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On the Neutron Star-Black Hole Binaries Produced by Binary-driven-Hypernovae

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Binary-driven-hypernovae (BdHNe) within the induced gravitational collapse (IGC) paradigm have been introduced to explain energetic ($E_{\rm iso} \gtrsim 10^{52}$ erg), long gamma-ray bursts (GRBs) associated with type Ic supernovae (SNe). The progenitor is a tight binary composed of a carbon-oxygen (CO) core and a neutron star (NS) companion, a subclass of the newly proposed "ultra-stripped" binaries. The CO-NS short-period orbit causes the NS to accrete appriciable matter from the SN ejecta when the CO core collapses, ultimately causing it to collapse to a black hole (BH) and producing a GRB. These tight binaries evolve through the SN explosion very differently than compact binaries studied in population synthesis calculations. First, the hypercritical accretion onto the NS companion alters both the mass and momentum of the binary. Second, because the explosion timescale is on par with the orbital period, the mass ejection can not be assumed to be instantaneous. This dramatically affects the post-SN fate of the binary. Finally, the bow shock created as the accreting NS plows through the SN ejecta transfers angular momentum, braking the orbit. These systems remain bound even if a large fraction of the binary mass is lost in the explosion (well above the canonical 50% limit), and even large kicks are unlikely to unbind the system. Indeed, BdHNe produce a new family of NS-BH binaries unaccounted for in current population synthesis analyses and, although they may be rare, the fact that nearly 100% remain bound implies they may play an important role in the compact merger rate, important for gravitational waves (GWs) that, in turn, can produce a new class of ultrashort GRBs.

Keywords: Type Ic Supernovae — Hypercritical Accretion — Induced Gravitational Collapse — Gamma Ray Bursts – Gravitational Waves

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INTRODUCTION

Binary massive star systems evolve into a broad set of compact binaries from X-ray binaries consisting of stars accreting onto either BH or NS companions to the more exotic binary compact objects such NS-BH and NS-NS binaries. The formation scenarios of these compact binaries typically argue that, after the first SN explosion, the compact remnant enters a common envelope phase with its companion, tightening the orbit. If the system remains bound after the companion star collapses, a NS-BH or NS-NS binary is formed. A range of scenarios have been invoked [1–3], including exotic scenarios where both components expand off the main sequence concurrently, causing a single common envelope around two helium cores [4].

Recently, two independent communities have argued for a "new" evolutionary scenario forming these compact binaries where, after the collapse of the primary star to a NS, the system undergoes a series of mass transfer phases, ejecting both the hydrogen and helium shells of the secondary to produce a binary composed of a massive CO core and a NS. When the CO core collapses and produces a SN explosion, a compact binary system is formed. In the X-ray binary/SN community, these systems are called "ultra-stripped" binaries. In the past few years, such systems have been invoked to both explain the population of NS-NS binaries as well as a growing set of low-luminosity and/or rapid decay-rate SNe [5, 6]. Low-mass ejecta can match the observational features of these SNe and ultra-stripped binaries without hydrogen and helium layers in their pre-SN progenitor produce small cores with such low-mass explosions. The rate of these systems are predicted to be 0.1–1% of the total SN rate [5]. These binaries are extremely tight, and most of the systems studied have orbital periods lying between 3000 and 300,000 s. Proponents of the ultra-stripped systems argue that this scenario dominates the formation of NS-NS binaries and that there are virtually no systems that are formed where the CO core collapses directly to a BH.

The IGC scenario for GRBs [7–9] introduced a subset of extremely short-period CO-NS binaries where the ejecta from the exploding CO star accretes onto its NS companion, causing the NS, in some cases, to collapse to a BH. If ultra-stripped binaries dominate the formation of NS-NS binaries, this scenario would dominate the formation of NS-BH binaries. This collapse to a BH releases energy to drive the GRB emission [9, 10]. The CO core is a requirement to allow the tight orbits needed to produce sufficient accretion to cause the NS collapse, but it also provides a natural explanation for the fact that these GRBs are always associated with type Ic SNe. The recently introduced ultra-stripped binaries are a wel-

