Prompt merger collapse and the maximum mass of neutron stars

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We perform hydrodynamical simulations of neutron-star mergers for a large sample of temperature-dependent, nuclear equations of state, and determine the threshold mass above which the merger remnant promptly collapses to form a black hole. We find that, depending on the equation of state, the threshold mass is larger than the maximum mass of a nonrotating star in isolation by between 30 and 70 per cent. Our simulations also show that the ratio between the threshold mass and maximum mass is tightly correlated with the compactness of the nonrotating maximum-mass configuration. We speculate on how this relation can be used to derive constraints on neutron-star properties from future observations.

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Introduction: Merging neutron stars (NSs) are among the most promising sources of gravitational radiation for the new generation of gravitational wave (GW) interferometers. Detection rates for Advanced LIGO 1 and Advanced Virgo 2 have been estimated to be between 0.4 and 400 events per year 3. The merger may result either in a black hole (BH) with a hot accretion torus, or a massive, hot, differentially rotating NS. Compact binary mergers were also suggested as the central engines of short gamma-ray bursts (GRBs) 4, 5. Material that becomes gravitationally unbound during the coalescence may undergo rapid neutron-capture nucleosynthesis and contribute to the galactic enrichment by heavy, neutron-rich elements 6, 7. The heat release by the radioactive decay of the nucleosynthesis products may also power electromagnetic counterparts 8–9, which are already being searched for 10, 11.

The dynamics and observable signatures of NS merger depend on the binary masses \( M_1 \) and \( M_2 \) and the equation of state (EoS) 12, 23 (see also 24, 25 for reviews). At nuclear densities, the EoS is not completely known (see, e.g., 26) but plays a crucial role in determining the immediate outcome of coalescence. For sufficiently low-mass binaries the merger results in a stable NS. For more massive binaries the remnant will ultimately form a BH. In the delayed collapse scenario, the two stars form a single, differentially rotating merger remnant that is temporarily supported against gravitational collapse by centrifugal and thermal effects 27, 31. Viscous processes, radiation of GWs and emission of neutrinos redistribute and reduce the remnant’s angular momentum and energy, prompting a delayed collapse on a secular timescale. Alternatively, the merger may lead to an immediate, prompt collapse on a dynamical timescale. Such a collapse is triggered for more massive binaries, whose total mass \( M_{\text{tot}} = M_1 + M_2 \) cannot be stabilized. For a given EoS one can thus define a threshold binary mass \( M_{\text{thres}} \) that separates the two scenarios of prompt and delayed collapse. The former occurs for \( M_{\text{tot}} > M_{\text{thres}} \), while a dynamically stable remnant is formed for \( M_{\text{tot}} < M_{\text{thres}} \).

It is intuitive to assume that \( M_{\text{thres}} \) scales with the maximum mass \( M_{\text{max}} \) of isolated, nonrotating NSs 20,

\[
M_{\text{thres}} = k \cdot M_{\text{max}}. \tag{1}
\]

Here \( M_{\text{max}} \) is determined by the EoS and can be found by integrating the Tolman-Oppenheimer-Volkoff (TOV) equations (equations of relativistic hydrostatic equilibrium) 32, 33. The coefficient \( k \) also depends on the EoS, or equivalently on NS properties 12, 14, 20.

In this paper we adopt a large set of temperature-dependent, nuclear EoSs in numerical simulations of binary neutron-star mergers to examine the dependence of \( k \) on the EoS, and to establish a relation between \( M_{\text{thres}} \) and \( M_{\text{max}} \). We focus on equal-mass binaries, but also comment on asymmetric systems below. We find that \( k \) is tightly correlated with the compactness \( C_{\text{max}} = (GM_{\text{max}})/(c^2 R_{\text{max}}) \) of the maximum-mass TOV configuration (\( G \) is the gravitational constant and \( c \) the speed of light). We provide a simple, analytical model to motivate such a correlation, and discuss how our results can be used to constrain NS properties, in particular \( M_{\text{max}} \), from future observations. For a given EoS our findings predict which binary systems undergo prompt or delayed collapse upon merger with corresponding consequences for the post-merger GW signal, the mass ejection during coalescence and the particular conditions for launching a collimated outflow favorable for a GRB (e.g. torus properties and baryon loading of the environment).

