The lowest-mass stellar black holes: catastrophic death of neutron stars in gamma-ray bursts

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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 [1, 2] and the conversion of the torus mass-energy to radiation can power a gamma-ray burst [3]. 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 a majority of short gamma-ray bursts originate in double neutron star mergers. Specifically, we find that the maximum neutron star mass must be within $2 - 2.5 M_\odot$. Moreover, a single unambiguous measurement of a neutron star mass above $2.5 M_\odot$ would exclude double neutron star mergers as short gamma-ray burst progenitors.

Gamma-ray bursts (GRBs) have been separated into two classes: long-soft bursts, and short bursts [3, 4]. The origin of long-soft bursts has been connected to the death of low-metallicity massive stars[4, 5]. However, while observations support a binary merger origin for short bursts [3, 4], 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 [6], but black hole birth spins are not well constrained observationally or theoretically. On the other hand, NS–NS binaries are only observed 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 [3, 7].

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 [8]. The code employs state-of-the-art predictions for neutron star and black hole masses based on hydrodynamic core collapse simulations [9] and detailed stellar structure and evolution calculations for massive stars [10]. Our models predict a Galactic NS–NS merger rate in the range $\sim 10 - 100$ Myr^{-1} [7], in good agreement with the empirical estimate of $\sim 3 - 190$ Myr^{-1} [11]. 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 [7].

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 [12], we estimate the local universe NS–NS merger rate to be in the range $\sim 100 - 1000$ Gpc^{-3} yr^{-1}. By comparison, the estimated conservative lower limit on the short GRB rate is ~ 10 Gpc^{-3} yr^{-1}, based on the BATSE/SWIFT sample [3]. 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 f_{grb} that produce GRBs must be greater than at least 10^{-2} to explain the majority of known short bursts.

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 progenitor (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, [6] 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 current observed 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

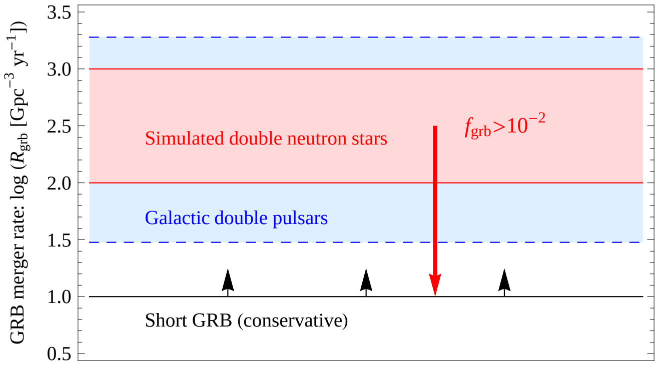

FIG. 1: Comparison of the double neutron star merger rates and short GRB event rates. The solid black line and arrows indicate a firm lower bound on the short GRB event rate [3], based solely on the rate of detected bursts. Depending on the amount of beaming and the fraction of distant faint short GRBs that are missed, the true event rate is often estimated to be at least 10 times larger [3]. 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_{grb} of binary mergers that lead to short GRBs should be greater than 10^{-2} if double neutron stars are the progenitors of short GRBs.