come support for the IGC scenario from the point of view of stellar evolution, with the only caveat that IGC progenitors are a small subset of the ultra-stripped binaries where the initial orbital separation and CO core mass are aligned to produce binaries with orbital periods lying in the 100–1000 s range. This requires fine-tuning both of the CO star mass and the binary orbit. From an astrophysical point of view the IGC scenario is uniquely characterized by the formation of the BH during the accretion process of the SN ejecta onto the companion NS and the associated GRB emission. Since the rate of the high-luminosity GRBs (BdHNe) explained through the IGC scenario is (1.1–1.3) $\times 10^{-2}$ Gpc^{-3} y^{-1} [11], and 0.1–1% of the SN Ibc population could be ultra-stripped binaries [5], only 0.005–0.07% of the latter are needed to explain the BdHNe population (assuming a SN Ibc rate of 2×10^4 Gpc^{-3} y^{-1} [12]).

Studies of ultra-stripped binaries have expanded our understanding of stellar radii, confirming these results: CO cores with masses below 2 $M_\odot$ have radii of 1–4×10^9 cm [13], in agreement with the assumptions used in IGC studies [10]. Even if some helium remains on the stripped core, it will be ejected if it expands to interact with its compact-object companion. These radii are sufficiently small to produce the tight orbits required to produce the rapid accretion of the ejecta onto the NS companion and the formation of the BH.

In typical systems, most of the binaries become unbound during the SN explosion because of the ejected mass and momentum imparted (kick) on the newly formed compact object in the explosion of the massive star. Under the instantaneous explosion assumption, if half of the binary system's mass is lost in the SN explosion, the system is disrupted, forming two single compact objects. Although SN kicks may allow some systems to remain bound, in general, these kicks unbind even more systems. In general, it is believed that the fraction of massive binaries that can produce double compact object binaries is low: ∼0.001–1% [1–3].

For ultra-stripped binaries, the fate is very different. In these systems, the mass ejected is extremely low and, if the SN kick is low, these systems remain bound [5, 6]. In the tighter binaries leading to IGC progenitors, the assumption of instantaneous mass ejection is no longer valid. We demonstrate in this work that, removing this assumption, even with a strong SN kick nearly all of these systems will remain bound. In this case, even though IGC progenitors are rare, the compact binaries produced by these progenitors may dominate the total NS-BH binaries in the Universe, and lead to a new previously unaccounted family of GRBs.

We shall describe below the differences between these systems and typical massive star binaries, modeling these orbits through the SN explosion. We then calculate the evolution of these NS-BH binaries via GWs emission up to the merger point, and assess their detectability. We conclude with a discussion of the additional observational predictions of these NS-BH binaries, introducing a new class of short GRBs, with specific observational signatures, here referred to as ultrashort GRBs.

POST-EXPLOSION ORBITS

The mass ejected during the SN alters the binary orbit, causing it to become wider and more eccentric. Assuming that the mass is ejected instantaneously, the post-explosion semi-major axis is $a/a_0 = (M_0 - \Delta M)/(M_0 - 2a_0\Delta M/r)$, where a_0 and a are the initial and final semi-major axes respectively, M_0 is the total initial mass of the binary system, ΔM is the change of mass (equal to the amount of mass ejected in the SN), and r is the orbital separation at the time of explosion [14]. For circular orbits, like the ones expected from our systems after going through a common envelope evolution, we find that the system is unbound if it loses half of its mass. But, for these close binaries, a number of additional effects can alter the fate of the binary.

The time it takes for the ejecta to flow past a companion in a SN is roughly 10–1000 s. These explosions follow a so-called homologous velocity profile where the velocity is proportional to the position. Although the shock front is moving above 10,000 km s^{-1}, the denser,lower-velocity ejecta can be moving at below 1000 km s^{-1}. Our estimates are based on simulated supernova explosions [10]. The broad range of times arises because the SN ejecta velocities varies from 100–10,000 km s^{-1}. The accretion peaks as the slow-moving (inner) ejecta flows past the NS companion. Note that the initial SN explosion in this case is not a hypernova. The observed "hypernova" is actually produced when the GRB from the BH collapse sweeps up this SN (and circumstellar) material [15]. For normal binaries, this time is a very small fraction of the orbital period and the "instantaneous" assumption is perfectly valid. However, in the close binary systems considered here, the orbital period ranges from only 100–1000 s, and the mass loss from the SN explosion can no longer be assumed to be instantaneous.

