Recent observations show that the temporal decay of the $R$-band afterglow from GRB 990123 steepened about 2.5 days after the burst. We here propose a possible explanation for such a steepening: a shock expanding in a dense medium has undergone the transition from a relativistic phase to a nonrelativistic phase. We find that this model is consistent with the observations if the medium density is about $3 \times 10^{6}$ cm$^{-3}$. By fitting our model to the observed optical and X-ray afterglow quantitatively, we further infer the electron and magnetic energy fractions of the shocked medium and find that the two parameters are about 0.1 and $2 \times 10^{-6}$, respectively. The former parameter is near the equipartition value, while the latter is about 6 orders of magnitude smaller than inferred from the GRB 970508 afterglow. We also discuss possibilities that the dense medium can be produced.

Subject heading: gamma rays: bursts — shock waves

1. INTRODUCTION

GRB 990123 was an extraordinary event. It is the brightest burst yet detected with the Wide Field Camera on the BeppoSAX satellite (Feroci et al. 1999) and had a total gamma-ray fluence of $\sim 5 \times 10^{-2}$ ergs cm$^{-2}$, which is in the top 0.3% of all bursts. It was the first burst to be simultaneously detected in the optical bands. Optical emission with peak magnitude of $I \sim 9$ was discovered by the Robotic Optical Transient Search Experiment during the burst and was found to have rapidly faded down immediately after the gamma-ray emission (Kulkarni et al. 1999). The detection of the redshift showed that the burst appears at $z \geq 1.6$ (Andersen et al. 1999; Kulkarni et al. 1999a). This implies that if the gamma-ray burst (GRB) emission was directed isotropically, the inferred energy release is $\geq 1.6 \times 10^{54}$ ergs (Kulkarni et al. 1999a; Briggs et al. 1999).

The burst’s afterglow was detected and monitored at X-ray, optical, and radio bands. It is the brightest of all GRB X-ray afterglows observed thus far. BeppoSAX detected the flux of the afterglow to be $1.1 \times 10^{-11}$ ergs cm$^{-2}$ s$^{-1}$ at $2-10$ keV 6 hr after the gamma-ray trigger and the subsequent temporal decay index to be $\alpha_{\gamma} = -1.44 \pm 0.07$ (Heise et al. 1999a, 1999b). The $R$-band optical afterglow about 3.5 hr after the burst showed a power-law decay with index $\alpha_{R} = -1.1 \pm 0.03$ (Kulkarni et al. 1999a; Castro-Tirado et al. 1999; Fruchter et al. 1999b). This law continued until about 2.04 $\pm$ 0.46 days after the burst. Then the optical emission began to decline based on another power law with index $\alpha_{\gamma R} = -1.65 \pm 0.06$ (Kulkarni et al. 1999a), $-1.75 \pm 0.11$ (Castro-Tirado et al. 1999), or $-1.8$ (Fruchter et al. 1999b). In addition, a radio flare was also detected about 1 day after the burst (Kulkarni et al. 1999b; Galama et al. 1999).

A scenario has been proposed to explain these observations. If the burst is assumed to be produced from a jet, the steepening of the late optical afterglow decay is caused by the possibility that this jet has undergone the transition from a spherical-like phase to a sideways-expansion phase (Rhoads 1997, 1999; Kulkarni et al. 1999a; Fruchter et al. 1999b; Sari, Piran, & Halpern 1999) or that we have observed the edge of the jet (Panaitescu & Mészáros 1998; Mészáros & Rees 1999).

