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THE AFTERGLOW OF GRB 010222: A CASE OF CONTINUOUS ENERGY INJECTION[1]

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ABSTRACT

The optical light curve of GRB 010222 exhibited one of the slowest decays of any gamma-ray burst to date. Its broadband properties have been difficult to explain with conventional afterglow models, as they require either the power-law index of the underlying electron energy distribution to be low, $p < 2$, or the outflow to be quasi-spherical, thus reviving the energy problem. We argue that the slow decay of GRB 010222 and a linear polarization of 1.36% ± 0.64% are naturally explained by a jet model with continuous energy injection. The electron energy distribution then has $p = 2.49 \pm 0.05$, fully consistent with the expectation from detailed modeling of acceleration in relativistic shocks that $p > 2$, thus alleviating the "p-problem."

Subject headings: gamma rays: bursts — polarization

1. INTRODUCTION

GRB 010222 was a bright gamma-ray burst (GRB) localized by *BeppoSAX* (Piro 2001). X-ray observations were reported by in 't Zand et al. (2001). The optical afterglow (OA) was discovered by Henden & Vrba (2001), 4.3 hr after the burst, and a redshift of $z = 1.477$ was determined by Jha et al. (2001). Further optical/near-infrared observations have been reported by Stanek et al. (2001), Lee et al. (2001), Masetti et al. (2001), Cowsik et al. (2001), Sagar et al. (2001), and Mirabal et al. (2002). In our analysis, we adopt the light-curve fit of A. A. Henden et al. (2002, in preparation), which is based on data extending up to 80 days after the burst. Their best fit in the R band gives a prebreak power-law slope of $\alpha_1 = -0.66 \pm 0.03$ and a postbreak slope of $\alpha_2 = -1.40 \pm 0.02$, with a break time of $t_b = 0.58 \pm 0.04$ days. The observed optical spectral index is about $\beta = -1.0$ (e.g., Stanek et al. 2001), but as it may be strongly affected by host extinction, it can lead to ambiguous inference of the afterglow properties. In particular, the relationship between the light-curve decay indices, α, and the spectral index, β, that is predicted by synchrotron models of afterglows (e.g., Sari, Piran, & Narayan 1998; Sari, Piran, & Halpern 1999; Price et al. 2002) can lead to inconsistent interpretations owing to the unknown host extinction.

To date, interpretation of the GRB 010222 afterglow observations has mainly relied on two possible scenarios: (1) a narrow sideways expanding jet propagating in a low-density medium (e.g., Stanek et al. 2001) and (2) a wide jet or spherical fireball transiting from a relativistic to nonrelativistic regime (e.g., Masetti et al. 2001; in 't Zand et al. 2001). The latter models require a very dense medium and imply a very large energy release, thus bringing back the energy problem (Kulkarni et al. 1999; Andersen et al. 1999). Both classes of models require a hard electron energy distribution, i.e., $p < 2$, in the first case even as low as $p \approx 1.4$. This is contrary to most other bursts that seem to be adequately fitted with models where $p \approx 2.3$–2.5 (van Paradijs, Kouvelioutu, & Wijers 2000). Recently, Panaitescu & Kumar (2002) presented fits to several afterglows, concluding that p is smaller than 2 in a number of them. Such small inferred values of p signal a departure from the standard fireball model (Mészáros 2002) and introduce additional free parameters into the model, such as an upper cutoff in the electron energy distribution, or additional assumptions about the electron acceleration mechanism to facilitate the generation of flat energy distributions (Dai & Cheng 2001; Bhattacharya 2001). The p-problem then arises from the fact that detailed modeling of particle acceleration in relativistic shocks indicates that $p \approx 2.2$–2.3 (Achterberg et al. 2001).

