THE LOWEST-MASS STELAR BLACK HOLES: CATASTROPHIC DEATH OF NEUTRON STARS IN GAMMA-RAY BURSTS

K. Belczynski, R. O’Shaughnessy, V. Kalogera, F. Rasio, R. E. Taam, and T. Bulik

Received 2007 December 16; accepted 2008 May 9; published 2008 May 27

ABSTRACT

Mergers of double neutron stars are considered the most likely progenitors for short gamma-ray bursts. Indeed, such a merger can produce a black hole with a transient accreting torus of nuclear matter, and the conversion of a fraction of the torus mass-energy to radiation can power a gamma-ray burst. Using available binary pulsar observations supported by our extensive evolutionary calculations of double neutron star formation, we demonstrate that the fraction of mergers that can form a black hole–torus system depends very sensitively on the (largely unknown) maximum neutron star mass. We show that the available observations and models put a very stringent constraint on this maximum mass under the assumption that black hole formation is required to produce a short gamma-ray burst in a double neutron star merger. Specifically, we find that the maximum neutron star mass must be within \( 2 \sim 2.5 \, M_\odot \). Moreover, a single unambiguous measurement of a neutron star mass above \( 2.5 \, M_\odot \) would exclude a black hole–torus central engine model of short gamma-ray bursts in double neutron star mergers. Such an observation would also indicate that if in fact short gamma-ray bursts are connected to neutron star mergers, the gamma-ray burst engine is best explained by the lesser known model invoking a highly magnetized massive neutron star.

Subject headings: binaries: close — black hole physics — gravitational waves — stars: evolution — stars: neutron

Online material: color figures

Gamma-ray bursts (GRBs) have been separated into two classes: long-soft bursts and short bursts (Nakar 2007; Gehrels et al. 2007). The origin of long-soft bursts has been connected to the death of low-metallicity massive stars (Piran 2005; Gehrels et al. 2007). However, while observations support a binary merger origin for short bursts (Nakar 2007; Gehrels et al. 2007), the exact nature of the progenitor remains uncertain: they could be either double neutron stars (NS-NS) or black hole–neutron star (BH-NS) binaries. The number of BH-NS binaries that both merge and produce GRBs is hard to estimate since (i) no such system has yet been observed, (ii) formation models are rather uncertain and predict very small BH-NS merger rates (likely too small to explain most of the short bursts), and (iii) theory suggests that the fraction of BH-NS mergers producing bursts depends sensitively on the black hole spin and spin–orbit orientation (Belczynski et al. 2008b), but black hole birth spins are not well constrained observationally or theoretically. On the other hand, NS-NS binaries are observed only in the Milky Way, but their properties and numbers are also in agreement with theoretical models, and their merger rate is sufficient to explain the present-day short-burst population (Nakar 2007; Belczynski et al. 2007).

We have performed an extensive theoretical study of high-mass binary stars (potential progenitors of NS-NS systems) using StarTrack, a population synthesis code incorporating the most up-to-date and detailed input physics for massive stars (Belczynski et al. 2008a). The code employs state-of-the-art predictions for neutron star and black hole masses based on hydrodynamic core collapse simulations (Fryer & Kalogera 2001) and detailed stellar structure and evolution calculations for massive stars (Timmes et al. 1996). Our models predict a Galactic NS-NS merger rate in the range \( \sim 10–100 \, \text{Myr}^{-1} \) (Belczynski et al. 2007), in good agreement with the empirical estimate of \( \sim 3–190 \, \text{Myr}^{-1} \) (Kim et al. 2006). The spread in our predicted rates originates from including the most significant model uncertainties associated with the treatment of dynamical mass transfer episodes (common-envelope phases), which are involved in the formation of most double compact objects (Belczynski et al. 2007).

