THE ENIGMATIC RADIO AFTERGLOW OF GRB 991216

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ABSTRACT

We present broadband radio observations spanning 1.4–350 GHz of the afterglow of GRB 991216, taken 1–80 days after the burst. The optical and X-ray afterglow of this burst were fairly typical and are explained by a jet fireball. In contrast, the radio afterglow is unusual in two respects: (1) the radio light curve does not show the usual rise to maximum flux on timescales of weeks and instead appears to be declining already on day 1; and (2) the power-law indices show significant steepening from the radio through the X-ray bands. We show that the standard fireball model, in which the afterglow is from a forward shock, is unable to account for point 1, and we conclude that the bulk of the radio emission must arise from a different source. We consider two models, neither of which can be ruled out with the existing data. In the first (conventional) model, the early radio emission is attributed to emission from the reverse shock, as in the case of GRB 990123. In the second “dual fireball” model, the radio emission originates from the forward shock of an isotropically energetic fireball (10⁴⁴ ergs) expanding into a tenuous medium (10⁻⁴ cm⁻³), while the optical and X-ray emission originate in a jetlike outflow. Finally, we note that the near-IR bump of the afterglow is similar to that seen in GRB 971214, and no fireball model can explain this bump.

Subject headings: cosmology: observations — gamma rays: bursts — radio continuum: general

1. INTRODUCTION

The intense gamma-ray burst GRB 991216 was detected on 1999 December 16.67 UT by the Burst and Transient Source Experiment (BATSE) on board the Compton Gamma Ray Observatory satellite (Kippen, Preece, & Giblin 1999). Follow-up observations with the positional counterarray (PCA) instrument on the Rossi X-Ray Timing Explorer (RXTE) satellite resulted in the detection of a previously uncataloged X-ray source, which was subsequently seen to fade by a factor of 5, 7 hours later (Takeshima et al. 1999). Uglesich et al. (1999) identified a fading optical source at a position consistent with the RXTE transient, and shortly thereafter the radio counterpart was discovered (Taylor & Berger 1999). Vreeswijk et al. (1999) derive a lower limit of z > 1.02 based on a system of Fe ii, Mg ii, and Mg i absorption lines.

Here we present radio measurements of this burst from 1 to 350 GHz. While the emission from X-ray and optical afterglow was fairly typical (Halpern et al. 2000), the radio afterglow of GRB 991216 was unusual in two respects. First, the onset of the decay began much earlier (<1.5 days) than that in most radio afterglows (10–100 days). Second, the temporal decay indices in the radio, optical, and X-ray bands are markedly different from each other. We explore a number of possible explanations for this behavior.

2. OBSERVATIONS AND RESULTS

Very Large Array (VLA).—A log of the observations and flux density measurements are summarized in Table 1. We used J0509+1011 (at 8.46 and 4.86 GHz) and J0530+135 (at 1.43 GHz) for phase calibration. J0542+498 was used for flux calibration at all frequencies.

Very Long Baseline Array (VLBA).—A single 2 hr observation was carried out at 8.42 GHz, and 2 bit samples of a 64 MHz bandwidth signal in one hand of polarization were recorded. The nearby (<171) calibrator J0509+1011, a core jet source, was observed every 3 minutes for delay, fringe rate, and fringe phase calibration. The radio afterglow was detected at a position of (epoch J2000) α = 5°9′31′′2983, δ = +11°17′7″262 (with 1 σ error of 0′′01 in each coordinate). The source is unresolved with a size of less than 0′′01.

Ryle Telescope.—Observations at 15 GHz with the Ryle Telescope at Cambridge (UK) were made by interleaving 15 minute scans of GRB 991216 with short scans of the phase calibrator J0509+1011. The flux density scale was tied to observations of 3C 48 and 3C 286. The source was detected only on the first epoch.

Ovens Valley Radio Observatory (OVRO) Interferometer.—The source was observed for a single 13 hr track in two continuum 1 GHz bands (central frequencies 98.481 and 101.481 GHz) under good 3 mm weather conditions. Gain calibration used the quasar 0528+134, while observations of Uranus and 3C 454.3 provided the flux density calibration scale with an estimated uncertainty of ~20%. See Shepherd et al. (1998) for details of the calibration and imaging. No source was detected.

