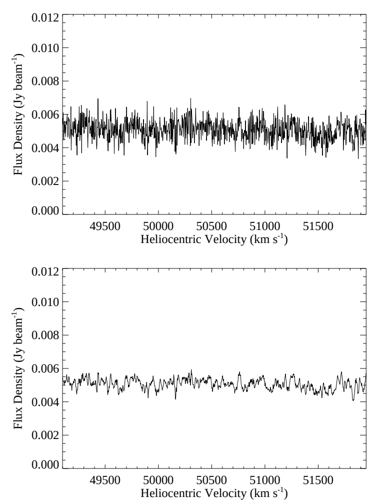

FIG. 4.— Redshifted OH $\lambda 18$ cm 1720 MHz satellite line spectra toward the GRB 030329. The top spectrum is Hanning-smoothed with 5.80 km s^{-1} (24.4 kHz) spectral resolution. The bottom plot is a five-channel smoothed version of the top plot, with a velocity resolution of 14.50 km s^{-1} and an rms noise level of 0.282 mJy $beam^{-1}$.

a two-dimensional Gaussian model since our resolution does not permit us to discriminate between a Gaussian, ring, disk, or more complex profile.

A gamma-ray burst drives a relativistic blast wave into a circumburst medium of density ρ whose radius R is related to the energy of the explosion approximately by $E \sim R^3 \rho c^2 \gamma^2$, where γ is the bulk Lorentz factor of the fireball. More complete treatments are given by (Blandford & McKee 1976; Chevalier & Li 2000; Granot & Loeb 2003). The density profile of the circumburst medium is generally taken to be either a $1/r^2$ wind, or a constant density ISM, such as one might find beyond the termination shock of the progenitor's stellar wind (Chevalier, Li, & Fransson 2004). The deceleration at late times currently favors the ISM model of (Granot, Ramirez-Ruiz & Loeb 2005) which shows a break in the expansion rate (see their Figures 4 and 6). Unfortunately, the large uncertainty in our measurement of the size of GRB 030329 at late times does not permit us to discriminate strongly between the various models.

Chevalier, Li, & Fransson (2004) place the termination shock of the Wolf-Rayet wind at a distance of 0.4 pc from the progenitor. Beyond that they predict a fairly constant density out to the red supergiant shell at a radius of 1.7 pc. With a current diameter of 0.5 pc for GRB 030329 (radius of 0.25 pc) at day 217 it is near the termination shock, especially if the progenitor had a shorter lifetime, or a relatively high density ISM has stalled the shock.

3.3. *Implications of low Polarization*

From 8.4 GHz VLBA observations on April 6 Taylor *et al.* (2004) derived a 3σ limit on the linear polarization of 0.16 mJy/beam, corresponding to a limit on the fractional polarization of <1.0%. In a contemporaneous optical observation Greiner *et al.* (2003) measure a polarization of 2.2+/-0.3%. The decrease in polarization at lower frequencies has been explained as the result of the source being optically thick at 8.4 GHz at these early times since the maximum degree of linear polarization of an optically thick synchrotron source is 12% while the maximum polarization of an optically thin synchrotron source is about 80% (Pacholczyk 1970). To look for any change in polarization with time as the source transitions to optically thin at 8.4 GHz we have analyzed the very sensitive, late time phased VLA observations for polarimetry. We find no detection at either epoch and place 3σ limits of <1.8% and <4.7% on 2003 Jun. 20 and 2003 Nov. 1 respectively. The total intensity measured with the VLA on these epochs is 3.11 ± 0.03 and 0.75 ± 0.02 mJy respectively.

The emission mechanism for the GRB afterglow is widely accepted to be synchrotron radiation, which is intrinsically linearly polarized if there is an ordered component to the magnetic field, or if the magnetic field is generated at the internal shocks (Medvedev & Loeb 1999). The recent detection of 80 ± 20% polarization in the prompt γ-ray emission from GRB 021206 (Coburn & Boggs 2003), although controversial (Rutledge & Fox 2004; Wigger et al. 2004), has led to an increased interest in modeling the time and frequency dependent behavior of the polarization from the afterglow (Nakar, Piran & Waxman 2003; Granot 2003; Granot & Taylor 2005).

To have an observed polarization of <5% in the late time afterglow (see §2.2) could be explained as the result of highly disordered magnetic fields (Granot & Königl 2003).

Propagation effects can also reduce the intrinsic linear polarization below detectable levels. A Faraday screen produced by ionized gas and magnetic fields can cause gradients in the observed polarization angle across the source, leading to depolarization if the resolution element of the telescope, or the size of the source if unresolved, is large compared to the gradients. The rotation measures (RM) can be related to the line-of-sight magnetic field, $B_{\parallel}$, by