In this Letter, we propose another possible scenario, in which the steepening of the late optical afterglow decay is caused by the shock, which has evolved from a relativistic phase to a nonrelativistic phase in a dense medium. According to the standard afterglow shock model (for a review, see Piran 1999), the afterglow is produced by synchrotron radiation or inverse Compton scattering in the external forward wave (blast wave) of the GRB fireball expanding in a homogeneous medium. The external reverse shock of the fireball may lead to a prompt optical flash (Sari & Piran 1999). As more and more ambient matter is swept up, the forward shock gradually decelerates and eventually enters a nonrelativistic phase. In the meantime, the emission from such a shock fades down, dominating at the beginning in X-rays and progressively at the optical-to-radio energy band. There are two limiting cases (adiabatic and highly radiative) for the hydrodynamical evolution of the shock. These cases have been well studied both analytically (e.g., Mészáros & Rees 1997; Wijers, Rees, & Mészáros 1997; Waxman 1997a, 1997b; Reichart 1997; Sari 1997; Vietri 1997; Katz & Piran 1997; Mészáros, Rees, & Wijers 1998; Dai & Lu 1998a; Sari, Piran, & Narayan 1998) and numerically (e.g., Panaitescu, Mészáros, & Rees 1998; Huang et al. 1998; Huang, Dai, & Lu 1998). A partially radiative (intermediate) case has been investigated (Chiang & Dermer 1998; Cohen, Piran, & Sari 1998; Dai, Huang, & Lu 1999). Here we only consider the limiting cases. In the highly radiative model, since all shock-heated electrons cool faster than the age of the shock, the optical afterglow should have the same temporal decay index as the X-ray afterglow (Sari et al. 1998), which is incompatible with the observations (Kulkarni et al. 1999a). In the adiabatic model, however, the difference in the decay index between optical and X-ray afterglows is found to likely be 1/4, which is consistent with the observational result $\Delta \alpha = \alpha_{R} - \alpha_{X} \approx 0.3$. This implies that the shock producing the afterglow of GRB 990123 has evolved adiabatically. This is the starting point of our analysis. For an adiabatic shock, the time at which it enters a nonrelativistic phase is proportional to $n^{-1/3}$, where $n$ is the baryon number density of the medium. Therefore, this time for a shock expanding in a dense medium with density of $n \sim 10^{6}$ cm$^{-3}$ is 2 orders of magnitude smaller than that for a shock with the same energy in a thin medium with density of
$n \sim 1 \text{ cm}^{-3}$. Furthermore, as given in § 2, the afterglow at the nonrelativistic phase decays faster than at the relativistic phase. It is natural to expect that this effect can provide an explanation for the steepening feature of the afterglow from GRB 990123.

Dense media have been discussed in the context of GRBs. First, Katz (1994) suggested collisions of relativistic nucleons with a dense cloud as an explanation of the delayed hard photons from GRB 940217. Second, to explain the radio flare of GRB 990123, Shi & Guyk (1999) speculated that a relativistic shock may have ploughed into a dense medium off the line of sight. Third, Piro et al. (1999) and Yoshida et al. (1999) have reported an ion emission line in the X-ray afterglow spectrum of GRB 970508 and of GRB 970828, respectively. The observed line intensity requires a dense medium with a large iron mass concentration in the vicinity of the burst (Lazzati, Campana, & Ghisellini 1999). Finally, dense media (e.g., clouds or ejecta) may appear in the context of some energy source models, e.g., failed supernovae (Woosley 1993), hypernovae (Paczyński 1998), supranovae (Vietri & Stella 1998), phase transition of neutron stars to strange stars (Dai & Lu 1998b), and baryon decay of neutron stars (Pen & Loeb 1998).

2. THE EVOLUTION OF A SHOCK IN A DENSE MEDIUM

2.1. Relativistic Phase

Now we consider an adiabatic relativistic shock expanding in a dense medium. The Blandford-McKee (1976) self-similar solution gives the Lorentz factor of the shock:

$$\gamma = \left( \frac{17E(1 + z)^{3/2}}{\pi m_e^5 c^4} \right)^{1/2},$$

$$= 2E_{51}^{1/3}n_5^{-1/3}t_{day}^{2/3}(1 + z)/2.6)^{3/8},$$

where $E = E_{51} \times 10^{54}$ ergs is the total isotropic energy, $n_5 = n/10^5 \text{ cm}^{-3}$, $t_{day} = t_{day} \times 1$ day is the observer’s time since the gamma-ray trigger, $z$ is the redshift of the source generating this shock, and $m_e$ is the proton mass.