Method: We perform numerical simulations of NS mergers to determine the EoS dependence of \( M_{\text{thres}} \), using a 3D relativistic smoothed particle hydrodynamics (SPH) code that employs the conformal flatness approximation of Einstein’s field equations and includes a GW backreaction scheme to account for energy and angular momentum losses due to GW emission (see 15, 34, 35 for...
details of the code). Our study considers 12 microphysical, fully temperature-dependent EoSs with maximum masses in the range of 1.95 to 2.79 \(M_\odot\), which is compatible with the observation of a 1.97 \(\pm 0.04\) \(M_\odot\) pulsar [30] (see Tab. 1). With the exception of the IUF EoS, these EoSs are also consistent with the detection of a NS with a mass of 2.01 \(\pm 0.04\) \(M_\odot\) [37]. The radii \(R_{\max}\) of the maximum-mass configurations vary between 10.32 and 14.33 km (see also [23] for the mass-radius relations of most EoSs considered here). The EoSs are chosen without any selection procedure and cover approximately the full range of high-density models regarding their stellar properties. As initial conditions we set up cold NSs in neutrinoless beta-equilibrium on a quasi-equilibrium orbit a few revolutions before merging. We assume irrotational stars since tidal locking is unlikely [38, 39] and the orbital period is short compared to possible stellar rotation. Unless stated otherwise we use a resolution of about 340,000 SPH particles.

For each EoS we determine \(M_{\text{thres}}\) by performing simulations of binaries with different values of \(M_{\text{tot}}\), which is defined as the binary’s total gravitational mass at infinitely large binary separation. We focus on equal-mass binaries here and increase \(M_{\text{tot}}\) in increments of 0.1 \(M_\odot\). We identify \(M_{\text{stab}}\) with the mass of the most massive binary in our sample with dynamically stable remnant, i.e. the most massive system that results in a delayed collapse. We similarly identify \(M_{\text{unstab}}\) with the mass of the least massive binary whose merger triggers prompt collapse. We then estimate \(M_{\text{thres}} = \frac{(M_{\text{stab}} + M_{\text{unstab}})}{2} \pm 0.05M_\odot\).

Since thermal pressure has an important effect on the collapse behavior (see, e.g., [31, 32, 52]), we have only considered fully temperature-dependent EoSs in this study. Many other simulations instead supplement a barotropic, zero-temperature EoS with a thermal ideal-gas component in order to approximate finite-temperature effects [12, 14, 19, 20, 22, 26, 33]. We have found that in such a “hybrid” treatment the threshold mass \(M_{\text{thres}}\) depends strongly on the ideal-gas index \(\Gamma_{\text{th}}\). Since \(\Gamma_{\text{th}}\) is neither unambiguously defined nor constant [32], fully temperature-dependent EoSs will provide more reliable values for \(M_{\text{thres}}\) than a hybrid treatment.

In order to calibrate the error introduced by the conformal flatness approximation we reproduced the fully relativistic simulations of [20] and found the same collapse behavior in all but one case, for which we obtained a small shift in \(M_{\text{thres}}\) [64]. We conclude that the effects of the conformal flatness approximation on our results are small. We verified that our resolution with SPH particles is sufficient by reproducing our findings for the DD2 EoS with both 731,000 and 1,200,000 SPH particles. Finally, we reran our simulations for the DD2 EoS starting with different initial binary separations (leading to 2.5, 3.5 and 4.5 orbits before merging) to confirm that this separation does not affect our results.

### Results

The EoS dependence of \(M_{\text{thres}}\) and \(k\) can be expressed by the stellar parameters of nonrotating NSs, which are uniquely determined by the EoS and thus characterize a given EoS. Our survey reveals that \(k\) scales very well with the compactness \(C_{\max} = (GM_{\max}^2)/(c^2R_{\max})\) of the maximum-mass configuration of nonrotating NSs (Fig. 1). We find a similarly tight relation when \(k\) is expressed as a function of \(C_{1.6} = (GM_{\max}^2)/(c^2R_{1.6})\), where \(R_{1.6}\) is the radius of a 1.6 \(M_\odot\) NS (see Fig. 1). Since \(R_{1.6}\) may be more easily determined than \(R_{\max}\), both by future observations [22, 24, 53, 54] and theoretical considerations [55], \(C_{1.6}\) might be a more useful quantity than \(C_{\max}\).

As can be seen in Fig. 1, \(k\) is a nearly linear function of \(C_{1.6}^6\) in the regime of interest. The maximum residual from the linear fit \(k = j \cdot C_{1.6}^6 + a\) with \(j = -3.606\) and \(a = 2.380\) is only 0.025 [65]. By fixing \(R_{1.6}\) or \(R_{\max}\) (see also the discussion of Fig. 3), \(M_{\text{thres}}\) becomes a quadratic function of \(M_{\max}\) only. Considering the maximum deviation of \(k\) from the fit implies that \(M_{\text{thres}}\) can be converted to \(M_{\max}\) with a precision of a few per cent for a fixed \(R_{1.6}\). An uncertainty of, for instance, 0.5 km in \(R_{1.6}\) would add another \(\sim 5\) per cent error. The actual error may be smaller because the deviation of \(k\) from the fit includes the intrinsic scatter among different EoSs but also an artificial contribution from the finite sampling of \(M_{\text{tot}}\) values.

