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GENERAL RELATIVISTIC BINARY MERGER SIMULATIONS AND SHORT GAMMA-RAY BURSTS

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ABSTRACT

The recent localization of some short-hard gamma-ray bursts (GRBs) in galaxies with low star formation rates has lent support to the suggestion that these events result from compact object binary mergers. We discuss how new simulations in general relativity are helping to identify the central engine of short-hard GRBs. Motivated by our latest relativistic black hole–neutron star merger calculations, we discuss a scenario in which these events may trigger short-hard GRBs and compare this model to competing relativistic models involving binary neutron star mergers and the delayed collapse of hypermassive neutron stars. Distinguishing features of these models may help guide future GRB and gravitational wave observations to identify the nature of the sources.

Subject headings: black hole physics — gamma rays: bursts — gravitational waves — stars: neutron

1. INTRODUCTION AND OBSERVATIONS

Gamma-ray bursts (GRBs) are short-duration phenomena characterized by time-varying, high-energy, nonthermal electromagnetic emission. On the basis of their duration and energy spectra, they are typically categorized into two categories: "short/hard" and "long/soft" (Kouveliotou et al. 1993). Many optical and X-ray counterparts of long bursts have been seen, some in coincidence with Type Ib/c supernovae, representing extremely energetic collapses of massive stars (Paczyński 1998; Hjorth 2003). By contrast, it has been much more difficult to identify counterparts for short GRBs (SGRBs), except for the known soft gamma repeaters, which may be observed as SGRBs (Palmer et al. 2005) but cannot explain more than a small fraction of the observed SGRB sample (Lazzati et al. 2005; Nakar et al. 2005b).

Recently, the *Swift* and *HETE-2* satellites have localized for the first time the X-ray afterglow following short-period GRBs: GRBs 050509b (Gehrels et al. 2005), 050724 (Barthelmy et al. 2005; Berger et al. 2006), 050813 (Berger 2005), and 051221 (Soderberg et al. 2006) by *Swift*; GRB 050709 (Hjorth et al. 2005; Fox et al. 2005) by *HETE-2*. Details about the physical parameters observed and inferred from these bursts can be found in Berger (2006). In all cases, the inferred host had a rather low star formation rate. This finding disfavors the collapse of a massive star as a progenitor, since those systems have very short lifetimes. Instead, it favors the identification of a compact object binary merger as the progenitor, as originally suggested by Paczyński (1986); a significant fraction of both neutron star–neutron star (NSNS) and black hole–neutron star (BHNS) binaries will take longer than 1 Gyr between formation and merger (Belczynski et al. 2002). Other scenarios, such as the accretion-induced collapse of an NS with a white dwarf companion have been proposed (Dermer & Atoyan 2006) but have not been studied numerically in as much detail.

The observed characteristics of SGRBs can be examined in light of population synthesis calculations for compact object binaries, but it is difficult to disentangle BHNS versus NSNS merger scenarios given the current observational and theoretical uncertainties. The inferred rate of observed SGRBs and the merger rate of their putative sources are consistent, but the latter are uncertain by at least 2 orders of magnitude: $\mathcal{R}_{\rm GRB} \equiv (\Omega/4\pi)\mathcal{R}_m \equiv (\theta^2/2)\mathcal{R}_m$, where θ is the beaming angle. The most recent GRB rate estimates yield $\mathcal{R}_{\rm GRB} \sim 1$–$3\ {\rm Myr}^{-1}$ per Milky Way (Guetta & Piran 2006; Nakar et al. 2005a), over an order of magnitude larger than previous results (Guetta & Piran 2005; Ando 2004). Breaks in the observed X-ray spectra imply $\theta \sim 0.2$–0.3, and thus $\Omega/4\pi = 0.02$–0.05 (Soderberg et al. 2006). The predicted compact object merger rates per Milky Way fall in the range $\mathcal{R}_m \sim 1$–$100\ {\rm Myr}^{-1}$ for NSNS mergers and $\mathcal{R}_m \sim 0.5$–$10\ {\rm Myr}^{-1}$ for BHNS mergers (Voss & Tauris 2003; Belczynski et al. 2002; Kalogera et al. 2004). The rates are uncertain by at least an order of magnitude, and the beaming angle by a factor of a few. An extremely high SGRB rate may indicate that at least some SGRBs are the products of NSNS mergers, as these are much more common than BHNS mergers in population synthesis calculations (Voss & Tauris 2003; Belczynski et al. 2002).