In analyzing the spectrum and light curve of synchrotron radiation from the shock, one needs to know two crucial frequencies: the synchrotron radiation peak frequency ($\nu_\text{p}$) and the cooling frequency ($\nu_\text{c}$). In the standard afterglow shock picture, the electrons heated by the shock are assumed to have a power-law distribution: $dN_e/d\gamma \propto \gamma^{-\gamma_e}$ for $\gamma_e \geq \gamma_\text{em}$, where $\gamma_e$ is the electron Lorentz factor and the minimum Lorentz factor $\gamma_\text{em} = 610v_c\gamma$. The power-law index $p \approx 2.56$ by fitting the spectrum and light curve of the observed afterglow of GRB 990123 (see below). We further assume that $\epsilon_e$ and $\epsilon_B$ are the ratios of the electron and magnetic energy densities to the thermal energy density of the shocked medium, respectively. Based on these assumptions, the synchrotron radiation peak frequency in the observer’s frame can be written as

$$\nu_\text{p} = \frac{\gamma \nu_\text{em}}{1 + z} \frac{eB'}{2\pi m_e c},$$

$$= 8.0 \times 10^{30} \epsilon_e^{1/2} \epsilon_{B,54}^{-1/2} t_{day}^{1/2}(1 + z)^{3/2}/2.6, \text{ Hz},$$

where $\epsilon_{B,54} = \epsilon_B/10^{-6}$, and $B' = (32\pi \epsilon_B \gamma_e^{-1} n_5 m_e c^2)^{1/2}$ is the internal magnetic field strength of the shocked medium. According to Sari et al. (1998), the cooling frequency, the frequency of electrons with Lorentz factor of $\gamma_e$ that cool on the dynamical time of the shock, is given by

$$\nu_\text{c} = \frac{\gamma \nu_\text{em}}{1 + z} \frac{eB'}{2\pi m_e c},$$

$$= 1.9 \times 10^{32} \epsilon_e^{1/2} E_{54}^{-1/2} n_5^{-1/2} t_{day}^{1/2},$$

$$\times [(1 + z)/2.6]^{-1/2} \text{ Hz},$$

where $\sigma_T$ is the Thompson scattering cross section. From equations (2) and (3), Sari et al. (1998) have further derived two critical times, when the breaking frequencies $\nu_\text{em}$ and $\nu_\text{c}$ cross the observed frequency $\nu = \nu_{15} \times 10^{15}$ Hz: $t_{15} = 8.6 \times 10^{-5} \epsilon_e^{-1} \epsilon_{B,54}^{-1/3}[(1 + z)/2.6]^{1/3} \nu_{15}^{2/3}$ days, and $t_c = 380 \epsilon_e^{-1} \epsilon_{B,54}^{-1/3}[(1 + z)/2.6]^{-1/3} \nu_{15}^{2/3}$ days. Therefore, we see that for $E_{54} \sim 1.6$, $\epsilon_e \sim 0.1$, $\epsilon_{B,54} \sim 0.02$, and $n_5 \sim 30$ inferred in the next section, the optical afterglow in several days after the burst should result from those slowly cooling electrons and the X-ray afterglow from those fast-cooling electrons.

The observed synchrotron radiation peak flux can be obtained by

$$F_\nu = \frac{N_e \nu^p \nu_{15}^{p/4}}{4\pi D_l^2},$$

$$= 4.2 \epsilon_e^{1/2} \epsilon_{B,54}^{1/2} E_{54}^{1/2}(1 + z)/2.6)D_{L,28}^2 \text{ Jy},$$

where $N_e$ is the total number of swept-up electrons, $\nu^p = m_e c^2 \sigma_T B'(3e)$ is the radiated power per electron per unit frequency in the frame comoving with the shocked medium, and $D_l = D_{L,28} \times 10^{28}$ cm is the distance to the source. In the light of equations (2)–(4), one can easily find the spectrum and light curve of the afterglow,

$$F_\nu = \left( \frac{\nu \nu_{15}^{-1/4}}{\nu_{15}^{p/4}} \right)^{-1/2} F_{\nu_{15}} \propto \nu^{-p/2} t_{day}^{(2 - 3p)/2}, \nu < \nu_\text{c};$$