James Clark Maxwell Telescope (JCMT).—Observations in the 350 GHz band were made using the Submillimeter Common-User Bolometer Array (Holland et al. 1999). The data were taken under good sky conditions on both nights. For flux calibration we used the source CRL 618 and assumed its flux density to be 4.57 ± 0.21 Jy. The pointing was monitored and found to vary by less than 2″. See Kulkarni et al. (1999) for

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In contrast, the optical and X-ray afterglow appears to find a straightforward explanation in the standard afterglow model in which a jet geometry is invoked (Halpern et al. 2000). Below we show that the radio observations cannot be reconciled with a standard jet (or sphere) afterglow model. We explore possible modifications to the standard model.

The simplest afterglow model is one in which the broadband afterglow emission arises from the forward shock of a relativistic blast wave propagating into a constant density medium (Sari, Piran, & Narayan 1998). It is assumed that the electrons in the forward shock region are accelerated to a power-law distribution for $\gamma_e > \gamma_{\text{min}}$, $dN/d\gamma_e \propto \gamma_e^{-\alpha} \propto r^{-\alpha}$; here $\gamma_e$ is the Lorentz factor of the electrons, $p$ is the power-law index and $\gamma_{\text{min}}$ is the minimum Lorentz factor. Gyration of these electrons in strong postshocked magnetic fields gives rise to broadband afterglow emission. Two modifications to this picture are routinely considered: (1) an inhomogeneous circumburst medium (specifically, $\rho(r) \propto r^{-\gamma}$; here $\rho$ is the density at distance $r$ from the source)—such a circumburst medium is expected should GRBs originate from massive stars (Chevalier & Li 1999); and (2) a jetlike geometry for the blast wave (Rhoads 1997; Sari, Piran, & Halpern 1999).

Regardless of these modifications, the broadband spectrum is composed of three characteristic frequencies: $\nu_{\text{syn}}$, the synchrotron self-absorption frequency; $\nu_{\text{p}}$, the frequency at which the emission peaks (and attributed to the electrons with Lorentz factor $\gamma_{\text{min}}$); and $\nu_{\text{c}}$, the cooling frequency. Electrons radiating photons with frequency greater than $\nu_{\text{c}}$ cool on timescales faster than the age of the blast wave. The evolution of these fre-

### TABLE 1

| Epoch (UT)  | $\Delta t$ (days) | Telescope | $\nu_p$ (GHz) | $S \pm \sigma$ (mJy) |
|-------------|------------------|-----------|--------------|---------------------|
| 1999 Dec 18.00 | 1.33 | Ryle | 15.0 | $1100 \pm 250$ |
| 1999 Dec 18.16 | 1.49 | VLA | 8.46 | $960 \pm 67$ |
| 1999 Dec 18.32 | 1.65 | VLBA | 8.42 | $705 \pm 85$ |
| 1999 Dec 18.48 | 1.81 | JCMT | 350 | $650 \pm 1560$ |
| 1999 Dec 19.30 | 2.63 | OVRO | 99.9 | $90 \pm 700$ |
| 1999 Dec 19.35 | 2.68 | VLA | 8.46 | $607 \pm 32$ |
| 1999 Dec 19.45 | 2.78 | JCMT | 350 | $-2000 \pm 1670$ |
| 1999 Dec 20.09 | 3.42 | Ryle | 15.0 | $-100 \pm 400$ |
| 1999 Dec 22.01 | 5.34 | Ryle | 15.0 | $-10 \pm 200$ |
| 1999 Dec 23.30 | 6.63 | VLA | 8.46 | $343 \pm 43$ |
| 1999 Dec 24.29 | 7.62 | VLA | 8.46 | $127 \pm 58$ |
| 1999 Dec 26.40 | 9.73 | VLA | 8.46 | $170 \pm 72$ |
| 1999 Dec 28.24 | 11.57 | VLA | 8.46 | $211 \pm 25$ |
| 1999 Dec 29.43 | 12.76 | VLA | 8.46 | $136 \pm 37$ |
| 1999 Dec 31.26 | 14.59 | VLA | 8.46 | $123 \pm 39$ |
| 2000 Jan 02.01 | 16.34 | VLA | 8.46 | $130 \pm 22$ |
| 2000 Jan 03.11 | 17.44 | VLA | 8.46 | $131 \pm 36$ |
| 2000 Jan 03.11 | 17.44 | VLA | 8.46 | $126 \pm 31$ |
| 2000 Jan 03.11 | 17.44 | VLA | 1.43 | $257 \pm 100$ |
| 2000 Jan 06.15 | 20.48 | VLA | 8.46 | $123 \pm 30$ |
| 2000 Jan 23.95 | 38.28 | VLA | 8.46 | $79 \pm 31$ |
| 2000 Jan 28.16 | 42.49 | VLA | 8.46 | $148 \pm 33$ |
| 2000 Feb 05.18 | 50.51 | VLA | 8.46 | $31 \pm 30$ |
| 2000 Feb 15.07 | 60.40 | VLA | 1.43 | $-55 \pm 37$ |
| 2000 Feb 15.07 | 60.40 | VLA | 8.46 | $9.6 \pm 24$ |
| 2000 Mar 03.85 | 78.18 | VLA | 8.46 | $47.0 \pm 19$ |