The projected distance from a localized SGRB to the center of its host galaxy is insensitive to whether the merging binary is an NSNS or BHNS system. Recent results show the respective projected distance likelihood functions are nearly the same for large galaxies, and have only minor differences in smaller ones, which would rule out positive identifications based on location alone (Belczynski et al. 2006).

The range of fluxes seen from SGRBs is rather large, indicating that the burst energy must depend sensitively on at least one parameter of the progenitor system. The observed fluxes of SGRBs typically fall in the range 5×10^{-6} to 10^{-4} ergs cm^{-2} s^{-1}, and fluences $10^{-7.5}$ to $10^{-5.5}$ ergs cm^{-2} (Balázs et al. 2003). Assuming a characteristic distance of 1 Gpc, we see that the luminosities L and total energy released E for the burst satisfy $(4\pi/\Omega)L = 10^{50.5}$–$10^{52}$ ergs s^{-1} and $(4\pi/\Omega)E = 10^{48.5}$–$10^{50.5}$ ergs, respectively.

The first localized short burst, GRB 050509b, has an extremely low measured isotropic energy in γ-rays, $E_\gamma = 3 \times 10^{48}(\Omega/4\pi)$ ergs, compared to previously observed SGRBs. If we assume that the GRB is at the measured redshift of $z = 0.225$, the luminosity of the burst is actually similar to the other localized bursts, $\sim 10^{50}$ ergs s^{-1}, but it lasted for a much shorter time. In general, as we see from Table 1 of Janka et al. (2006), there is significantly smaller variation in the peak luminosity than in the isotropic energy output.

We note that the low energy for GRB 050509b argues for an extremely low density of baryons surrounding the GRB. Typically, it is assumed that the Lorentz factor of the jet Γ will

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be no bigger than the ratio η of the energy in the jet to the rest energy of the baryons through which it must travel, i.e., $\Gamma \leq \eta \equiv E_\gamma/M_b c^2$ (Shemi & Piran 1990). For GRB 050509b, the least energetic of the observed bursts, assuming the Lorentz factor $\Gamma \gtrsim 100$ (Oechslin & Janka 2006) implies that at most $10^{-8}(\Omega/4\pi)\ M_\odot$ of material can surround the progenitor. These results are confirmed by the numerical calculations of Aloy et al. (2005), who find that the density of baryons surrounding the burst must fall rapidly with increasing radius. For sufficiently large baryonic loading, they find the observational counterpart to a merger is not a GRB.

2. PROGENITOR MODELS: THEORETICAL AND OBSERVATIONAL CONSTRAINTS

Standard models for merger-induced short-duration GRBs involve hot, massive accretion disks ($M > 0.01\ M_\odot$) around spinning BHs (see Piran 2005 for a thorough review). As the disk is accreted, one of two possible mechanisms is responsible for the creation of a gamma-ray jet. One suggestion is that the hot material emits neutrino-antineutrino pairs that annihilate above and below the disk to produce a relativistic jet containing e^--e^+ pairs and photons (see, e.g., Paczyński 1986; Goodman et al. 1987). Calculations of accreting disks have shown that they can generate sufficient energy to power a GRB (Popham et al. 1999). The viscosity in the disk primarily determines the timescale of the resulting burst (Narayan et al. 2001), while the mass of the BH may determine the overall energy scale (Popham et al. 1999). These results are supported by Setiawan et al. (2004, 2005), who find that the viscosity (and to a lesser extent, BH spin and disk mass) is responsible for determining the overall burst energy. Roughly speaking, luminosities of up to 10^{50} ergs s^{-1} can be produced, so long as the disk is sufficiently massive (representing 5% of the total binary mass) and the effective viscosity sufficiently strong ($\alpha = 0.1$).