In Figure 1 we compare short GRB rates with NS-NS merger rates in the present-day (redshift 0) universe. Extrapolating the NS-NS merger rates to the local universe by assuming a star-forming density of \( 10^{-2} \) Milky Way equivalents per Mpc\(^3 \), we estimate the local universe NS-NS merger rate to be in the range \( \sim 100–1000 \, \text{Gpc}^{-3} \, \text{yr}^{-1} \). By comparison, the estimated conservative lower limit on the short GRB rate is \( \sim 10 \, \text{Gpc}^{-3} \, \text{yr}^{-1} \), based on the BATSE/Swift sample (Nakar 2007). This estimate relies on very conservative assumptions: (i) there is no collimation and (ii) there are no bursts dimmer than we have already observed, thus providing a true lower limit on the rate. Therefore, even adopting the most optimistic predictions for the NS-NS merger rate and the most pessimistic bound on the local short GRB event rate, the fraction of NS-NS mergers that produce GRBs must be greater than at least \( 10^{-2} \) to explain the majority of known short bursts.

In this Letter we start with the assumption that all short GRBs are connected with NS-NS system mergers that produce a black hole. We discuss the implications of relaxing this stringent assumption at the end of the Letter.

From our models we also derive physical properties of double neutron stars, with individual masses of neutron stars being of particular interest. Figure 2 shows the relation between pro-
genitor (single star) mass and final remnant mass used in our evolutionary calculations. Mass transfer and other binary interactions change this simple picture, through both accretion and mass loss, which can either increase or decrease an individual binary component mass. However, Belczynski et al. (2008b) argues that we do not expect significant mass accretion onto the components of NS-NS binaries. The population model we adopt for our discussion here produces NS mass distributions that appear consistent with the observed current NS-NS sample, at least in the extent of the mass ranges (Fig. 3). While mass transfer does influence the remnant masses (e.g., smearing the narrowly peaked mass distribution implied by Fig. 2), the qualitative structure is largely preserved, as one would expect from isolated stellar evolution combined with an initial mass function that falls steeply with increasing initial mass. The predicted neutron star mass distribution only very weakly depends on evolutionary model assumptions because the neutron star formation mass is almost independent of the progenitor mass (Timmes et al. 1996) and mass accretion in NS-NS progenitor binaries is rather small (Belczynski et al. 2007). Although more observations are needed to constrain the shape of this distribution, the mass ranges of observed and predicted systems are in agreement. We use direct mass estimates for B1913+16, B1534+12, J0737−3039, and J1756−2251 (O’Shaughnessy et al. 2008), while for J1906+0746 we assume that both neutron stars have masses of 1.3 $M_\odot$ (total system mass is 2.6 $M_\odot$; Lorimer et al. 2006). The few compact objects found in our simulations with masses as high as ~2.5 $M_\odot$ may well be low-mass black holes (see also Fig. 1). [See the electronic edition of the Journal for a color version of this figure.]

where the initial neutron star masses are denoted by $M_{\text{ns,1}}$, $M_{\text{ns,2}}$ and we have assumed that the torus mass is sufficiently large to power a GRB (i.e., ~0.1 $M_\odot$) (Setiawan et al. 2004; Lee & Ramirez-Ruiz 2007) and that 10% of the rest mass is lost in neutrinos (Lattimer & Yahil 1989; Timmes et al. 1996). Higher rest mass loss (e.g., Metzger et al. 2007) would only strengthen our subsequent conclusions. Because stars more massive than 18 $M_\odot$ (progenitors of massive neutron stars with

![Fig. 1.—Comparison of the double neutron star merger rates and short GRB event rates. The solid black line and arrows indicate a firm lower bound on the short GRB event rate (Nakar 2007), based solely on the rate of detected bursts. Depending on the amount of beaming and the fraction of distant faint short GRBs that are missed, the true event rate is often estimated to be at least 10 times larger (Nakar 2007). This lower limit is smaller than the double neutron star merger rate estimated for the Milky Way both from (i) observations of Galactic binary pulsars (filled blue region) and (ii) our population synthesis simulations (filled red region), when these two estimates are extrapolated to cosmological scales. Based on the maximum plausible double neutron star merger rate with the minimum plausible short GRB event rate, the fraction $f_{\text{grb}}$ of binary mergers that lead to short GRBs should be greater than $10^{-7}$ if double neutron stars are the progenitors of short GRBs. [See the electronic edition of the Journal for a color version of this figure.]