This has already been pointed out in [16] where it was shown that in BdHNe the accretion process is fast and massive enough to produce the BH formation in a time-interval as short as the orbital period. We here deepen this analysis to study the effect of the SN explosion in such a scenario with a specific example, for which we have produced an orbit code using a simple staggered leapfrog integration (see [17] for details of this integration method). We have tested both stability (by modeling many orbits) and convergence (decreasing the time step by 2 orders of magnitude confirming identical results). We also reproduce the results of the instantaneous limit. From figure 1, as the ejecta timescale becomes just a fraction of the orbital timescale, the fate of the

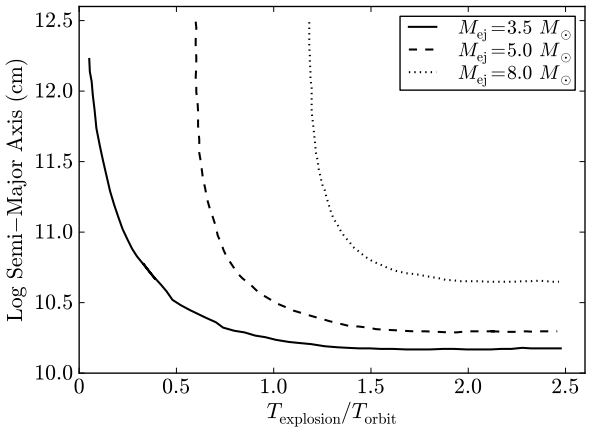

FIG. 1. Semi-major axis versus explosion time for 3 different mass ejecta scenarios: $3.5\,M_\odot$ (solid), $5.0\,M_\odot$ (dotted), $8.0\,M_\odot$ (dashed). The CO core collapse to form a $1.5\,M_\odot$ NS (its initial mass is the ejecta mass plus the NS mass), and the companion NS has a mass of $2.0\,M_\odot$. If the explosion were instantaneous, all of our systems with ejecta masses above $3.5\,M_\odot$ would be unbound. For explosion times above 1.2 times the orbital time, not only are the systems bound, but the final orbital semi-major axis is less than 10 times the initial separation.

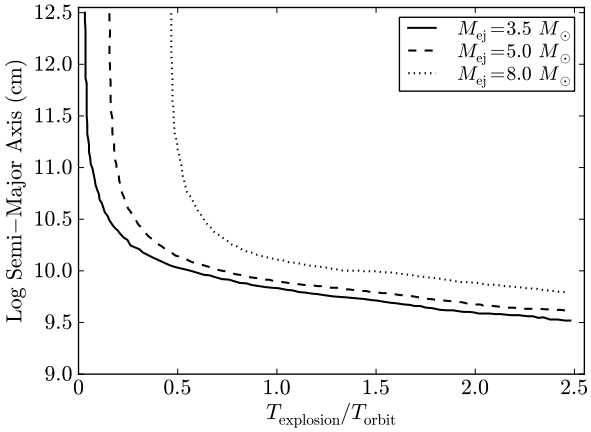

FIG. 2. Semi-major axis versus explosion time for the same 3 binary systems as in figure 1 including mass accretion and momentum effects. Including these effects, all systems with explosion times above 0.7 times the orbital time are bound and the final separations are on par with the initial separations.

post-explosion binary can be radically altered. For these models, we assumed very close binaries with an initial orbital separation of 7×10^9 cm in circular orbits (such close binaries are only formed through a common envelope phase which circularizes the orbit). With CO core radii of 1–4 $\times\ 10^9$ cm [13], such a separation is small, but achievable. We assume the binary consists of a CO core and a 2.0 $M_\odot$ NS companion. When the CO core collapses, it forms a 1.5 $M_\odot$ NS, ejecting the rest of the core. We then vary the ejecta mass and time required for most of the ejected matter to move out of the binary. Note that even if 70% of the mass is lost from the system (the 8 $M_\odot$ ejecta case), the system remains bound as long as the explosion time is just above the orbital time ($T_{\rm orbit}$ = 180 s) with semi-major axes of less than 10^{11} cm.