Alternatively, general relativistic (GR) magnetohydrodynamic (MHD) effects may allow infalling matter to tap the spin energy of a BH via the Blandford-Znajek effect to produce an energetic jet (Blandford & Znajek 1977). In this case, the crucial parameters to determine the energetics are the mass accretion rate and the spin of the BH. A review of GRB models tapping spin energy can be found in Zhang & Mészáros (2004).

2.1. *Neutron Star–Neutron Star Binaries and Hypermassive Remnants*

There has been a great deal of numerical work performed to study merging NSNS binaries, including recent calculations performed using fully GR hydrodynamics and physically realistic nuclear equations of state (EOSs; Shibata et al. 2005; Shibata & Taniguchi 2006). From these results, two separate channels have been identified that could lead from a merger to the production of an SGRB.

If the total binary mass is below some critical threshold, $M_{\rm thr}$, a differentially rotating hypermassive neutron star (HMNS) can be formed that is initially stable against gravitational collapse, even though its mass is above the maximum value for uniformly rotating configurations (Baumgarte et al. 2000; Morrison et al. 2004). Delayed gravitational collapse follows, triggered either by gravitational wave dissipation if the remnant forms a bar or by magnetic redistribution of angular momentum (Baumgarte et al. 2000; Shapiro 2000; Cook et al. 2003; Duez et al. 2006; M. D. Duez et al. 2006, in preparation; Shibata et al. 2006). The numerical simulations of Shibata et al. use a stiff, realistic EOS (Akmal et al. 1998), for which the maximum mass is slightly higher than the highest measured pulsar mass, $M = 2.1 \pm 0.2\ M_\odot$ for PSR J0751$-$1807 (Nice et al. 2005). These simulations set a lower limit for the critical mass $M_{\rm thr} \gtrsim 2.7\ M_\odot$. This exceeds all known NSNS binaries containing a radio pulsar, with the possible exception of PSR 1913+16 ($M_{\rm tot} = 2.83\ M_\odot$; Stairs 2004). Thus, it appears that HMNS formation is likely in most merging NSNS binaries. MHD simulations in full GR show that the HMNS undergoes a delayed collapse, resulting in a hot, magnetized torus surrounding a rotating BH, together with a magnetic field collimated along the polar axis. These conditions are favorable for a burst powered by either neutrino annihilation or MHD effects (Duez et al. 2006; M. D. Duez et al. 2006, in preparation; Shibata et al. 2006).

Alternatively, for higher mass NSs, mergers with binary mass ratios sufficiently far from unity might lead to the formation of a relatively massive disk around a BH formed promptly during the merger (Shibata & Taniguchi 2006). For mass ratios $q \sim 0.7$, disk masses of 0.01–0.1 $M_\odot$ are possible, whereas more equal-mass mergers produce much lower mass disks, with insufficient thermal energy to power an SGRB (Shibata et al. 2005).

The key unanswered question for the HMNS scenario is whether “baryon pollution” from merger ejecta along the polar axis can be cleared out of the funnel through which the presumed GRB jet will propagate. Relativistic numerical calculations (Duez et al. 2006; M. D. Duez et al. 2006, in preparation; Shibata et al. 2006) indicate that MHD effects seem to be sufficient to accomplish this task, producing baryon densities along the polar axis that satisfy the constraints described in Shemi & Piran (1990). For the unequal-mass NSNS merger case, the polar axis is essentially free of intervening matter, but the likelihood of this scenario depends on how far from unity binary mass ratios are likely to fall, as all observed systems containing radio pulsars have $q \gtrsim 0.9$. Systems with components too close together in mass produce significantly lower mass disks, which lack the required neutrino luminosity to power the SGRB (Shibata & Taniguchi 2006).