$$\left( \frac{\nu \nu_{15}^{-1/4}}{\nu_{15}^{p/4}} \right)^{-1/2} F_{\nu_{15}} \propto \nu^{p/2} t_{day}^{(2 - 3p)/2}, \nu > \nu_\text{c},$$

where the low-frequency radiation component has not been considered (Sari et al. 1998). In the GRB 990123 case, we require $\nu_c < \nu < \nu_\text{c}$ for the optical afterglow and $\nu > \nu_c$ for the X-ray afterglow. Thus, the R-band afterglow decay index $\alpha_R = 3(1 - p)/4$ and the X-ray decay index $\alpha_X = (2 - 3p)/4$, which are quite consistent with the observational results $\alpha_{R,I} = 1.1 \pm 0.03$ and $\alpha_{X,I} = -1.44 \pm 0.07$ if $p \approx 2.56$.

2.2. Nonrelativistic Phase

Since it sweeps up sufficient ambient matter, the shock will eventually go into a nonrelativistic phase. During such a phase, the shock’s velocity $\nu \propto t_{day}^{3/5}$, its radius $r \propto t_{day}^{2/5}$, the internal field strength $B' \propto t_{day}^{3/5}$, and the typical electron Lorentz factor $\gamma_e \propto t_{day}^{3/5}$. Thus, we obtain the synchrotron peak frequency $\nu_e \propto \gamma_e^2 B' \propto t_{day}^{3/5}$, the cooling frequency $\nu_e \propto B'^{-3} \propto t_{day}^{-3/5}$, and the peak flux $F_e \propto N_e P_e \propto r B' \propto t_{day}^{3/5}$. According to these scaling laws, we further derive the spectrum and light curve at the nonrelativistic stage:

$$F_\nu = \left( \frac{\nu \nu_{15}^{-1/4}}{\nu_{15}^{p/4}} \right)^{-1/2} F_{\nu_{15}} \propto \nu^{-p/2} t_{day}^{(2 - 3p)/2}, \nu < \nu_\text{c};$$

$$\left( \frac{\nu \nu_{15}^{-1/4}}{\nu_{15}^{p/4}} \right)^{-1/2} F_{\nu_{15}} \propto \nu^{p/2} t_{day}^{(2 - 3p)/2}, \nu > \nu_\text{c}.$$
From equation (6), we can see the R-band decay index \( \alpha_g = (21 - 15p)/10 \) for radiation from slowly cooling electrons or \( \alpha_g = (4 - 3p)/2 \) for radiation from rapidly cooling electrons. If \( p \approx 2.56 \), then \( \alpha_g \approx -1.74 \) or \( -1.84 \), in excellent agreement with the observations in the time interval of 2.5–20 days after the burst (Kulkarni et al. 1999a; Fruchter et al. 1999b; Castro-Tirado et al. 1999).

3. CONSTRAINTS ON PARAMETERS

In the above section, we show that as an adiabatic shock expands in a dense medium from an ultrarelativistic phase to a nonrelativistic phase, the decay of the radiation from such a shock will steepen. This effect may fit the observed steepening better than the alternative interpretation—jet sideways expansion. In the latter interpretation, the temporal decay of a late afterglow is very likely to be proportional to \( t_{\text{gw}}^{-\gamma} \) (Rhoads 1997, 1999; Sari et al. 1999). We further analyze our effect and infer some parameters of the model.

According to the analysis on the R-band light curve of the GRB 990123 afterglow (Kulkarni et al. 1999a; Fruchter et al. 1999b; Castro-Tirado et al. 1999), the observed break occurred at \( t_{\text{gw}} = 2.04 \pm 0.46 \) days. This implies \( \gamma \approx 1 \) at \( t_{\text{gw}} \approx 2.5 \). From equation (1), therefore, we find \( n_s \sim 16E_{54}^{1.5} \), where the redshift \( z = 1.6 \) has been used. We now continue to consider two observational results. First, on January 23.577 UT, the Palomar 60 inch (1.5 m) telescope detected the R-band magnitude \( R = 18.65 \pm 0.04 \), corresponding to the flux \( F_R \sim 100 \mu\text{Jy} \) at \( t_{\text{gw}} \approx 0.17 \) (Kulkarni et al. 1999a). Considering this result in equation (5) together with equations (2) and (4), we can derive