In addition, if p is assumed to be constant throughout the fireball evolution, the magnitude of the observed light-curve break in the case of GRB 010222, $\Delta\alpha = \alpha_1 - \alpha_2 = 0.74 \pm 0.04$, cannot be explained by the above models. The sideways expanding jet model predicts a break magnitude of $\Delta\alpha = 1 - \alpha_1/3 = 1.22 \pm 0.01$, while the fireball transiting to the nonrelativistic regime gives $\Delta\alpha = (\alpha_1 + \frac{3}{5}) = 0.06 \pm 0.03$ for slow cooling electrons. For fast cooling electrons, the latter model predicts $\Delta\alpha = (\alpha_1 + 1) = 0.34 \pm 0.03$. The break magnitudes predicted by the models are in all cases very different from the observed value, which is, however, in perfect agreement with the prediction of a jet model with a fixed opening angle (Mészáros & Rees 1999), $\Delta\alpha = \frac{3}{4}$, being essentially of geometrical origin.

In this Letter, we use polarization measurements to argue against interpretations based on spherical models transiting to the nonrelativistic regime. Furthermore, we demonstrate that the observations of GRB 010222 can be naturally interpreted with a jet model with a small opening angle and continuous energy injection.

2. OBSERVATIONS

2.1. *Polarimetry*

Polarimetric imaging observations were obtained at the 2.56 m Nordic Optical Telescope on La Palma, The Canary Islands, with the Andalucía faint object spectrograph, using two calcite plates together with a V-band filter. Each calcite plate provides the simultaneous measurement of the ordinary and the extraordinary components of two orthogonally polarized beams. Thus, one image gives either the 0° and 90° components or the 45° and 135° components simultaneously. The calcite plates produce a vignetted field of about 140″ in diameter. The detector

[1] Based on observations made with the Nordic Optical Telescope, operated on the island of La Palma jointly by Denmark, Finland, Iceland, Norway, and Sweden, in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias.

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TABLE 1
JOURNAL OF POLARIMETRY OBSERVATIONS OF GRB 010222

Time (2001 February UT)	Orientation (deg)	Exposure Time (s)	V (mag)
23.22499	45/135	900	20.423 ± 0.011
23.23640	0/90	900	20.444 ± 0.011
23.24782	45/135	900	20.436 ± 0.011
23.25925	0/90	900	20.468 ± 0.011
23.26894	45/135	600	20.484 ± 0.014
23.27688	0/90	600	20.499 ± 0.016
23.28154	0/90	30	...
23.28289	45/135	30	...

NOTE.—The photometric zero point was determined assuming $V = 14.582$ for star A (A. A. Henden et al. 2002, in preparation).

was a thinned Loral 2048 × 2048 pixel charge-coupled device (CCD), giving a pixel scale of 0.″188. The ordinary and extraordinary beams appear as images separated by about 15″ on the CCD detector.

Observations began 21.88 hr after the burst, with observing and reduction procedures similar to those used for GRB 990123 (Hjorth et al. 1999), each image providing fluxes in two of the four orientations required. Individual exposure times were 600 or 900 s, resulting in total exposure times of 2400 s per orientation at a mean epoch of 2001 February 23.25169 UT, 22.65 hr after the burst (see Table 1). No information on the position angle is available, as no polarization standards were observed. The images were flat-fielded using standard procedures with appropriate dome flats in each of the two orientations. The three images in each orientation were combined. Absolute photometric calibration was performed relative to star A of A. A. Henden et al. (2002, in preparation), which has $V = 14.582 \pm 0.022$. Meteorological conditions were fine, and the measured resolution of the images was ~0.″8–1.″0. Figure 1*a* shows an excerpt of the combined images.

Aperture photometry was performed on the combined images with the DAOPHOT II/ALLSTAR (Stetson 1987, 1994) software package. Point-spread function (PSF) photometry turned out to be difficult owing to the lack of suitable PSF stars and the strongly orientation-dependent PSF shape and width. Aperture growth curves were computed for the OA, star B, and a galaxy (G) in the field (see Fig. 1*a*). Star A was saturated in these images. Aperture photometry of star A was therefore performed on the short exposures obtained immediately after the six long exposures (see Table 1).