**Note.**—Col. (1): UT date of the start of each observation. Col. (2): Time elapsed since the GRB 991216 event (i.e., $t_{\text{p}} = 1999$ December 16.67 UT). Col. (3): Telescope. Col. (4): Observing frequency. Col. (5): Flux density of the radio transient, with the error given as the rms noise on the image. The epoch on 1999 January 23.95 UT is an average of 2 days of data (January 19-25 UT). All VLA observations were obtained in the B-array configuration.

Available at [http://lheawww.gsfc.nasa.gov/docs/gamcosray/legr/bacodine/ gcnc_main.html](http://lheawww.gsfc.nasa.gov/docs/gamcosray/legr/bacodine/gcnc_main.html)
quencies is determined by the dynamics of the blast wave. The usual ordering of these frequencies at epochs relevant to the discussion here is \( \nu_r < \nu_m < \nu_e \).

For GRB 991216 the early radio decay implies that \( \nu_m \) is already below the centimeter radio band at 1.49 days. The steepening of the afterglow emission from optical to X-ray can be explained by placing \( \nu_e \) between the optical and X-ray bands. The expected steeping \( \Delta \alpha \approx 1/5 \), which is consistent with \( \alpha_e - \alpha_o = 0.28 \pm 0.06 \). However, we are unable to explain the decay in the radio band, since no additional steepening is expected between \( \nu_m \) and \( \nu_e \).

The standard afterglow model can be made to agree with the light curves by postulating an energy slope \( p \), which gradually steepens with increasing electron energy \( \gamma_e \). Nonetheless, the invocation of curvature in the energy distribution of the electrons cannot explain the observed broadband spectrum (Fig. 2) of the afterglow on December 18 (corresponding to 1.33 days after the burst). A plausible fit to the entire data is obtained for \( p = 2.2 \) with \( \nu_e = 1.3 \) GHz, \( \nu_m = 270 \) GHz, \( \nu_g = 7 \times 10^{10} \) Hz, and \( f_m = 3.4 \) mJy; this fit is displayed by the dashed line in Figure 2. As the blast wave slows down, \( \nu_m \) moves to lower values while preserving \( f_m \), and thus we expect the flux in the centimeter band to rise, whereas the observed flux falls. If the afterglow has a jetlike geometry, then the radio afterglow is expected to rise until the epoch \( t_f \) and subsequently decay very slowly (\( f_e \propto t^{-2.2} \)) until \( \nu_m \) passes through the centimeter band, after which we expect to see a decline similar to that seen in the optical (\( f_e \propto t^{-1.8} \); Harrison et al. 1999). As can be seen from Figure 1, the radio observations are grossly inconsistent with these expectations; in particular, the decay is much faster than \( t^{-1/3} \).

To summarize, while the optical and X-ray observations can be accounted for by a jet model, the radio observations are inconsistent with the standard model. This forces us to consider afterglow models in which some of the radio emission arises from a source other than the usual forward shock.