2.2. *Black Hole–Neutron Star Binaries*

The defining parameter for determining the qualitative evolution of a BHNS merger is the binary mass ratio $q \equiv M_{\rm NS}/M_{\rm BH}$. If we assume that the tidal disruption of the NS begins at a separation $a_{\rm R}$ where its volume in isolation is equal to the volume of its Roche lobe,

$$a_{\rm R}/M_{\rm BH} = 2.17 q^{2/3}(1+q)^{1/3}\mathcal{C}^{-1} \quad (1)$$

for an NS of compactness $\mathcal{C} \equiv M_{\rm NS}/R_{\rm NS}$ (Paczyński 1971), using geometrized units with $G = c = 1$. For a sufficiently large BH (and thus small q), $a_{\rm R}$ is smaller than the innermost stable circular orbit (ISCO) $a_{\rm ISCO}$, so that the NS passes through the ISCO before being disrupted tidally. For a typical NS of compactness $\mathcal{C} = 0.15$, the critical mass ratio at which tidal disruption occurs at $a_{\rm ISCO}$ is approximately $q = 0.24$. It has been argued that even for this “fiducial” binary the rapid plunge timescale at the ISCO might prevent significant disk formation (Miller 2005). Our simulations suggest, however, that rapid angular momentum transfer during tidal disruption ejects a significant fraction of the matter back outside the ISCO, leading to a sizable disk. Clearly, a detailed understanding of this dynamical process requires an accurate description of the strong field BHNS spacetime, as we discuss below.

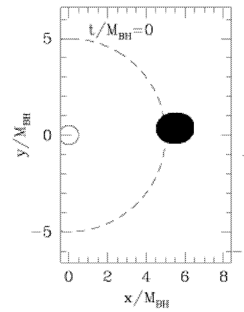

FIG. 1.—Initial (*left*), early (*center*), and intermediate (*right*) configurations of the NS in case B, projected into the orbital plane. The NS has a compactness $M/R = 0.09$, and the binary mass ratio is $M_{NS}/M_{BH} = 0.1$. We see the NS disrupts near the ISCO (*dashed curve*) to produce a single mass transfer stream, which eventually wraps around the BH (*solid curve*) to form a torus. The initial orbital period is $P = 105M_{BH}$.

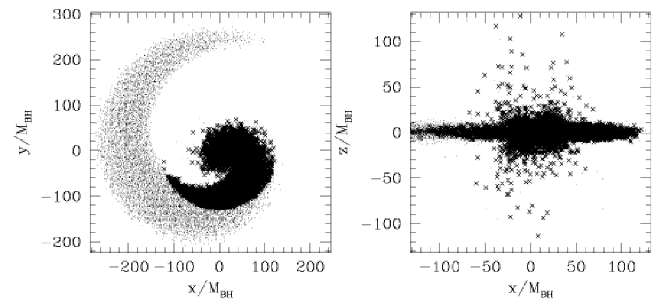

FIG. 2.—Matter configuration at the end of the simulation, $T = 990M_{BH}$, projected onto the equatorial (*left panel*) and meridional (*right panel*), showing the hot torus located within $r < 50M_{BH}$. Bound fluid elements (satisfying $u_0 - 1 < 0$ are shown as crosses, unbound elements as points. Note the different scales.

We performed 3+1-dimensional smoothed particle hydrodynamics calculations of BHNS mergers in the conformal flatness (CF) approximation to GR (Faber et al. 2006, hereafter FBSTR). For a Schwarzschild BH, our scheme identifies including the relativistic ISCO exactly and accounts for relativistic dynamics within the ISCO, unlike previous pseudo-Newtonian calculations (Lee & Kluźniak 1999; Janka et al. 1999; Rosswog et al. 2004, 2005). We adopt the relativistic, irrotational binary models of Taniguchi et al. (2005) as initial data. Our adiabatic evolution scheme is the same as that described in FBSTR, but we solve the coupled nonlinear elliptic field equations of the CF scheme using an iterative fast Fourier transform convolution–based solver and add artificial viscosity to the hydrodynamical equations in order to study the shock heating of the material during the merger process (compare Hernquist & Katz 1989). Both the initial data and the evolution scheme represent the state of the art for including NS self-gravity self-consistently within a GR hydrodynamical formalism.