In order to correct for possible interstellar polarization, polarization induced by the telescope and instrument, and the significant variations in stellar shape as a function of orientation, we computed aperture growth curves for the OA, B, and G relative to A.

The Stokes vector, the instrumental Q- and U-values, and the linear polarization were computed from the derived fluxes in the four orientations (Hjorth et al. 1999; Wijers et al. 1999; Rol et al. 2000) as a function of aperture radius. The results are dependent on the aperture radii used. For small radii, the results are dominated by photon noise and small variations in the shapes and widths of the objects relative to star A. For large radii, the noise from and difficulty in subtracting the sky background dominates. Thus, one can only hope for reliable results for intermediate aperture radii. We used two criteria for selecting the aperture radius, namely, (1) minimizing photon noise that favored aperture radii between 4 and 6 pixels and (2) insensitivity to the aperture radii of the Q- and U-values that favored aperture radii between 5 and 7 pixels. We note that B never reached independence of aperture radius and shows a variation in Q larger than that expected from photon noise. We therefore consider the results for B unreliable, probably owing to relatively high photon noise from the fainter star. Aperture radii between 5 and 7 pixels for the OA and G are shown as filled circles in Figure 1*b*. The mean of these give $P(\mathrm{OA}) = 1.50\% \pm 0.64\%$ and $P(\mathrm{G}) = 0.4\% \pm 0.9\%$. We