The short orbits (on ejecta timescales) are not the only feature of these binaries that alters the post-explosion orbit. The NS companion accretes both matter and momentum from the SN ejecta, reducing the mass lost from the system with respect to typical binaries with larger orbital separations and much less accretion. In addition, as with common envelope scenarios, the bow shock produced by the accreting NS transfers orbital energy into the SN ejecta. In figure 2, we show the final orbital separation of our same three binaries, including the effects of mass accretion (we assume $0.5\,M_\odot$ is accreted with the momentum of the SN material) and orbit coupling (30% of the orbital velocity is lost per orbit). With these effects, not only do the systems remain bound even for explosion times greater than 1/2 the orbital period but, if the explosion time is long, the final semi-major axis can be on par with the initial orbital separation.

The tight separation of these binaries facilitates tidal locking and the angular momentum axis of the CO core will be aligned with the orbital angular momentum. For many of the kick mechanisms in the literature, the kick is often aligned with the rotation axis. For example, both in neutrino-driven mechanisms [18, 19] and asymmetric explosions driven by convection [18, 20, 21] the kick is aligned with the rotation axis. However, it is still possible to have some misalignment leading to some eccentricity and "tumbling" of the system with specific signatures in the light curve following the prompt emission of the GRB. Hence, we here consider both kicks aligned with the rotation (and hence orbital) axis as well as random kicks. If the kick is aligned with the orbital plane, the system can remain bound even with kick velocities as high as 1000 km s^{-1}. However, if the kick is in the same direction as the star is moving, the systems can be disrupted if the kick is above 500–700 km s^{-1} if the accretion phase is longer than an orbital period.

The tight compact binaries produced in these explosions will emit GW emission, ultimately causing the system to merge. For typical massive star binaries, the merger time is many Myr. For BdHNe, the merger time is typically 10,000 y, or less (figure 3).

GRAVITATIONAL WAVES FROM THE NS-BH BINARY

To better understand the GW signal from these mergers, we study the evolution of the orbital binding energy E_b up to the merger following the effective one-body

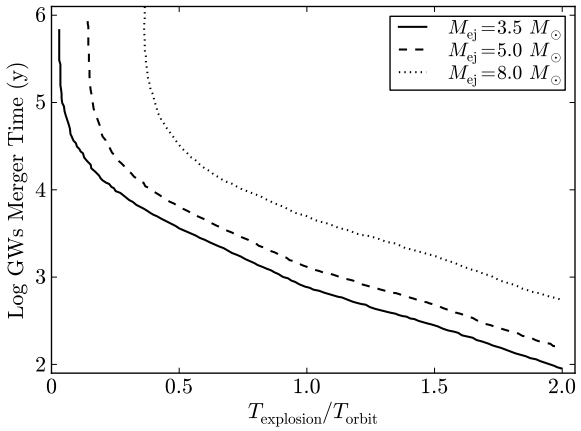

FIG. 3. Merger time due to GW emission as a function of explosion time for the same 3 binary as in figure 1 including mass accretion and momentum effects. Beyond a critical explosion time (0.1–0.6 $T_{\rm orbit}$ depending on the system), the merger time is less than roughly 10,000 y. For most of our systems, the explosion time is above this limit and we expect most of these systems to merge quickly.

(EOB) formalism [22–25] up to the 4th Post-Newtonian approximation (see Refs. [26, 27] and references therein). We adopt here $M_{\rm NS} = 1.5\ M_\odot$ and $M_{\rm BH} = 2.67\ {\rm M}_\odot$ [28], the latter corresponding to the critical mass $M_{\rm crit}$ of a non-rotating NS obeying the nuclear NL3 equation of state (EOS). Uncertainties in the EOS at supranuclear densities lead to a variety of NS mass-radius relations and consequently to different values of $M_{\rm crit}$, hence of $M_{\rm BH}$. Both rotation [29] and different binary parameters may lead to different amounts of angular momentum transferred to the NS, affecting its mass [30].