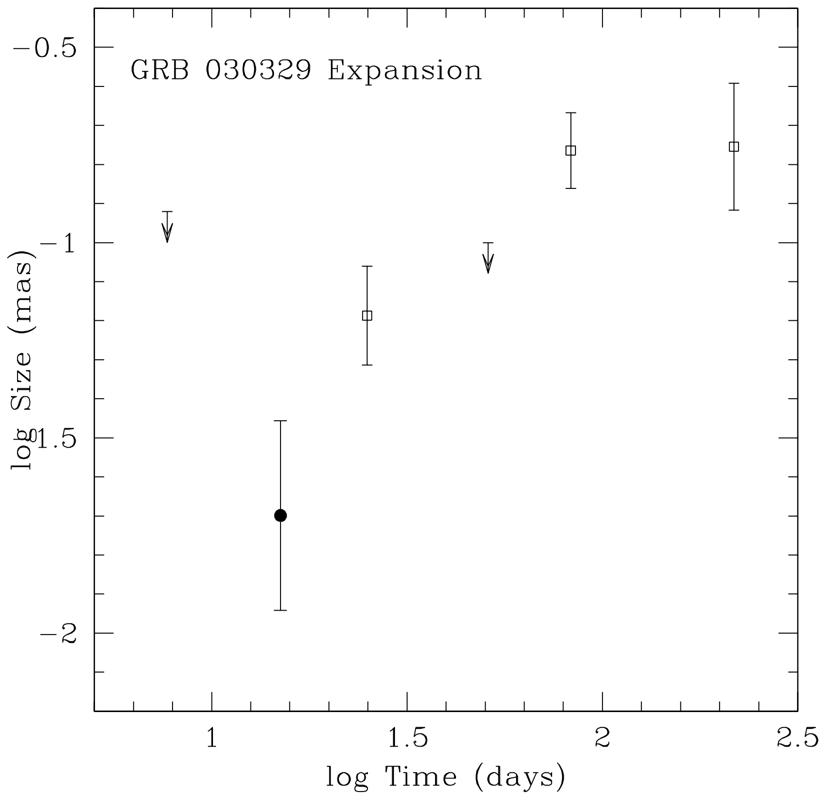

FIG. 5.— The apparent expansion of GRB 030329 derived from measurements and limits on the angular size as a function of time. The two upper limits at 7.7 and 51 days are from Taylor *et al.* (2004), as are the measurements on days 25 and 83 (open squares). The measurement on day 15 (filled circle) is a model dependent estimate based on the quenching of scintillation by Berger *et al.* (2003). Finally, the measurement on day 217 (open square) comes from this work.

$$RM = 812 \int_0^L n_{\rm e} B_{\parallel} {\rm d}l \text{ radians m}^{-2} , \quad (1)$$

where $B_{\parallel}$ is measured in mG, n_e in cm^{-3}, dl in pc, and the upper limit of integration, L, is the distance from the emitting source to the end of the path through the Faraday screen along the line of sight. We can estimate the minimum magnetic field needed to produce a gradient across the source. To produce a 90° rotation at 8.4 GHz requires a RM of 1200 rad m^{-2}. Assuming a density within the red supergiant shell of 0.2 cm^{-3} (Chevalier, Li, & Fransson 2004) and a path length of 2 pc, then the magnetic field strength required is $B_{\parallel} = 4$ mG. This field strength is similar to the equipartition field strengths Dougherty et al. (2003) have found from modeling the radio emission from colliding-wind Wolf-Rayet (WR) binary systems, although the field strengths in these systems have probably been enhanced by the collision. Faraday screens in the GRB environment are considered in more detail by Granot & Taylor (2005).

4. CONCLUSIONS

While no detection of atomic (H I) or molecular (OH) material is found towards GRB 030329, the limits of $N_H < 8.5 \times 10^{20}$ cm^{-2} are not particularly constraining. Observations of more shielded molecules like NH_3 towards future bursts at early times would be of interest, and given the expected strength of a nearby afterglow of ∼50 mJy or more, could yield detections, or place interesting limits on the amount of material in the GRB environment.

Although GRB 030329 has faded considerably, it may still be detectable with VLBI techniques. Even crude estimates of the size could differentiate between the predictions of wind and constant-density environments at these late times. Radio re-brightening of GRB 030329 has been predicted by Granot & Loeb (2003), and Li & Song (2004) estimate a level of 0.6 mJy 1.7 years after the burst. This re-brightening might occur as the counterjet becomes non-relativistic and therefore radiatively isotropic. This brightening will be accompanied by a temporary rapid growth in the size of the source as two, well-separated jets become visible, and by a change in the light centroid (Granot & Loeb 2003). If such a re-brightening occurs then a precise size estimate at late times becomes readily achievable with existing facilities.

Rather surprisingly, we find no detectable linear polarization from GRB 030329 at cm wavelengths to limits as low as 1%. This could indicate less order than expected in the magnetic fields of the external shock that drives the afterglow, or a Faraday screen that depolarizes the radio emission. All of these limits are from 8 days or more after the burst. Given the RHESSI result (Coburn & Boggs 2003) of large polarization from the γ-rays, and predictions of some fireball models, it would be well worth searching for polarization from the prompt optical and radio emission (*e.g.*, Granot & Taylor 2005).

In the near future the *Swift* satellite[8] should dramatically increase the number of GRBs with measured redshifts, revealing some that are nearby. In future VLBI studies of GRB afterglows at redshifts less than 0.1 it should be possible to image the structure of the afterglow. Fireball models of heating by a single relativistic shock front predict that at late times the fireball should look like a ring (Granot, Piran & Sari 1999).

[8] see http://swift.gsfc.nasa.gov

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