\[
\epsilon_g^{-1} \epsilon_{\text{gw}, -6} E_{54}^{-1} \sim 0.01, 
\]

where the number on the right-hand side has been obtained by taking \( p \approx 2.56 \) and \( D_{L, 28} \approx 3.7 \). Second, on January 24.65 UT, BeppoSAX observed the X-ray (2–10 keV) flux \( F_E \sim 5 \times 10^{-2} \mu\text{Jy} \) (Heise et al. 1999a, 1999b). Combining this result with equations (2)–(5), we can also derive

\[
\epsilon_g^{-1} \epsilon_{\text{gw}, -6} E_{54}^{-2} \sim 0.03. 
\]

Since \( E_{54} \approx 1.6 \) (Briggs et al. 1999; Kulkarni et al. 1999a), the medium density \( n_s \sim 30 \) and the solution of equations (7) and (8) is \( \epsilon_g \sim 0.1 \) and \( \epsilon_{\text{gw}, -6} \sim 0.02 \). Our inferred value of \( \epsilon_g \) is near the equipartition value, in agreement with the result of Wijers & Galama (1999) and Granot, Piran, & Sari (1999), while our \( \epsilon_{\text{gw}, -6} \) is about 6 orders of magnitude smaller than the value inferred from the afterglow of GRB 970508. Of course, the field density for GRB 971214 has been estimated to be less than \( 10^{-15} \) times the equipartition value (Wijers & Galama 1999). As suggested by Galama et al. (1999), such differences in field strength may reflect differences in energy flow from the central engine.

4. DISCUSSION AND CONCLUSION

In the above section, we find the medium density \( n \sim 3 \times 10^6 \text{ cm}^{-3} \) for our model to fit the observed optical and X-ray afterglow of GRB 990123. Now we show that even in the presence of such a dense medium, the optical and X-ray radiations from the forward shock were neither self-absorbed in the shocked medium nor scattered in the unshocked medium. First, the self-absorption frequency of the shocked medium is \( \nu_s \sim 10^1 \text{ GHz}(\epsilon_g/0.1)^{-1} (\epsilon_{\text{gw}, -6}/0.01)^{1/2} E_{54}^{1/2} (n_s/10)^{5/8} \) (Wijers & Galama 1999; Granot et al. 1998). This estimate should be the upper limit because of the presence of a possible low-energy electron population (Waxman 1997b). Clearly, \( \nu_s \) is much less than the optical frequency, implying that the self-absorption in the shocked medium did not affect the optical and X-ray afterglow. In fact, this estimate is valid only for \( \nu_s \ll \nu_r \). When \( \nu_s > \nu_r \), \( \nu_r \) must have decayed. As a result, the flux at 8.46 GHz first increased as \( t_{\text{gw}}^{-0.74} \) and then declined as \( t_{\text{gw}}^{-0.5} \) for \( \nu_s < 8.46 \text{ GHz} \) during the nonrelativistic phase. This might provide an explanation for the observed radio flare. Second, a photon emitted from the shock may be scattered by the electrons in the unshocked medium. The scattering optical depth \( \tau \approx \sigma_t n_R \) (where \( R \) is the typical radius of the medium). If the medium was distributed isotropically and homogeneously and its mass \( M \sim 10 M_\odot \) (the typical mass of a supernova ejecta), then \( \tau \approx 0.05(10 M_\odot)^{0.3}(n_s/10)^{-0.3} \ll 1 \). This implies that the afterglow from the shock was hardly affected by the medium.