In order to assess the detectability of the GW emission by advanced LIGO (aLIGO), we compute the signal-to-noise ratio (SNR), averaged over all sky locations and binary orientations, $\langle{\rm SNR}\rangle$, generated by the NS-BH spiraling-in binary up to the merger point [27]. Following [31], we adopt as a threshold for the aLIGO detection $\langle{\rm SNR}\rangle = 8$ in a single detector, which implies a GW horizon distance for these NS-BH binaries, which have a chirp mass $\mathcal{M}_{\rm ch} = (M_{\rm BH}M_{\rm NS})^{3/5}/(M_{\rm BH}+M_{\rm NS})^{1/5} \approx 1.73\ M_\odot$, $d_L \approx 335.4$ Mpc, or $z \approx 0.075$, using the maximum possible sensitive reachable by 2022. No BdHN has been up to now detected with such a low redshift. Figure 4 shows, for two sources shown to be consistent with the BdHN picture (GRB 130427A with $z = 0.34$ [15] and GRB 061121 with $z = 1.31$ [32]), the GW source amplitude spectral density, $\sqrt{S_h} = 2|\tilde{h}(f_d)|\sqrt{f_d} = h_c(f_d)/\sqrt{f_d}$, together with the one-sided ASD of the aLIGO noise, $\sqrt{S_n}(f_d)$. Here $h_c(f_d)$ and $\tilde{h}(f_d)$ are the characteristic strain and the Fourier transform of the signal and f_d the frequency of the GWs at the detector. For these sources, $\langle{\rm SNR}\rangle \approx 1.75$ and 0.45, respectively. For an optimally located and polarized source, the SNR could increase by up to a factor ≈ 2.26, which implies that SNR=8 could be obtained for a source as far as $d_L \approx 2.26 \times 335.4$ Mpc $\approx$ 758 Mpc, or $z \approx 0.160$. Furthermore, the SNR scales as $\mathcal{M}_{\rm ch}^{5/6}$, so it increases e.g. with larger BH masses. For rotating NS with the NL3 EOS, the maximum value of $M_{\rm crit}$ is $\approx 3.4\ M_\odot$ [29], which would increase the SNR only by ≈ 1.1. For this largest BH mass, the GW horizon becomes $d_L \approx 1.1 \times 758$ Mpc ≈ 834 Mpc, or $z \approx 0.174$. This largest possible GW horizon implies an upper limit of ~ 0.03 detections per year, adopting a BdHN rate of 1.2×10^{-2} Gpc^{-3} y^{-1} [11].

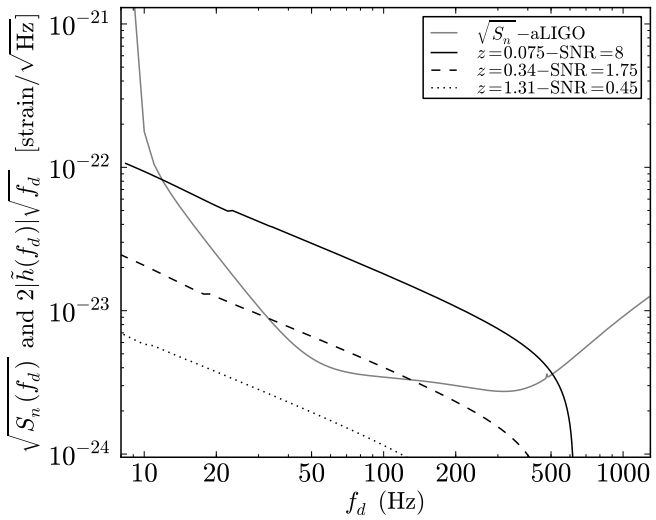

FIG. 4. ASD of the spiraling-in phase up to the merger, $\sqrt{S_h} = 2|\tilde{h}(f_d)|\sqrt{f_d} = h_c(f_d)/\sqrt{f_d}$, of the NS-BH binaries produced by two BdHNe, GRB 130427A at redshift $z = 0.34$ and GRB 061121 at $z = 1.31$, compared with the noise ASD of aLIGO, $\sqrt{S_n}(f_d)$. We indicate the estimated SNR for these two sources and show the case of the NS-BH binary which would generate a positive detection with SNR=8. The binary dynamics is simulated via the EOB formalism up to the 4th Post-Newtonian approximation.

CONCLUSION

The evolutionary scenario for BdHNe requires much tighter binaries than typically studied in the literature of ultra-stripped binaries and this produces unique features in the end-fate of these systems. The progenitor of this GRB engine begins with two massive stars, in contrast to the one based on a massive core collapsing to a BH [33]. A tight binary is produced after a succession of common envelope phases, producing a CO core near Roche-Lobe overflow orbiting a NS, a subset of the ultra-stripped binaries [5, 6, 34, 35]. Since 0.1–1% of the total SN Ibc are expected to be ultra-stripped binaries [5], we estimate that only 0.005–0.07% of the latter are needed to explain the observed population of BdHNe. The fate of such systems evolves very differently than the standard

picture. The NS can accrete appreciable material in the SN explosion and this accretion causes it to collapse to a BH and form a GRB. However, the tight binary invalidates many of the assumptions about orbital evolution in the SN. The SN explosion does not pass "instantaneously" across the NS, and correcting this assumption alone drastically alters the binary fate. Including the interaction of the orbit and the ejecta further exacerbates these differences, causing these NS-BH to be very different than the systems prediction in standard population synthesis models.