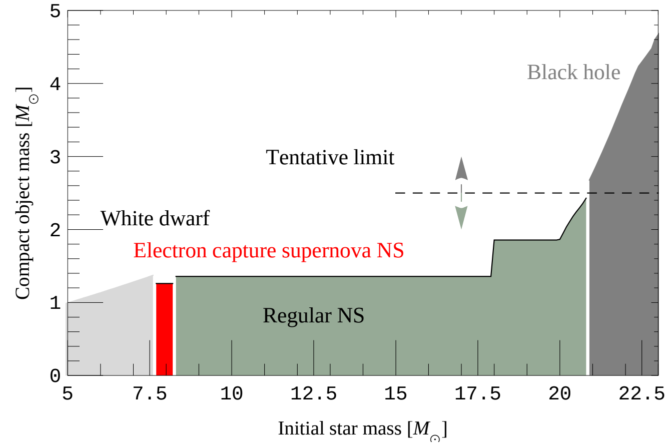

FIG. 2: Initial (Zero Age Main Sequence) mass to final compact object mass relation for single stars. This represents our current understanding of compact object formation. Stars below about $7.5M_\odot$ form white dwarfs; stars in the narrow range around $8M_\odot$ can potentially form very light neutron stars through electron capture supernovae [14]. More massive stars show a well defined bifurcation caused by different modes of energy transport in the stellar core: stars below $18M_\odot$ form light neutron stars ($\simeq 1.35M_\odot$), while stars above this mass form heavy neutron stars ($\simeq 1.8M_\odot$). Above $\simeq 20M_\odot$ stars experience partial fallback of material that can turn nascent neutron stars into black holes. Compact objects originating from stars of $\sim 20-22M_\odot$ 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 $2-3M_\odot$).

increasing initial mass.

Depending on the masses in the progenitor binary and the highly uncertain nuclear equation of state, the final remnant of a NS–NS merger may or may not collapse to a black hole. We estimate the final mass of the compact remnant as

$$M_{\rm rem} = 0.9(M_{\rm ns,1} + M_{\rm ns,2} - 0.1M_\odot), \qquad (1)$$

where the initial neutron star masses are denoted by $M_{\rm ns,1}$, $M_{\rm ns,2}$ and we have assumed that the torus mass is sufficiently large to power a GRB (i.e., $\simeq 0.1M_\odot$) [2, 13] and that 10% of rest mass is lost in neutrinos. Because stars more massive than $18M_\odot$ (progenitors of massive neutron stars with $M_{\rm ns} \simeq 1.8M_\odot$) are much rarer than those forming lighter neutron stars ($M_{\rm ns} \simeq 1.35M_\odot$) we *a priori* expect that most remnants from NS–NS mergers will have rather low mass $M_{\rm rem} \simeq 2.3M_\odot$ (see eq. 1 for two $1.35M_\odot$ neutron stars).

Neither observations nor nuclear theory have yet pinned down the maximum neutron star mass $M_{\rm ns,max}$ above which a black hole must form. Thus, the fraction of binary neutron stars which produce black holes and are able to power short GRBs is set by the fraction of mergers such that

$$M_{\rm rem} \geq M_{\rm ns,max}. \qquad (2)$$

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 $M_{\rm ns,max}$; see Fig. 4. Observations of the highest mass neutron stars ($\lesssim 2M_\odot$; [17, 18]) and lowest mass black holes ($\gtrsim 3M_\odot$; [19, 20]) only weakly constrain this parameter. Remnant masses from NS–NS mergers ($M_{\rm rem}$) obtained both from our simulations and from observations all fall very close to the range $2.2-2.5M_\odot$.

Comparing Figs 1 and 4 we immediately deduce that, since the fraction f_{grb} of NS–NS mergers that produce short GRBs must be greater than 10^{-2} (Fig. 1), the neutron star maximum mass $M_{\rm ns,max}$ must be less than $2.5M_\odot$ (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 $M_{\rm ns,max}$ obtained by assuming a negligible torus mass (i.e., replace $0.1M_\odot$ with 0 in eq. 1).

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 [21]. However, our proposed limit is robust: because of the sharp decrease in f_{grb} with $M_{\rm ns,max}$ shown in Fig. 4, our limit on the maximum neutron star mass 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. If, however, electromagnetic observations could constrain the least luminous short GRBs

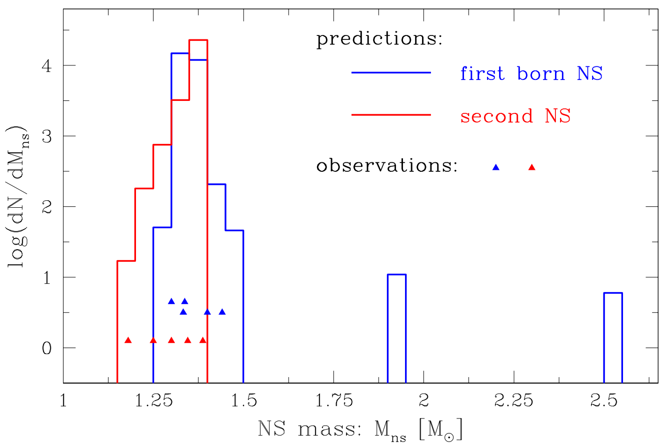

FIG. 3: Predicted mass distribution for neutron stars in merging double neutron star binaries. First born neutron stars are slightly heavier as they can accrete some matter from their unevolved binary companions. Population synthesis models (red and blue lines) are shown along with measured neutron star 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 [15], while for J1906+0746 we assume that both neutron stars have masses of $1.3 M_{\odot}$ (total system mass is $2.6 M_{\odot}$) [16]. The few compact objects found in our simulations with masses as high as $\simeq 2.5 M_{\odot}$ may well be low-mass black holes (see also Fig. 1).