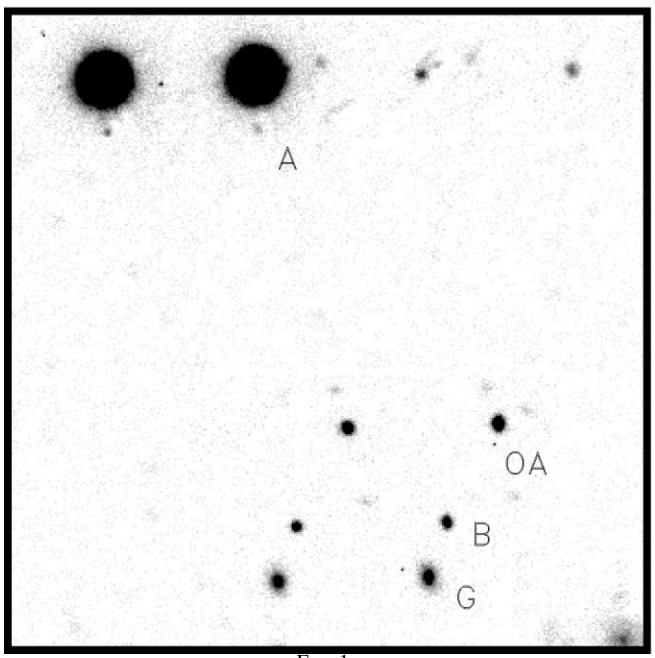

FIG. 1*a*

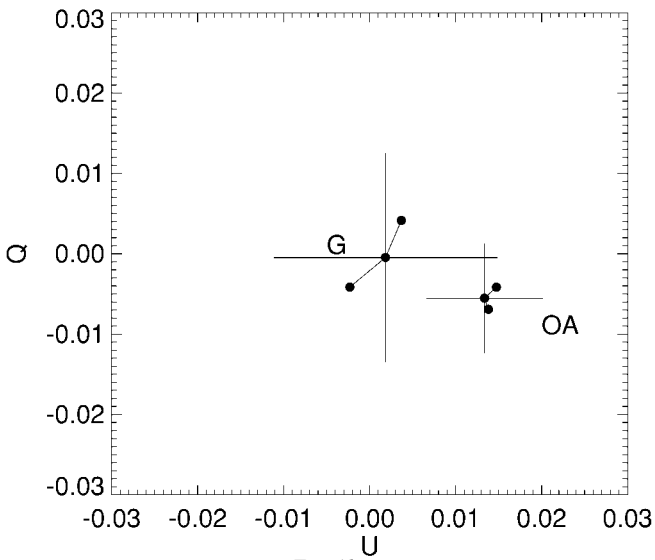

FIG. 1*b*

FIG. 1.—(*a*) Excerpt of the combined image containing the 0°/90° orientations. The image measures 60″ × 85″. North is up, and east is to the left. The optical afterglow of GRB 010222 (OA), A. A. Henden's bright star (A), a faint star (B), and a galaxy (G) are indicated. The orientations corresponding to 0° and 90° are separated by 15″ in the east-west direction. (*b*) Q vs. U for OA and G. Aperture radii of 5, 6, and 7 pixels are plotted with photon noise error bars shown for 6 pixels.

note that the polarization of the galaxy is consistent with zero, as it should if star A is unpolarized.

The effects of depolarization or interstellar polarization in the Milky Way are expected to be negligible at the high latitude of GRB 010222 ($b = 60\overset{\circ}{.}9$)— well out of the Galactic plane. For the low Galactic extinction of $E(B-V) = 0.023$ (Schlegel, Finkbeiner, & Davis 1998), the maximum interstellar polarization or depolarization is less than 0.2% (Serkowski, Mathewson, & Ford 1975; Berdyugin & Teerikorpi 1997). Thus, the interstellar polarization or depolarization toward GRB 010222 is negligible.

At low significance levels of the computed afterglow polarization, a correction must be applied to account for the non-Gaussian nature of the underlying probability distribution (Wardle & Kronberg 1974). When corrected for this effect, the *V*-band linear polarization of the OA of GRB 010222 is 1.36% ± 0.64%, similar to the degree of polarization observed in a number of other bursts (e.g., Covino et al. 1999; Rol et al. 2000).

As seen in Table 1, the OA decayed during the observations. As a check on the reliability of our polarization measurements, we computed the *V*-band magnitudes by taking the mean of the two orientations at each epoch. The resulting decay slope of -1.19 ± 0.25 is consistent with the observed light curve (e.g., A. A. Henden et al. 2002, in preparation).

2.2. *X-Rays*

We have also analyzed data from *Chandra X-Ray Observatory* observations starting about 15 hr after the burst, yielding a net exposure time of 29.5 ks. Owing to the brightness of the X-ray afterglow, the data are severely affected by pileup. Hence, the spectra were analyzed following the procedure suggested by Davis (2001), taking pileup effects explicitly into account in the spectral modeling. We extracted a spectrum from a circular 4″ diameter region centered on the X-ray afterglow and fitted the 0.5–10 keV spectrum with three model components: (1) an intrinsic power law, (2) Galactic absorption fixed at the nominal value $n_{\rm H} = 1.6 \times 10^{20}$ cm^{-2} (Dickey & Lockman 1990), and (3) intrinsic absorption in the GRB host fixed at the anticipated redshift of $z = 1.477$. This model provides an excellent fit ($\chi^2 = 116$ for 204 degrees of freedom), with a best-fit spectral index $\beta = -0.72 \pm 0.17$ and intrinsic GRB host absorption $n_{\rm H}^{i} = (6.5 \pm 0.11) \times 10^{21}$ cm^{-2} (1 σ errors). There is no evidence for additional spectral features. The 4 keV flux at the mean epoch of observations, 0.81 days, was 0.268 ± 0.054 μJy. The near contemporaneous *BeppoSAX* observations give $\beta = -0.97 \pm 0.05$ (in 't Zand et al. 2001). The difference between our spectral index and the *BeppoSAX* results is due to different derived values of $n_{\rm H}$. Using their method and fixing $n_{\rm H}$ at their value, we find $\beta = -1.13 \pm 0.20$.