![Fig. 2.—Initial (zero-age main sequence) mass to final compact object mass relation for single stars. This represents our current understanding of compact object formation. Stars below about 7.5 $M_\odot$ form white dwarfs; stars in the narrow range around 8 $M_\odot$ can potentially form very light neutron stars through electron capture supernovae (Podsiadlowski et al. 2004). More massive stars show a well-defined bifurcation caused by different modes of energy transport in the stellar core: stars below 18 $M_\odot$ form light neutron stars ($\sim$1.35 $M_\odot$), while stars above this mass form heavy neutron stars ($\sim$1.8 $M_\odot$). Above ~20 $M_\odot$ stars experience partial fallback of material that can turn nascent neutron stars into black holes. Compact objects originating from stars of ~20–22 $M_\odot$ form either very heavy neutron stars or low-mass black holes depending on the unknown limiting mass between these two remnant types (expected to lie around 2–3 $M_\odot$). [See the electronic edition of the Journal for a color version of this figure.]

![Fig. 3.—Predicted mass distribution for neutron stars in merging double neutron star binaries. Firstborn neutron stars are slightly heavier as they can accrete some matter from their unevolved binary companions. Population synthesis models (red and blue lines) are shown along with measured neutron star masses for the known double neutron star binaries. Although more observations are needed to constrain the shape of this distribution, the mass ranges of observed and predicted systems are in agreement. We use direct mass estimates for B1913+16, B1534+12, J0737−3039, and J1756−2251 (O’Shaughnessy et al. 2008), while for J1906+0746 we assume that both neutron stars have masses of 1.3 $M_\odot$ (total system mass is 2.6 $M_\odot$; Lorimer et al. 2006). The few compact objects found in our simulations with masses as high as ~2.5 $M_\odot$ may well be low-mass black holes (see also Fig. 1). [See the electronic edition of the Journal for a color version of this figure.]
that produce black holes and are able to power short GRBs is set by the fraction of mergers such that

\[ M_{\text{rem}} \geq M_{\text{black,max}}. \]  

We therefore calculate the fraction of our simulated NS-NS mergers that lead to black hole formation and a short GRB as a function of \( M_{\text{ns,max}} \); see Figure 4. Observations of the highest mass neutron stars (\( \approx 2 M_\odot \); Barziv et al. 2001; Ransom et al. 2005) and lowest mass black holes (\( \approx 3 M_\odot \); Orosz 2003; Casares 2006) only weakly constrain this parameter. Remnant masses from NS-NS mergers (\( M_{\text{rem}} \)) obtained both from our simulations and from observations all fall very close to the range 2.2–2.5 \( M_\odot \).

Comparing Figures 1 and 4 we immediately deduce that, since the fraction \( f_{\text{grb}} \) of NS-NS mergers that produce short GRBs must be greater than \( 10^{-2} \) (Fig. 1), the neutron star maximum mass \( M_{\text{ns,max}} \) must be less than 2.5 \( M_\odot \) (Fig. 4). Because we lack a robust lower bound on the mass of the residual torus surrounding the black hole, we have adopted a conservative upper limit on \( M_{\text{ns,max}} \) obtained by assuming a negligible torus mass (i.e., replace 0.1 \( M_\odot \) with 0 in eq. [1]).

This result has been obtained with the assumption that all \( k = 1.0 \) short GRBs are connected with NS-NS mergers. It is however possible that only a fraction of short GRBs is produced in NS-NS mergers. How does our result depend on the fraction \( k \) of short GRBs that are connected with NS-NS mergers? The lower limit on \( f_{\text{grb}} \) is then decreased by \( k \); see Figure 1. If \( k \gtrsim 0.1 \), then the limit lower limit becomes \( f_{\text{grb}} > 10^{-3} \), and as is clearly seen from Figure 3, the upper limit on the maximum mass of a neutron star remains unchanged. For values of \( k \lesssim 0.01 \) the NS-NS mergers are not important for the overall short GRB population, as the mergers would consist of only \( \lesssim 1\% \) of the short GRBs. Therefore, in this case short GRBs do not provide information about the merger product.