First and foremost, the fraction of the BdHNe that remain bound after the SN explosion is nearly 100% even with large $\sim$ 500–1000 km s^{-1} kicks imparted during the SN explosion instead of the $\lesssim$1% in standard scenarios. This means that even if BdHNe are rare, they may dominate the fraction of NS-BH binaries in the Universe. In addition, the merger timescales for these systems are typically <10,000 y, producing a set of rapidly-merging binaries. In view of such a short lifetime due to GW emission, the current number of such events is likely to be comparable with the original rate of long GRBs produced by BdHNe following the IGC paradigm. Because of this rapid merger, the systems are unlikely to travel that far from the site of the SN explosion that formed the GRB. Even with large kicks, we expect these binaries to merge within 10 pc of the BdHNe and we expect the merger to occur within the radius swept clean by the BdHN, giving a characteristic imprint in the GRB emission. In view of the expected paucity of the baryonic contamination around the merger site, it is expected that the characteristic prompt radiation emission time of the GRB produced by these sources be dominated by the general relativistic timescale of the BH, $GM/c^3 \approx 10^{-4}$–10^{-5} s, which justifies the attribution of the name of ultrashort GRBs to this new family of events.

Another observational feature of these binaries is that the BHs from these systems are low mass: $\sim$3–4 $M_\odot$, of the order of the critical mass of rotating NSs [29, 30], instead of the 5–10 $M_\odot$ produced by standard scenarios. However, further accretion of mass and angular momentum from material kept bound into the system after the BdHN process might lead the BH to larger masses and to approach maximal rotation [30]. Although the NS in this NS-BH binary should be rapidly rotating, producing pulsed emission, the short timescale between formation and merger means that it will be difficult to observe such systems through steady pulsed emission. However, if these systems make up a sizable fraction of the NS-BH population, they could be detecting by their GW signal. Although it is difficult to get the exact component masses from aLIGO, evidence [36], or the lack thereof, for binaries with low-mass BHs could support, or limit the rate of, this scenario.

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[1] C. L. Fryer, S. E. Woosley, and D. H. Hartmann, ApJ **526**, 152 (1999), astro-ph/9904122.
[2] M. Dominik, K. Belczynski, C. Fryer, D. E. Holz, E. Berti, T. Bulik, I. Mandel, and R. O'Shaughnessy, ApJ **759**, 52 (2012), arXiv:1202.4901 [astro-ph.HE].
[3] K. A. Postnov and L. R. Yungelson, Living Reviews in Relativity **17**, 3 (2014), arXiv:1403.4754 [astro-ph.HE].
[4] G. E. Brown, ApJ **440**, 270 (1995).
[5] T. M. Tauris, N. Langer, T. J. Moriya, P. Podsiadlowski, S.-C. Yoon, and S. I. Blinnikov, ApJL **778**, L23 (2013), arXiv:1310.6356 [astro-ph.SR].
[6] T. M. Tauris, N. Langer, and P. Podsiadlowski, MNRAS **451**, 2123 (2015), arXiv:1505.00270 [astro-ph.SR].
[7] R. Ruffini, C. L. Bianco, F. Fraschetti, S.-S. Xue, and P. Chardonnet, ApJL **555**, L117 (2001).
[8] R. Ruffini, M. G. Bernardini, and C. L. Bianco et al., in *The Eleventh Marcel Grossmann Meeting*, edited by H. Kleinert, R. T. Jantzen, and R. Ruffini (2008) pp. 368–505.
[9] J. A. Rueda and R. Ruffini, ApJL **758**, L7 (2012), arXiv:1206.1684 [astro-ph.HE].
[10] C. L. Fryer, J. A. Rueda, and R. Ruffini, ApJ **793**, L36 (2014), arXiv:1409.1473 [astro-ph.HE].
[11] M. Muccino, F. G. Oliveira, J. A. Rueda, R. Ruffini, and et al., to be submitted (2015).
[12] D. Guetta and M. Della Valle, ApJL **657**, L73 (2007), astro-ph/0612194.
[13] Y. Suwa, T. Yoshida, M. Shibata, H. Umeda, and K. Takahashi, ArXiv e-prints (2015), arXiv:1506.08827 [astro-ph.HE].
[14] J. G. Hills, ApJ **267**, 322 (1983).
[15] R. Ruffini, Y. Wang, M. Enderli, M. Muccino, M. Kovacevic, C. L. Bianco, A. V. Penacchioni, G. B. Pisani, and J. A. Rueda, ApJ **798**, 10 (2015), arXiv:1405.5723 [astro-ph.HE].
[16] L. Becerra, F. Cipolletta, C. L. Fryer, J. A. Rueda, and R. Ruffini, ApJ **812**, 100 (2015), arXiv:1505.07580 [astro-ph.HE].
[17] C. K. Birdsall and A. B. Langdon, *Plasma Physics via Computer Simulation, The Adam Hilger Series on Plasma Physics, edited by C. Birdsall and A. Langdon. Adam Hilger, Bristol, England (ISBN: 0-07-005371-5)* (1991).
[18] C. L. Fryer and A. Heger, ApJ **541**, 1033 (2000), astro-ph/9907433.
[19] C. L. Fryer and A. Kusenko, ApJS **163**, 335 (2006), astro-ph/0512033.