4. A FORWARD AND REVERSE SHOCK MODEL

The most natural explanation for two components would be an early contribution from a reverse shock followed by a forward shock element at later times. This is the explanation invoked to account for the early (1–2 day) radio emission from the afterglow of GRB 990123 (Sari & Piran 1999; Kulkarni et al. 1999). The two bursts share several common features. In both cases a jet was deduced with \( t_b \approx 5 \) days, both were quite bright at gamma-ray energies, and both had a seemingly small value of \( \nu_m \) (as measured in the centimeter band). However, in the case of GRB 990123, the peak flux of the forward shock was \( f_o < 260 \mu Jy \) and the radio light curve was dominated by the reverse shock. In contrast, the forward shock for GRB 991216 appears to be quite strong. This difference then explains the seemingly different radio light curves.

At late times (i.e., timescales greater than the duration of the burst) the flux from the reverse shock is expected to fall as \( t^{-1.8} \) (Kobayashi & Sari 1999). In contrast, the forward shock emission rises as \( t^{1/2} \) for \( t < t_f \) and then slowly decays, proportional to \( t^{-1.3} \), until the \( \nu_m \) moves into the centimeter band. Since \( t_f \) is known from optical observations (Halpern et al. 2000), the remaining unknowns are the strength of the reverse and forward shock emission.

In this picture, the reverse shock dominates the radio emission for the first few days, and the model fit mainly consists of fitting a power law with \( f_e \propto t^{-1.8} \). We note that at day 1.5, the VLA 8.46 GHz flux and the Ryle 15 GHz flux are comparable. This suggests that the reverse shock is already optically thin at 8.46 GHz at this epoch—similar to the situation for GRB 990123 (Kulkarni et al. 1999). We deduce the parameters of the forward shock by fitting the radio to optical spectrum around \( t_f = 5 \) days to the forward shock model (the contribution of the reverse shock is expected to be negligible thanks to the steep decay, and since \( t_f \) is comparable to \( t_b \), the spherical fireball model is still applicable); we find \( \nu_m = 1.4 \times 10^{12} \) Hz and \( f_m = 1.0 \) mJy. As can be seen from Figure 3 this reverse-forward model provides a reasonable fit to the observations.

There are three predictions of this model. First, we expect \( \nu_m \) to cross the centimeter band at \( t_b = t_f(\nu_m/8.46 \text{ GHz})^{1/2} \approx 64 \) days. For \( t > t_f \), we expect the radio flux to decline as steeply as the optical flux does for \( t > t_f \). The low flux values as measured at the VLA around this epoch are in agreement with this model. A second prediction is that for \( t < t_f \), the spectrum should rise as \( 1/t^{1/2} \) for \( \nu < 8.46 \) GHz. The observed radio slope between 1.43 and 8.46 GHz at day 17.44 can be described by a simple power law with slope \( \beta_R = -0.39 \) and agrees with the model prediction at the 90% confidence level (1.6 \( \sigma \)). Finally, within this interpretation, we expect there to have been an optical flash of approximately eighth magnitude.

5. A TWO-COMPONENT FORWARD SHOCK MODEL

We now consider a model in which much of the radio emission arises as the forward shock of an additional fireball (hereafter the second fireball). The principal attraction of the second fireball is that we no longer need to relate the radio decay rate to those at optical and radio frequencies. We clarify that the optical and X-ray observations are explained by the forward...
The three inferred parameters ($\nu_{\text{iso}}, f_{\nu_{\text{iso}}}, \nu_{\text{iso}}^2$) allow us to obtain the energy of the blast wave and the density of the ambient medium (Wijers & Galama 1999), $E_{\text{iso}} \sim 10^5$ and $n \sim 10^{-5} \text{ cm}^{-3}$; these values are relatively insensitive to the value of the unknown $\nu$ (which is, however, constrained to lie above the optical band). The large $E$ and small $n$ are primarily due to the small value of $t_{\text{iso}}$. If this interpretation is correct, then we have uncovered the first example of a GRB exploding in a very low density medium—perhaps the halo of a host galaxy.