Our proposed limit on the maximum neutron star mass is still above the maximum masses allowed by almost all proposed models for the nuclear equation of state (Lattimer & Prakash 2007). However, the proposed limit would remain unchanged even if a dramatic improvement in short GRB surveys led to a significantly larger lower bound on the local short GRB rate, because of the sharp decrease in \( f_{\text{grb}} \) with \( M_{\text{ns,max}} \) shown in Figure 4. If, however, electromagnetic observations could constrain the least luminous short GRBs and thus provide an upper bound on the short GRB rate, with gravitational wave observations at the same time accurately determining the NS-NS merger rate, then \( f_{\text{grb}} \) could also be constrained from above. If only a fraction of NS-NS mergers produce short bursts, because \( f_{\text{grb}} \) depends so sensitively on \( M_{\text{ns,max}} \), the combination of upper and lower limits would constrain the maximum neutron star mass extremely tightly, even if the assumptions going into equation (1) are relaxed.

While our limit on the effective maximum neutron star mass is entirely empirical, detailed merger models including realistic relativistic dynamics, neutrino transport, magnetic fields, and potentially even energy extraction from the final black hole remain under intense investigation (Janka & Ruffert 1996; Oechslin & Janka 2006). Many merger remnants are expected to be (temporarily) rotationally supported against collapse (Morrison et al. 2004), with a “hypermassive” remnant neutron star eventually spinning down and collapsing to a black hole (Faber et al. 2006; Duez et al. 2007; Shibata & Taniguchi 2006). Our model relies only on the current consensus on double neutron star mergers, as summarized by Oechslin & Janka (2006): sufficiently massive binary mergers produce a black hole and only mergers that produce a black hole extract enough energy to power short GRBs.

Known Galactic black holes extend in mass up to 10–15 \( M_\odot \) (Casares 2006), while two recently discovered black hole candidates in other galaxies (Orosz et al. 2007; Prestwich et al. 2007) have even higher masses of \( \approx 16 \) and \( \approx 24 M_\odot \). Clearly black holes can form with rather high masses in different types of environments. The lower mass limit is not well constrained observationally, as the highest-mass neutron stars barely reach 2 \( M_\odot \), while the lowest-mass black holes are above 3 \( M_\odot \). In order to explain the observed short GRBs with NS-NS mergers, under the assumption of a black hole–torus central engine model, we have shown that the maximum neutron star mass must be lower than 2.5 \( M_\odot \). However, pulsar surveys (Ransom et al. 2005) have discovered increasingly more massive neutron stars. So far in our analysis we have included only NS-NS systems formed in the field. There is one known relativistic double neutron star system in the Galactic globular cluster M15, which has probably formed through dynamical interactions. This binary consists of two low-mass neutron stars (1.36 and 1.35 \( M_\odot \); Jacoby et al. 2006) very similar to those in the Galactic field, so the results of our analysis are not changed by this isolated observation. Moreover, it was estimated that no more than 10%–30% of short GRBs can originate from mergers of double neutron stars formed in globular clusters (Grindlay et al. 2006).

If any observation can be made that establishes unambiguously a pulsar mass (either in the field or in a globular cluster) over 2.5 \( M_\odot \), this would exclude a black hole–torus short GRB central engine model for double neutron star mergers. We note that a tentative mass measurement for a pulsar of 2.74 ± 0.21 \( M_\odot \) was recently reported by Freire et al. (2007). If this measurement is confirmed, the double neutron star mergers may...
still be possible progenitors for short GRBs. However, the central engine model will need to be reexamined. In particular, it was proposed that a merger of two neutron stars may lead to the formation of a magnetar, a rapidly rotating highly magnetized and high-mass neutron star (with or without a torus) that can lead to a short GRB (e.g., Usov 1992; Kluzniak & Ruderman 1998; Dai et al. 2006; Metzger et al. 2008). Gravitational wave observatories (LIGO, VIRGO) may provide the direct evidence that a NS-NS merger can produce a short GRB if there is a coincidence of the burst and the inspiral gravitational wave signal. It may also be possible to distinguish a merger product (NS vs. BH) from the shape of the merger and ringdown signal or from radio pulses if a magnetar was formed in a nearby gamma-ray burst event.

We would like to thank Neil Gehrels, Duncan Lorimer, Scott Ransom, Ben Owen, Jerome Orosz, Chris Stanek, John Beacom, Paulo Freire, Chungle Kim, Todd Thompson, and an anonymous referee for very useful discussions.