3. A JET WITH CONTINUOUS ENERGY INJECTION

Sources of synchrotron radiation are generally expected to exhibit polarization in their emission, with the degree of polarization as high as 60%–70% (e.g., Rybicki & Lightman 1985). This is, however, strongly dependent on the degree of regularity in the magnetic field. In fireball models, the field is expected to be highly entangled with no preferred direction; hence, little or no polarization is expected. This would also be the case in a spherical fireball, due to symmetry, even if the magnetic field had a regular component.

In a jetlike fireball, if the magnetic field has a regular component and the line of sight is at an angle with the center of collimation, some polarization may be observed (Ghisellini & Lazzati 1999; Sari 1999). The degree of polarization observed in GRB 010222 thus suggests that the fireball is slightly asymmetric. It follows that a transition to a nonrelativistic regime of a spherical fireball or a wide jet is not likely to be a correct description of this event.

On the other hand, the observed light-curve break magnitude, $\Delta\alpha = 0.74 \pm 0.04$, is exactly what is expected in a jet of fixed opening angle (Mészáros & Rees 1999). We will henceforth adopt that geometry.

The isotropic energy release of GRB 010222, as estimated from the *SAX* data, is $E_{52} = 154.2 \pm 17.0$ (in units of 10^{52} ergs), in a cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $h_0 = 0.65$ (Amati et al. 2002). The initial Lorentz factor, estimated from equation (10) in Sari & Piran (1999), is then $\Gamma_0 \approx 350$, ignoring the weak dependence on the ambient number density, n_0. Using the light-curve break time $t_b = 0.58 \pm 0.04$ days (A. A. Henden et al. 2002, in preparation), we find that the corresponding collimation angle at t_b is $\theta_0 = 1/\Gamma_b \approx 2\overset{\circ}{.}0$, reducing the estimate of the energy released in the burst to $E \approx 10^{51}$ ergs, fully consistent with the results of Frail et al. (2001), although near the higher end of their distribution.

We advance the hypothesis that the exceptionally slow light-curve decay of GRB 010222 is the consequence of continuous energy injection. If the fireball energy injection is continuous over an extended period of time rather than instantaneous, it may be modeled as a power law in ejected mass (Rees & Mészáros 1998; Sari & Mészáros 2000). The resulting time evolution of the Lorentz factor can then be expressed as $\Gamma = \Gamma_0 (t/t_0)^{-(3-g)/(7+s)}$, where s is the power-law exponent of the ejected mass distribution and g is the power-law index of the ambient density distribution. We will henceforth assume a homogeneous environment ($g = 0$). Then $s = 1$ reproduces the instantaneous case, as the energy release is then constant, while $s > 1$ implies that the energy is dominated by material with low Lorentz factors (Rees & Mészáros 1998). We will take $s = 2$ as a representative case of moderate energy injection (Sari & Mészáros 2000). Knowing the hydrodynamic evolution allows one to derive the corresponding light curve and spectral evolution as in the standard fireball model with instantaneous energy injection. General expressions, valid also for an inhomogeneous external medium, can be found in Sari & Mészáros (2000). We will use their notation in what follows. It should be emphasized that a reverse shock is expected to produce substantial flux at low frequencies, especially at late times.

Interpreting the optical and X-ray light curves as due to the forward shock, we find, using $\alpha_1 = -0.66 \pm 0.03$ and $s = 2$, that

$$p = \frac{3(s+1) - (7+s)\alpha_1}{6} = 2.49 \pm 0.05, \qquad (1)$$

in agreement with many other bursts. It follows that the intrinsic spectral index is $\beta = -(p-1)/2 = -0.75 \pm 0.03$. This is fully consistent with the X-ray observations, if the cooling frequency ν_c was above the X-rays at the time of observations, but it requires moderate extinction in the optical (Lee et al. 2001; Masetti et al. 2001). It provides a consistent picture of the broadband spectrum from the optical through the X-rays. The uncorrected *V* flux at 0.81 days is 45 μJ, using the temporal index $\alpha = -1.19$ as inferred from our polarimetry. Adopting the SMC extinction correction of Lee et al. (2001), we find that $A_V =$

0.3 corresponds to $\beta = -0.72$, consistent with the intrinsic spectral slope we inferred above and our X-ray observations.