We compared our findings with those of [20], where

| EoS       | \(M_{\max}\) \([M_\odot]\) | \(R_{\max}\) \([\text{km}]\) | \(C_{\max}\) | \(R_{1.6}\) \([\text{km}]\) | \(M_{\text{thres}}\) \([M_\odot]\) | \(\rho_c/\rho_0\) | \(f_{\text{peak}}\) \([\text{kHz}]\) |
|-----------|------------------|------------------|---------|------------------|------------------|------------------|------------------|
| NL3 [40, 41] | 2.79 | 13.43 | 0.307 | 14.81 | 3.85 | 5.6 | 2.78 |
| GS1 [42] | 2.75 | 13.27 | 0.306 | 14.79 | 3.85 | 5.7 | 2.81 |
| LS375 [43] | 2.71 | 13.24 | 0.325 | 13.71 | 3.65 | 6.5 | 3.05 |
| DD2 [41, 44] | 2.42 | 11.90 | 0.300 | 13.26 | 3.35 | 7.2 | 3.06 |
| Shen [45] | 2.22 | 13.12 | 0.250 | 14.46 | 3.45 | 6.7 | 2.85 |
| TM1 [46, 47] | 2.21 | 12.57 | 0.260 | 14.36 | 3.45 | 6.7 | 2.91 |
| SFHX [48] | 2.13 | 10.76 | 0.292 | 11.98 | 3.05 | 8.9 | 3.52 |
| GS2 [49] | 2.09 | 11.78 | 0.262 | 13.31 | 3.25 | 7.6 | 3.19 |
| SFHO [48] | 2.06 | 10.32 | 0.294 | 11.76 | 2.95 | 9.8 | 3.67 |
| LS220 [43] | 2.04 | 10.62 | 0.284 | 12.43 | 3.05 | 9.4 | 3.52 |
| TMA [47, 50] | 2.02 | 12.09 | 0.247 | 13.73 | 3.25 | 7.2 | 2.96 |
| IUF [41, 51] | 1.95 | 11.31 | 0.255 | 12.57 | 3.05 | 8.1 | 3.34 |

Table I: Sample of temperature-dependent, nuclear EoSs used in this study. Here \(M_{\max}\), \(R_{\max}\), \(C_{\max}\), and \(\rho_c\) are the gravitational mass, areal radius, compactness, and central energy density of the maximum-mass TOV configurations. We list \(\rho_c\) in units of the nuclear saturation density \(\rho_0 = 2.7 \times 10^{14}\) g/cm\(^3\). \(R_{1.6}\) is the areal radius of 1.6 \(M_\odot\) NSs. \(M_{\text{thres}}\) denotes the total binary mass that separates prompt from delayed collapse (see text). \(f_{\text{peak}}\) is the dominant GW frequency in the post-merger phase of the binary with \(M_{\text{tot}} = M_{\text{thres}}\), the most massive binary configuration of our sample that does not collapse promptly.
six barotropic EoSs with a hybrid treatment of finite-temperature effects were adopted and an approximate relation between $k$ and the radius $R_{1.4}$ of a 1.4 $M_\odot$ NS was suggested. Testing this relationship with our extended set of temperature-dependent EoSs results in a distribution with rather wide scattering instead of a tight correlation (see Fig. 2 left panel, and Tab. $R_{1.6}$ is very similar to $R_{1.4}$). However, using the numerical data of [21] and expressing $k$ as a function of $C_{1.6}^*$ or $C_{\text{max}}$ rather than $R_{1.4}$, we found a tight correlation, as for our results. Therefore, we suspect that the approximate scaling with $R_{1.4}$ suggested in [21] is a selection effect due to the limited number of EoSs used therein [60].