REFERENCES

Barziv, O., Kaper, L., Van Kerkwijk, M. H., Teeling, J. H., & Van Paradijs, J. 2001, A&A, 377, 925
Belczynski, K., Kalogera, V., Rasio, F., Taam, R., Zezas, A., Macarone, T., & Ivanova, N. 2008a, ApJS, 174, 223
Belczynski, K., Taam, R. E., Kalogera, V., Rasio, F. A., & Bulik, T. 2007, ApJ, 662, 504
Belczynski, K., Taam, R. E., Rantsiou, E., & Sluys, M. v. d. 2008b, ApJ, in press (astro-ph/0703131)
Casares, J. 2006, in IAU Symp. 238, Black Holes: From Stars to Galaxies—Across the Range of Masses, ed. V. Karas & G. Matt (Cambridge: Cambridge Univ. Press), in press (astro-ph/0612312)
Dai, Z., Wang, X., Wu, X., & Zhang, B. 2006, Science, 311, 1127
Duez, M. D., Liu, Y. T., Shapiro, S. L., Shibata, M., & Stephens, B. C. 2007, in Proc. Eleventh Marcel Grossmann Meeting (Singapore: World Scientific), in press (gr-qc/0701145)
Faber, J. A., Baumgarte, T. W., Shapiro, S. L., & Taniguchi, K. 2006, ApJ, 641, L93
Freire, P. C. C., Ransom, S. M., Begin, S., Stairs, I. H., Hessels, J. W. T., Frey, L. H., & Camilo, F. 2007, in AIP Conf. Proc. 983, 40 Years of Pulsars: Millisecond Pulsars, Magnetars, and More, ed. C. Bassa, Z. Wang, A. Cumming, & V. M. Kaspi (Melville: AIP), in press (arXiv:0711.2028)
Fryer, C. L., & Kalogera, V. 2001, ApJ, 554, 548
Gehrert, N., Cannizzo, J. K., & Norris, J. P. 2007, New J. Phys., 9, 37
Grindlay, J., Portegies Zwart, S., & McMillan, S. 2006, Nature Phys., 2, 116
Jacoby, B., et al. 2006, ApJ, 644, L113
Janka, H.-T., & Ruffert, M. 1996, A&A, 307, L33
Kim, C., Kalogera, V., & Lorimer, D. R. 2006, in Proc. A Life with Stars, ed. L. Kapers, M. van der Klis, & R. Wijers (Amsterdam: Elsevier), in press (astro-ph/0608280)
Kluzniak, W., & Ruderman, M. 1998, ApJ, 505, L113
Lattimer, J. M., & Prakash, M. 2007, Phys. Rep., 442, 109
Lattimer, J. M., & Yahli, M. 1989, ApJ, 340, 426
Lee, W. H., & Ramirez-Ruiz, E. 2007, New J. Phys., 9, 17
Lorimer, D. R., et al. 2006, ApJ, 640, 428
Metzger, B., Quataert, E., & Thompson, T. 2008, MNRAS, 385, 1455
Metzger, B., Thompson, T., & Quataert, E. 2007, ApJ, 659, 561
Morrison, I. A., Baumgarte, T. W., & Shapiro, S. L. 2004, ApJ, 610, 941
Nakar, E. 2007, Phys. Rep., 442, 166
Oechslin, R., & Janka, H.-T. 2006, MNRAS, 368, 1489
Orosz, J. A. 2003, in IAU Symp. 212, A Massive Star Odyssey: From Main Sequence to Supernova, ed. K. van der Hucht, A. Herrero, & C. Esteban (San Francisco: ASP), 365
Orosz, J. A., et al. 2007, Nature, 449, 872
O’Shaughnessy, R., Kim, C., Kalogera, V., & Belczynski, K. 2008, ApJ, 672, 479
Piran, T. 2005, Rev. Mod. Phys., 76, 1143
Podsiadlowski, P., Langer, N., Poelarends, A. J. T., Rappaport, S., Heger, A., & Pfahl, E. 2004, ApJ, 610, 1044
Prestwich, A., et al. 2007, ApJ, 669, L21
Ransom, S., et al. 2005, Science, 307, 892
Setiawan, S., Ruffert, M., & Janka, H.-T. 2004, MNRAS, 352, 753
Shibata, M., & Taniguchi, K. 2006, Phys. Rev. D, 73, 064027
Timmes, F. X., Woosley, S. E., & Weaver, T. A. 1996, ApJ, 457, 834
Usov, V. 1992, Nature, 357, 472