We note that if $2 \leq p \leq 3$, when $s = 2$, then the prebreak slope would be in the range $0.33 \leq -\alpha_1 \leq 1.0$. For a jet with fixed θ_0, we would then have $1.08 \leq -\alpha_2 \leq 1.75$. It is not straightforward to estimate the postbreak slope in an expanding jet model, as it requires a knowledge of how the continuous energy injection modifies the jet evolution subsequent to the moment when $\Gamma < 1/\theta_0$. This is the subject of a separate paper (G. Björnsson et al. 2002, in preparation). We expect, however, a transition period where the temporal slope depends both on p and s. The asymptotic decay slope will in the end approach $-p$, but this may not be reached in all cases before the optical transient fades below detectability or the host galaxy starts to dominate the emission. The late-time decay slope derived by Fruchter et al. (2001), $\alpha_2 = -1.7 \pm 0.05$, may indeed indicate that the afterglow continued to steepen at very late times. We suggest that the above scenario may also apply, e.g., to GRB 020813, as its light-curve decay is very similar to that of GRB 010222 (e.g., Bloom, Fox, & Hunt 2002; Gladders & Hall 2002).

The flux from the forward shock has a maximum at the frequency ν_m^f, which in this interpretation is below the optical. The spectral region from optical through X-rays is therefore represented by the same power law, $F_\nu \propto \nu^{-0.75}$. From our X-ray data at 0.81 days, we obtain

$$n_0^{1/2} \epsilon_{B,-2}^{7/8} \epsilon_{e,0.5}^{3/2} = 2.53 \times 10^{-5}. \quad (2)$$

To solve for the model parameters, we need two more constraints. The optical and the X-rays are degenerate in the sense that they are both between ν_m^f and ν_c. The reverse shock is expected to produce substantial emission around the frequency ν_m^r, which is defined analogously to ν_m^f and is related to it by $\nu_m^r = \nu_m^f/\Gamma^2$, the peak flux of the reverse shock being a factor Γ larger than the peak flux of the forward shock. For $\nu_m^f \approx 10^{14}$ Hz, ν_m^r could be from a few hundred gigahertz to 10^{12} Hz. Furthermore, the flux from the reverse shock may be expected to stay constant or even increase for a period of time (Panaitescu, Mészáros, & Rees 1998) or decay as $t^{-1/2}$ (Sari & Mészáros 2000). The radio and submillimeter observations of Frail et al. (2002) show a constant flux onward from about 0.35 and 0.8 days at 350 and 250 GHz, respectively. They convincingly argue that this flux originates in the host galaxy rather than the afterglow. That sets an upper limit on the emission predicted by the model, in principle enabling us to further constrain the parameters. In practice, as ν_m^f is unknown, the constraints in this case are very weak. It is apparent though from equation (2) that for reasonable values of n_0, and $\epsilon_{e,0.5}$, the magnetic field is very weak.

A generic property of extended injection models is that the afterglow fades more slowly than in the case of instantaneous injection. We have chosen a simple power-law distribution of Γ as an example of such a scenario. Other, perhaps more detailed models, are of course possible (e.g., Zhang & Mészáros 2002) but would only affect the above interpretation in the details. The interpretation presented here requires the introduction of an additional model parameter (s), but this is also true in other models for the case of $p < 2$ as discussed above. An inferred value of $p > 2$ is furthermore supported by detailed modeling of particle acceleration in relativistic shocks (Achterberg et al. 2001).