For other well-studied afterglows, e.g., GRB 970228 and GRB 970508, their ambient densities must be very low for three reasons: (1) In these bursts there was no observed break in the optical light curve as long as the afterglow could be observed (Fruchter et al. 1999a; Zharikov, Sokolov, & Baryshev 1998). (2) The fluctuation appearing in the radio afterglow light curve of GRB 970508 requires that the shock had been relativistic for several weeks (Waxman, Kulkarni, & Frail 1998). (3) The analysis of the afterglow spectrum of GRB 970508 leads to a low ambient density \( n < 10^3 \text{ cm}^{-3} \) (Wijers & Galama 1999; Granot et al. 1998). However, the observed iron emission line in the X-ray afterglow spectrum of GRB 970508 indeed requires a dense medium with density \( \sim 10^5 \text{ cm}^{-3} \) (Lazzati et al. 1999). The only way to reconcile a power-law afterglow that lasts a few months with iron line emission is through a particular geometry, in which the line of sight is devoid of the dense medium. In contrast to this idea, we suggest that for GRB 990123 a dense medium of \( n \sim 3 \times 10^6 \text{ cm}^{-3} \) appears at least at the line of sight or perhaps isotropically.

How was the dense medium produced? One possibility was a cloud, and another possibility was an ejecta from the GRB site. There have been several source models (mentioned in § 1) in the literature that may lead to massive ejecta. Here we want to discuss one of them in detail. Timmes, Woosley, & Weaver (1996) showed that Type II supernovae may produce a kind of neutron star with \( \sim 1.73 M_\odot \). If these massive neutron stars have very short periods at birth, they may subsequently convert into strange stars because of rapid loss of angular momenta (Cheng & Dai 1998), and perhaps the strange stars are differentially rotating (Dai & Lu 1998b). Even though this model is somewhat similar to the supernova model of Vietri & Stella (1998), resultant compact objects are strange stars in our model and black holes in the supernova model. We further discuss implications of our model. First, the model leads to low-mass loading matter because of thin baryonic crusts of the strange stars. Second, such stars result in GRBs with spiky light curves, being consistent with the analytical result from the observed data of GRB 990123 (Fenimore, Ramirez-Ruiz, & Wu 1999). The third advantage of this model is to be able to explain well the property of the early afterglow of GRB 970508 by considering energy injection from the central pulsar (Dai & Lu 1998b, 1998c). Finally, a dense medium, the supernova ejecta, appears naturally.

Our scenario proposed in this Letter requires a dense medium with density \( \sim 3 \times 10^6 \text{ cm}^{-3} \) to explain the steepening in the temporal decay of the \( R \)-band afterglow about 2.5 days after GRB 990123. We also suggest that this medium could be a supernova/supranova/hypernova ejecta. Thus, if the mass of
the medium is assumed to be \( M \sim 10 M_\odot \), its radius can be estimated to be \( R \sim 3 \times 10^{17} \text{ cm} (M/10 M_\odot)^{1/3} (n_e/10)^{-1/3} \). According to equation (1), we can integrate over \( dr = 2\gamma^2 c \, dt \) and thus find that the postburst 2.5 day time in the observer’s frame corresponds to about 20 days in the unshocked medium’s frame. This implies that the radius at which the shock entered a nonrelativistic phase is about \( 5 \times 10^{16} \text{ cm} \). This radius is much less than that of the medium. Therefore, the medium discussed here was so wide and dense that the ultrarelativistic shock must have become nonrelativistic about 2.5 days after the burst.

In summary, a simple explanation for the “steepening” observed in the temporal decay of the late \( R \)-band afterglow of GRB 990123 is that a shock expanding in a dense medium with density of \( \sim 10^{17} \text{ cm}^{-3} \) has evolved from a relativistic phase to a nonrelativistic phase. We find that this scenario not only explains well the optical afterglow, but also accounts for the observed X-ray afterglow quantitatively.

We would like to thank J. I. Katz, S. R. Kulkarni, A. Mitra, and the anonymous referee for invaluable suggestions and Y. F. Huang and D. M. Wei for helpful discussions. This work was supported by the National Natural Science Foundation of China (grants 19825109 and 19773007).