We consider two models, both containing $n = 1$ polytropic NS. First is an NS of compactness 0.15, denoted "case A." As in FBSTR, our current method is limited to extreme mass ratios, so we choose $q = 0.1$, for which $a_R = 3.2M_{BH}$ according to equation (1). We cannot directly simulate the fiducial case ($q = 0.24$, $\mathcal{C} = 0.15$) under these assumptions, so we take an alternate approach for our second calculation. Simultaneously reducing the mass ratio to $q = 0.1$ and the NS compactness to $\mathcal{C} = 0.09$ leaves a_R/M_{BH} virtually unchanged. From the argument above, this binary, denoted "case B," should tidally disrupt slightly within the ISCO, mimicking the dynamics of the fiducial binary.

The evolution of case A is straightforward and probably uninteresting as an SGRB source: the entire NS spirals toward the BH, and no matter is ejected outside the ISCO to form an accretion disk. Case B, on the other hand, does lead to the formation of an accretion disk, as we show in Figure 1. Note that radii are measured in isotropic coordinates, in which the BH radius is $r_{BH} = 0.5M_{BH}$ and the ISCO radius $a_{ISCO} \approx 5M_{BH}$. We see that while the NS inspirals until 98% of its mass lies within the ISCO, rapid redistribution of angular momentum during tidal disruption causes an outwardly directed spiral arm to form, sending some matter back outside the ISCO.

Eventually, the BH accretes $M_{acc} \approx 0.75M_{NS}$ directly, while part of the remaining mass forms a disk of mass $M_{disk} \approx 0.12M_{NS}$ and part is ejected completely from the system ($M_{ej} \approx 0.13M_{NS}$). Here we distinguish bound and unbound trajectories by the sign of $u_0 - 1$, where u_0 is the time component of the matter 4-velocity, which remains nearly constant in time for outflowing gas on approximately geodesic trajectories. We note that this configuration satisfies all the geometric constraints required for a GRB progenitor, as all matter lies in the equatorial plane rather than the polar axis.

The bound matter in the disk is relatively cold at first, as the matter in the arm is initially ejected without strong shock heating. Over time, this disk generates heat via shocks as matter falls back and wraps around the BH forming a torus out to a radius of $r \sim 50M_{BH}$ within $t = 1000M_{BH} \sim 0.07$ s (see Fig. 2). The specific internal energy in the inner part of the torus corresponds to a temperature $T \approx$ 3–10 MeV $\approx (2–7) \times 10^{10}$ K (see Fig. 3). The surface density in this region is $\Sigma \approx (2–3) \times 10^{17}$ g cm^{-2}. Assuming an opacity $\kappa = 7 \times 10^{-17}(T/10^{11}\ \mathrm{K})^2$ (Di Matteo et al. 2002), we conclude that the disk is optically thick out to $r \sim 15M$. Using the diffusion limit, the neutrino flux is given by $F_\nu \approx (7N_\nu/3)(\sigma T^4/\kappa\Sigma)$, where $N_\nu = 3$ is the number of neutrino families and σ is the Stefan-Boltzmann constant. The neutrino luminosity is $L_\nu \approx 2\pi r^2 F_\nu \sim 10^{54}$ ergs s^{-1}. This value is roughly an order of magnitude larger than that seen in the collapse of an HMNS (Shibata et al. 2006) and should produce at least a comparable annihilation luminosity, $L_{\nu\bar{\nu}} \sim 10^{49}$–$10^{50}$ ergs s^{-1}.

Qualitatively, the hot torus described here is similar both to the initial data used to study hydrodynamic disk evolution in earlier GRB models (Setiawan et al. 2004, 2005; Aloy et al. 2005) as well as to that formed by the collapse of an HMNS