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REFERENCES

Achterberg, A., Gallant, Y. A., Kirk, J. G., & Guthmann, A. W. 2001, MNRAS, 328, 393
Amati, L., et al. 2002, A&A, 390, 81
Andersen, M. I., et al. 1999, Science, 283, 2075
Berdyugin, A., & Teerikorpi, P. 1997, A&A, 318, 37
Bhattacharya, D. 2001, Bull. Astron. Soc. India, 29, 107
Bloom, J. S., Fox, D. W., & Hunt, M. P. 2002, GCN Circ. 1476 (http://gcn.gsfc.nasa.gov/gcn/gcn3/1476.gcn3)
Covino, S., et al. 1999, A&A, 348, L1
Cowsik, R., Prabhu, T. P., Anupama, G. C., Bhatt, B. C., Sahu, D. K., Ambika, S., Padmakar, & Bhargavi, S. G. 2001, Bull. Astron. Soc. India, 29, 157
Dai, Z. G., & Cheng, K. S. 2001, ApJ, 558, L109
Davis, J. E. 2001, ApJ, 562, 575
Dickey, J. M., & Lockman, F. J. 1990, ARA&A, 28, 215
Frail, D. A., et al. 2001, ApJ, 562, L55
———. 2002, ApJ, 565, 829
Fruchter, A., Burud, I., Rhoads, J., & Levan, A. 2001, GCN Circ. 1087 (http://gcn.gsfc.nasa.gov/gcn/gcn3/1087.gcn3)
Ghisellini, G., & Lazzati, D. 1999, MNRAS, 309, L7
Gladders, M., & Hall, P. 2002, GCN Circ. 1514 (http://gcn.gsfc.nasa.gov/gcn/gcn3/1514.gcn3)
Henden, A. A., & Vrba, F. 2001, GCN Circ. 967 (http://gcn.gsfc.nasa.gov/gcn/gcn3/967.gcn3)
Hjorth, J., et al. 1999, Science, 283, 2073
in 't Zand, J. J. M., et al. 2001, ApJ, 559, 710
Jha, S., et al. 2001, ApJ, 554, L155
Kulkarni, S. R., et al. 1999, Nature, 398, 389
Lee, B. C., et al. 2001, ApJ, 561, 183
Masetti, N., et al. 2001, A&A, 374, 382
Mészáros, P. 2002, ARA&A, 40, 137
Mészáros, P., & Rees, M. J. 1999, MNRAS, 306, L39
Mirabal, N., et al. 2002, ApJ, in press (astro-ph/0207009)
Panaitescu, A., & Kumar, P. 2002, ApJ, 571, 779
Panaitescu, A., Mészáros, P., & Rees, M. J. 1998, ApJ, 503, 314
Piro, L. 2001, GCN Circ. 959 (http://gcn.gsfc.nasa.gov/gcn/gcn3/959.gcn3)
Price, P. A., et al. 2002, ApJ, 572, L51
Rees, M. J., & Mészáros, P. 1998, ApJ, 496, L1
Rol, E., et al. 2000, ApJ, 544, 707
Rybicki, G. B., & Lightman, A. P. 1985, Radiative Processes in Astrophysics (New York: Wiley)
Sagar, R., et al. 2001, Bull. Astron. Soc. India, 29, 91
Sari, R. 1999, ApJ, 524, L43
Sari, R., & Mészáros, P. 2000, ApJ, 535, L33
Sari, R., & Piran, T. 1999, ApJ, 520, 641
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
Serkowski, K., Mathewson, D. S., & Ford, V. L. 1975, ApJ, 196, 261
Stanek, K. Z., et al. 2001, ApJ, 563, 592
Stetson, P. B. 1987, PASP, 99, 191
———. 1994, PASP, 106, 250
van Paradijs, J., Kouveliotu, C., & Wijers, R. A. M. J. 2000, ARA&A, 38, 379
Wardle, J. F. C., & Kronberg, P. P. 1974, ApJ, 194, 249
Wijers, R. A. M. J., et al. 1999, ApJ, 523, L33
Zhang, B., & Mészáros, P. 2002, ApJ, 566, 712