### REFERENCES

Akerlof, C. W., et al. 1999, Nature, 398, 400
Andersen, M. I., et al. 1999, Science, 283, 2075
Blandford, R. D., & McKee, C. F. 1976, Phys. Fluids, 19, 1130
Briggs, M. S., et al. 1999, ApJ, submitted (astro-ph/9903247)
Castro-Tirado, A. J., et al. 1999, Science, 283, 2069
Cheng, K. S., & Dai, Z. G. 1998, Phys. Rev. Lett., 80, 18
Chiang, J., & Dermer, C. D. 1998, preprint (astro-ph/9803339)
Cohen, E., Piran, T., & Sari, R. 1998, ApJ, 509, 717
Dai, Z. G., Huang, Y. F., & Lu, T. 1999, ApJ, in press
Dai, Z. G., & Lu, T. 1998a, MNRAS, 298, 27
———, 1999b, Phys. Rev. Lett., 81, 4301
Fenimore, E. E., Ramirez-Ruiz, E., & Wu, B. 1999, preprint (astro-ph/9902007)
Feroci, M., et al. 1999, IAU Circ. 7095
Fruchter, A. S., et al. 1999a, ApJ, 516, 683
———, 1999b, preprint (astro-ph/9902236)
Galama, T. J., et al. 1999, Nature, 398, 394
Granot, J., Piran, T., & Sari, R. 1998, preprint (astro-ph/9808007)
Heise, J., et al. 1999a, IAU Circ. 7099
———, 1999b, Nature, in press
Huang, Y. F., Dai, Z. G., & Lu, T. 1998, A&A, 336, L69
Huang, Y. F., Dai, Z. G., Wei, D. M., & Lu, T. 1998, MNRAS, 298, 459
Katz, J. I. 1994, ApJ, 432, L27
Katz, J. I., & Piran, T. 1997, ApJ, 490, 772
Kulkarni, S. R., et al. 1999a, Nature, 398, 389
———, 1999b, preprint (astro-ph/9903441)
Lazzati, D., Campana, S., & Ghisellini, G. 1999, MNRAS, 304, L31
Mészáros, P., & Rees, M. J. 1997, ApJ, 476, 232
Mészáros, P., & Rees, M. J. 1999, MNRAS, in press (astro-ph/9902367)
Paciesa, B. 1998, ApJ, 494, L45
Panaitescu, A., & Mészáros, P. 1998, ApJ, 492, 683
Panaitescu, A., Mészáros, P., & Rees, M. J. 1998, ApJ, 503, 314
Pen, U.-L., & Loeb, A. 1998, ApJ, 500, 537
Piran, T. 1999, Phys. Rep., in press (astro-ph/9810256)
Piro, L. et al. 1999, ApJ, 514, L73
Reichart, D. E. 1997, ApJ, 485, L57
Rhoads, J. 1997, ApJ, 487, L1
———, 1999, ApJ, submitted (astro-ph/9903399)
Sari, R. 1997, ApJ, 489, L37
Sari, R., & Piran, T. 1999, preprint (astro-ph/9902009)
Sari, R., Piran, T., & Halpern, J. P. 1999, preprint (astro-ph/9903339)
Sari, R., Piran, T., & Narayan, R. 1998, ApJ, 497, L17
Shi, X. D., & Guzik, G. 1999, preprint (astro-ph/9903023)
Timmes, F. X., Woosley, S. E., & Weaver, T. A. 1996, ApJ, 457, 834
Vietri, M. 1997, ApJ, 488, L105
Vetri, M., & Stella, L. 1998, ApJ, 507, L45
Waxman, E. 1997a, ApJ, 485, L5
———, 1997b, ApJ, 489, L33
Waxman, E., Kulkarni, S. R., & Frair, D. A. 1998, ApJ, 497, 288
Wijers, R. A. M. J., & Galama, T. J. 1999, ApJ, in press (astro-ph/9805341)
Wijers, R. A. M. J., Rees, M. J., & Mészáros, P. 1997, MNRAS, 288, L51
Woosley, S. 1993, ApJ, 405, 273
Yoshida, A., et al. 1999, ApJ, submitted
Zharikov, S. V., Sokolov, V. V., & Baryshev, Yu. V. 1998, A&A, 337, 356