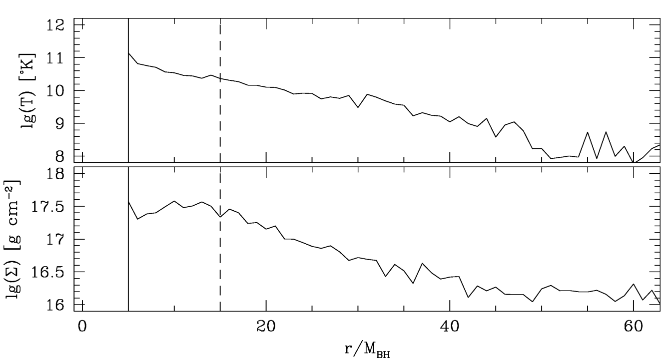

FIG. 3.—Temperature T and surface density Σ as a function of cylindrical radius for the configuration shown in Fig. 2. The solid vertical line denotes the ISCO, and the dashed line the transition radius between matter optically thick to neutrinos within and optically thin outside.

(Shibata et al. 2006; M. D. Duez et al. 2006, in preparation). However, we note that the torus described here is physically larger. Unlike previous pseudo-Newtonian calculations of BHNS mergers (Janka et al. 1999; Lee & Kluźniak 1999; Rosswog et al. 2004), we find prompt disruption of the NS during the plunge (rather than an NS core that survives the initial mass-loss phase) and a lower mass disk, but at a temperature similar to those calculations that included a detailed microphysical treatment (Janka et al. 1999).

While we do not follow the long-term evolution of the accretion torus and surrounding material, we can estimate the fallback time for the bound component, assuming geodesic orbits. Approximately $0.03M_{NS}$ should return back toward the BH on timescales equal to or longer than a second, which could in principle produce lower energy bursts at later times. It is conceivable that this fallback accretion might explain the secondary X-ray flares observed in SGRBs many seconds after the initial burst (see Berger 2006 for a summary of the observations), especially if self-gravity leads to the formation of higher density clumps of material, but further simulations are required to establish this identification.

Future observations should help to determine which progenitor candidates are responsible for the observed SGRB population. Gravitational wave measurements would provide important evidence if detected in coincidence: a GRB resulting from hypermassive collapse would occur noticeably delayed relative to the gravitational wave signal from the inspiral and plunge phases of nearly equal mass objects, whereas one resulting from a BHNS binary would occur almost immediately after the signal from a very unequal mass merger.