[20] T. Shimizu, S. Yamada, and K. Sato, ApJL **432**, L119 (1994).
[21] C. L. Fryer and M. S. Warren, ApJ **601**, 391 (2004), astro-ph/0309539.
[22] A. Buonanno and T. Damour, Phys. Rev. D **59**, 084006 (1999), gr-qc/9811091.
[23] A. Buonanno and T. Damour, Phys. Rev. D **62**, 064015 (2000), gr-qc/0001013.
[24] T. Damour, P. Jaranowski, and G. Schäfer, Phys. Rev. D **62**, 084011 (2000), gr-qc/0005034.
[25] T. Damour, Phys. Rev. D **64**, 124013 (2001), gr-qc/0103018.
[26] D. Bini and T. Damour, Phys. Rev. D **87**, 121501 (2013), arXiv:1305.4884 [gr-qc].
[27] F. G. Oliveira, J. A. Rueda, and R. Ruffini, ApJ **787**, 150 (2014).
[28] R. Belvedere, D. Pugliese, J. A. Rueda, R. Ruffini, and S.-S. Xue, Nuclear Physics A **883**, 1 (2012).
[29] F. Cipolletta, C. Cherubini, S. Filippi, J. A. Rueda, and R. Ruffini, Phys. Rev. D **92**, 023007 (2015), arXiv:1506.05926 [astro-ph.SR].
[30] L. Becerra, F. Cipolletta, C. L. Fryer, J. A. Rueda, and R. Ruffini, ArXiv e-prints (2015), arXiv:1505.07580 [astro-ph.HE].
[31] LIGO Scientific Collaboration, Virgo Collaboration, J. Aasi, J. Abadie, B. P. Abbott, R. Abbott, T. D. Abbott, M. Abernathy, T. Accadia, F. Acernese, and et al., ArXiv e-prints (2013), arXiv:1304.0670 [gr-qc].
[32] R. Ruffini, L. Izzo, M. Muccino, G. B. Pisani, J. A. Rueda, Y. Wang, C. Barbarino, C. L. Bianco, M. Enderli, and M. Kovacevic, A&A **569**, A39 (2014), arXiv:1404.1840 [astro-ph.HE].
[33] S. E. Woosley and J. S. Bloom, Ann. Rev. A&A **44**, 507 (2006), astro-ph/0609142.
[34] K. Belczyński and V. Kalogera, ApJL **550**, L183 (2001), astro-ph/0012172.
[35] J. D. M. Dewi and O. R. Pols, MNRAS **344**, 629 (2003), astro-ph/0306066.
[36] M. Hannam, D. A. Brown, S. Fairhurst, C. L. Fryer, and I. W. Harry, ApJL **766**, L14 (2013), arXiv:1301.5616 [gr-qc].