We end this section by noting a worrisome and puzzling issue: we are unable to provide a consistent explanation for the near-IR, optical, and X-ray observations with a standard fireball afterglow spectrum. As noted in Figure 2, there is a broad maximum around $2 \times 10^{14}$ Hz, suggesting that this is the peak frequency ($\nu_p$) of the fireball. Fitting a template afterglow spectrum we obtain the following: $\nu_p = 2.4 \pm 0.7 \times 10^{14}$ Hz, $f_{\nu_p} = 144 \pm 10 \mu$Jy, and $\nu_1 = 2 \times 10^{16}$ Hz. A similar broad peak in the near-IR (and attributed to $\nu_2 \sim 3 \times 10^{17}$ Hz at $\Delta t = 0.5$ days) was observed for GRB 971214 (Ramaprakash et al. 1998). However, if we evolve this $\nu_p$ back in time (with $\nu_k \propto t^{-3/2}$), we predict a rising R-band light curve, inconsistent with the observations (Fig. 1). Moving $\nu_k$ to lower frequencies solves this problem, but we are left with no explanation for the near-IR bump.

To summarize, the radio afterglow of GRB 991216 is unusual and cannot be explained by the standard forward shock model. A conventional reverse-forward shock model or an exotic two-component forward shock model can reasonably account for the observations. Finally, we have no explanation for the near-IR bump seen on day 1.33. GRB 991216 shows that there may yet be new surprises in GRB afterglows.

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REFERENCES

Chevalier, R. A., & Li, Z.-Y. 1999, ApJ, 520, L29
Corbet, R., & Smith, D. 1999, GCN Circ. 506 (http://gcn.gsfc.nasa.gov/gcn/ gcn3/506.gcn3)
Frail, D. A., Waxman, E., & Kulkarni, S. R. 2000, ApJ, 537, 191
Fukugita, M., Shimasaku, K., & Ichikawa, T. 1995, PASP, 107, 945
Granot, J., Piran, T., & Sari, R. 1999a, ApJ, 513, 679
Grisoni, G., et al. 2000, ApJ, 527, 236
Halpern, J. P., et al. 2000, ApJ, in press (astro-ph/0006206)
Harrison, F. A., et al. 1999, ApJ, 523, L121
Holland, W. S., et al. 1999, MNRAS, 303, 659
Kippen, R., Fassnacht, C., Giblin, D., & Gallant, Y. 1999, GCN Circ. 32 (http:// gcn.gsfc.nasa.gov/gcn3/32.gcn3)
Kobayashi, S., & Sari, R. 1999, preprint (astro-ph/9910241)
Kulkarni, S. R., et al. 1999, ApJ, 522, L97
Panaitescu, A., Meszaros, P., & Rees, M. J. 1998, ApJ, 503, 314
Piro, L., Garmire, G., Garcia, M., Marshall, F., & Takeshima, T. 1999, GCN Circ. 300 (http://gcn.gsfc.nasa.gov/gcn3/300.gcn3)
Ramaprakash, A. N., et al. 1998, Nature, 393, 43
Rhoads, J. E. 1997, ApJ, 487, L1
Rol, E., Vreeswijk, P. M., Strom, R., Kouveliotou, C., Pian, E., Castro-Tirado, A., Hjorth, J., & Greiner, J. 1999, GCN Circ. 491 (http://gcn.gsfc.nasa.gov/ gcn3/491.gcn3)
Sari, R., Piran, T., & Halpern, J. P. 1999, ApJ, 519, L17
Sari, R., Piran, T., & Narayan, R. 1998, ApJ, 497, L17
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Shepherd, D. S., Frail, D. A., Kulkarni, S. R., & Metzger, M. R. 1998, ApJ, 497, 859
Takeshima, T., Markwardt, C., Marshall, F., Giblin, T., & Kippen, R. M. 1999, GCN Circ. 478 (http://gcn.gsfc.nasa.gov/gcn3/478.gcn3)
Taylor, G. B., & Berger, E. 1999, GCN Circ. 483 (http://gcn.gsfc.nasa.gov/ gcn3/483.gcn3)
Ugelsich, R., Mirabal, N., Halpern, J., Kassis, S., & Novati, S. 1999, GCN Circ. 472 (http://gcn.gsfc.nasa.gov/gcn3/472.gcn3)
Vreeswijk, P. M., et al. 1999, GCN Circ. 496 (http://gcn.gsfc.nasa.gov/gcn/ gcn3/496.gcn3)
Wijers, R. A. M. J., & Galama, T. J. 1999, ApJ, 523, 177