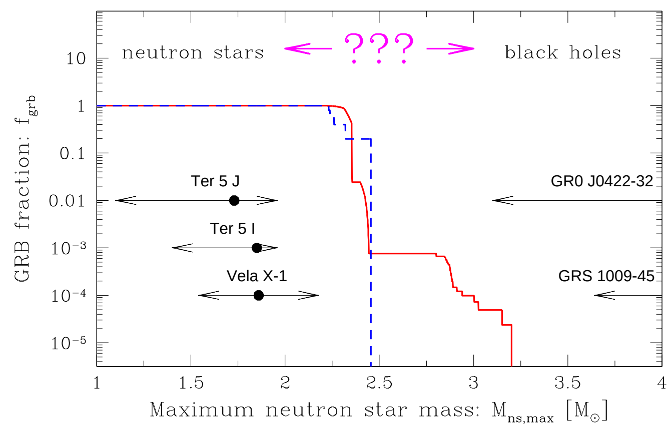

FIG. 4: Gamma Ray Burst production efficiency as a function of the maximum neutron star mass. If short GRBs are the outcome of NS–NS mergers, these must have enough mass to form a black hole. The mass of the merger product is plotted here as the blue (observations) and red (theory) lines. There is a sharp drop in number of NS–NS systems that can form a merger with mass over $2.5 M_{\odot}$. For example, only 1 in 10^3 NS–NS mergers can form a remnant with a mass of $2.5 M_{\odot}$ or higher. Therefore, if short GRBs are connected to NS–NS mergers, the maximum neutron star mass is required to be $M_{\rm ns,max} < 2.5 M_{\odot}$. For comparison we show observed masses of the lowest-mass black holes (GRO J0422−32, GRS 1009−45) [19, 20] and highest-mass neutron stars (Vela X-1, Terzan 5I, and Terzan 5J) [17, 18]. These observations, along with our findings, constrain the maximum mass of a neutron star to lie in the narrow range of $2 - 2.5 M_{\odot}$.

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 $f_{\rm grb}$ could also be constrained from *above*. If only a fraction of NS–NS mergers produce short bursts, because $f_{\rm grb}$ depends so sensitively on $M_{\rm ns,max}$, the combination of upper and lower limits would constrain the maximum neutron star mass extremely tightly, even if the assumptions going into eq. 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 [1, 22]. Many merger remnants are expected to be (temporarily) rotationally supported against collapse, [23] with a “hypermassive” remnant neutron star eventually spinning down and collapsing to a black hole [24, 25, 26]. Our model only relies upon the current consensus on double neutron star mergers, as summarized by Oeschlin and Janka [24]: 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 $10 - 15 M_{\odot}$ [20], while two recently discovered black hole candidates in other galaxies [27, 28] have even higher masses of $\simeq 16$ and $\gtrsim 24 M_{\odot}$. 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, the favorite progenitor model, we have shown that the maximum neutron star mass must be lower than $2.5 M_{\odot}$. However, pulsar surveys [18] keep discovering heavier and heavier 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, that has probably formed through dynamical interactions. This binary consists of two low-mass neutron stars (1.36 and $1.35 M_{\odot}$)[29] 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 $10 - 30\%$ short GRBs can originate from mergers of double neutron stars formed in globular clusters [30].

If any observation can be made that establishes unambiguously a pulsar mass (either in the field or a globular cluster) over $2.5 M_{\odot}$, this would exclude double neutron stars as short GRB progenitors. We note that a tentative mass measurement for a pulsar of $2.74 \pm 0.21 M_{\odot}$ was recently reported by [31]. If this measurement is confirmed, other possible progenitor models for short GRBs will need to be reexamined.

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