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REFERENCES

Akmal, A., Pandharipande, V. R., & Ravenhall, D. G. 1998, Phys. Rev. C, 58, 1804
Aloy, M. A., Janka, H.-T., & Müller, E. 2005, A&A, 436, 273
Ando, S. 2004, J. Cosmology Astropart. Phys., 6, 7
Balázs, L. G., Bagoly, Z., Horváth, I., Mészáros, A., & Mészáros, P. 2003, A&A, 401, 129
Barthelmy, S. D., et al. 2005, Nature, 438, 994
Baumgarte, T. W., Shapiro, S. L., & Shibata, M. 2000, ApJ, 528, L29
Belczynski, K., Bulik, T., & Rudak, B. 2002, ApJ, 571, 394
Belczynski, K., Perna, R., Bulik, T., Kalogera, V., Ivanova, N., & Lamb, D. Q. 2006, ApJ, submitted (astro-ph/0601458)
Berger, E. 2005, GCN Circ. 3801, http://gcn.gsfc.nasa.gov/gcn/gcn3/3801.gcn3
———. 2006, in Gamma-Ray Bursts in the *Swift* Era, ed. S. Holt, N. Gehrels, & J. Nousek (New York: AIP), in press (astro-ph/0602004)
Berger, E., et al. 2006, Nature, 438, 988
Blandford, R. D., & Znajek, R. L. 1977, MNRAS, 179, 433
Cook, J. N., Shapiro, S. L., & Stephens, B. C. 2003, ApJ, 599, 1272
Dermer, C. D., & Atoyan, A. 2006, ApJL, submitted (astro-ph/0601142)
Di Matteo, T., Perna, R., & Narayan, R. 2002, ApJ, 579, 706
Duez, M. D., Liu, Y. T., Shapiro, S. L., Shibata, M., & Stephens, B. C. 2006a, Phys. Rev. Lett., 96, 031101
Faber, J. A., Baumgarte, T. W., Shapiro, S. L., Taniguchi, K., & Rasio, F. A. 2006, Phys. Rev. D, 73, 024012 (FBSTR)
Fox, D. B., et al. 2005, Nature, 437, 845
Gehrels, N., et al. 2005, Nature, 437, 851
Goodman, J., Dar, A., & Nussinov, S. 1987, ApJ, 314, L7
Guetta, D., & Piran, T. 2005, A&A, 435, 421
———. 2006, in Gamma-Ray Bursts in the *Swift* Era, ed. S. Holt, N. Gehrels, & J. Nousek (New York: AIP), in press (astro-ph/0602208)
Hernquist, L., & Katz, N. 1989, ApJS, 70, 419
Hjorth, J. 2003, Nature, 423, 847
Hjorth, J., et al. 2005, Nature, 437, 859
Janka, H. T., Eberl, T., Ruffert, M., & Fryer, C. L. 1999, ApJ, 527, L39
Janka, H. T., Mazzali, P. A., Aloy, M. A., & Pian, E. 2006, ApJ, in press (astro-ph/0509722)
Kalogera, V., et al. 2004, ApJ, 601, L179
Kouveliotou, C., Meegan, C. A., Fishman, G. J., Bhat, N. P., Briggs, M. S., Koshut, T. M., Paciesas, W. S., & Pendleton, G. N. 1993, ApJ, 413, L101
Lazzati, D., Ghirlanda, G., & Ghisellini, G. 2005, MNRAS, 362, L8
Lee, W. H., & Kluźniak, W. 1999, ApJ, 526, 178
Miller, M. C. 2005, ApJ, 626, L41
Morrison, I. A., Baumgarte, T. W., & Shapiro, S. L. 2004, ApJ, 610, 941
Nakar, E., Gal-Yam, A., & Fox, D. B. 2005a, preprint (astro-ph/0511254)
Nakar, E., Gal-Yam, A., Piran, T., & Fox, D. B. 2005b, preprint (astro-ph/0502148)
Narayan, R., Piran, T., & Kumar, P. 2001, ApJ, 557, 949
Nice, D. J., Splaver, E. M., Stairs, I. H., Löhmer, O., Jessner, A., Kramer, M., & Cordes, J. M. 2005, ApJ, 634, 1242
Oechslin, R., & Janka, H. T. 2006, MNRAS, in press (astro-ph/0507099)
Paczyński, B. 1971, ARA&A, 9, 183
———. 1986, ApJ, 308, L43
———. 1998, ApJ, 494, L45
Palmer, D. M., et al. 2005, Nature, 434, 1107
Piran, T. 2005, Rev. Mod. Phys., 76, 1143
Popham, R., Woosley, S. E., & Fryer, C. 1999, ApJ, 518, 356
Rosswog, S. 2005, preprint (astro-ph/0505007)
Rosswog, S., Speith, R., & Wynn, G. A. 2004, MNRAS, 351, 1121
Setiawan, S., Ruffert, M., & Janka, H.-T. 2004, MNRAS, 352, 753
———. 2005, A&A, submitted (astro-ph/0509300)
Shapiro, S. L. 2000, ApJ, 544, 397
Shemi, A., & Piran, T. 1990, ApJ, 365, L55
Shibata, M., Duez, M. D., Liu, Y. T., Shapiro, S. L., & Stephens, B. C. 2006, Phys. Rev. Lett., 96, 031102
Shibata, M., & Taniguchi, K. 2006, Phys. Rev. D, 73, 064027
Shibata, M., Taniguchi, K., & Uryū, K. 2005, Phys. Rev. D, 71, 084021
Soderberg, A. M., et al. 2006, ApJ, submitted (astro-ph/0601455)
Stairs, I. H. 2004, Science, 304, 547
Taniguchi, K., Baumgarte, T. W., Faber, J. A., & Shapiro, S. L. 2005, Phys. Rev. D, 72, 044008
Voss, R., & Tauris, T. M. 2003, MNRAS, 342, 1169
Zhang, B., & Mészáros, P. 2004, Int. J. Mod. Phys. A, 19, 2385