The compactness $C_{\text{max}}$ is a measure of the EoS’s stiffness at high densities (Fig. 2 right panel; see also [24, 50]), where we characterize the stiffness by the ratio of the mean density, $\langle \rho \rangle = 3\rho_{\text{max}}/(4\pi R_{\text{max}}^3)$, to the central density $\rho_c$ (i.e., the inverse central condensation). A tight correlation between $k$ and $C_{\text{max}}$ thus implies that $k$ depends predominantly on the stiffness of the EoS. This dependence can be motivated qualitatively with the help of a simple Newtonian model. As suggested in [51], a rough estimate of the fractional increase in the maximum mass, $\delta M/M_{\text{max}}$, is given by $3T/|W|$, so that $k \approx 1 + 3T/|W|$. Here $T$ is the rotational kinetic energy and $W$ the potential energy. We compute $T = J^2/(2I)$, where $I$ is the remnant’s moment of inertia, from the angular momentum $J$ that the binary carries at the instant of merging. Approximating the merging of an equal-mass binary in circular orbit to occur when the binary separation is twice the radius of each individual (spherical) star, $R_\ast$, and assuming that the progenitors’ masses are concentrated at their centers, we find $J^2 \approx GM_{\text{tot}}^3 R_\ast / 8$. Neglecting mass loss as well as deviations from spherical symmetry, and assuming that the merger remnant forms a polytrope with polytropic index $n$, we have $W = -3G/(5 - n) M_{\text{tot}}^2 / R$, where $R$ is the radius of the remnant, and $I = 2\kappa_n M_{\text{tot}} R^2 / 5$. Here the coefficients $\kappa_n$ depend on $n$ only and are tabulated in [58]. The EoS’s stiffness as well as $\kappa_n$ increases with decreasing $n$. Using the polytropic mass-radius relationship for the merging NSs and merger remnant we also have $R_\ast / R = 2^{(n-1)/(3-n)}$. Collecting terms we now obtain $k \approx 1 + 5(5-n) 2^{(n-1)/(3-n)} / (32 \kappa_n)$. While this crude approximation overestimates the deviation of $k$ from unity by about a factor of two, it correctly predicts two important qualitative features of our numerical results: It suggests that $k$ depends predominantly on the EoS’s stiffness (since for Newtonian polytropes the stiffness $\langle \rho \rangle / \rho_c$ depends on $n$ only), and it shows that $k$ decreases with increasing stiffness (which can be seen by inserting values for $n$ and $\kappa_n$). Loosely speaking, a binary with a stiffer EoS (i.e., a larger $\langle \rho \rangle / \rho_c$) has less angular momentum when merging and its remnant has a larger moment of inertia. These effects combine to decrease $T/|W|$, thereby decreasing $k$.

For the EoSs in our sample we also observe a tight correlation between $R_{\text{max}}$ and $R_{1.6}$, which implies a close relation between $C_{\text{max}}$ and $C_{1.6}^*$. Observational constraints on the maximum NS mass: The findings of this study may help to place limits on the maximum mass $M_{\text{max}}$ of NSs in the case that future observations, e.g., GW detections, provide an estimate of $M_{\text{thres}}$ (cf. [12]). We assume that delayed and prompt collapse can be distinguished from the presence or absence of GW emission in the 2-4 kHz range produced by the oscillations of the merger remnant, and that the binary mass of the merger can be inferred from the preceding GW inspiral signal, which thus sets a bound on $M_{\text{thres}}$. Depending on the nature of available observations, this
information could be used in different ways. In the following we discuss three speculative possibilities.

We first assume that a number of detections of NS mergers have been made, and that observations of both prompt and delayed collapses bracket $M_{\text{thres}}$ to a certain accuracy. If $R_{1.6}$ (or the radius of a NS of any other mass [65]) is independently known to some accuracy, either from future GW measurements (e.g. [23, 53, 54]) or astronomical observations [29], then the relation shown in Fig. 1 provides an estimate for the maximum mass of nonrotating NSs in isolation. The measured binary mass $M_{\text{tot}}$ then forms an upper limit for $M_{\text{thres}}$. These simulations with the SFHO, DD2, and NL3 EoSs for binary NS systems suggest small mass ratios (see, e.g., [29] for a review). However, in order to evaluate the effect of unequal masses we have performed additional simulations with the SFHO, DD2, and NL3 EoSs for binaries with total masses $M_{\text{stable}}$ and $M_{\text{unstable}}$ (as found from the equal-mass simulations), but now with a mass ratio $q = M_1/M_2 \approx 0.9$. For the given sampling of $M_{\text{tot}}$ we found that symmetric and asymmetric systems of the same total mass show the same collapse behavior. Generalizing our analytical considerations to non-equal masses, and expanding the result in deviations from symmetry, $\epsilon = q - 1$, shows that corrections appear at order $\epsilon^2$. This corroborates our numerical finding that moderate deviations of the mass ratio from unity have a small effect on $k$.

Future work could improve our study in a number of different ways. Even though we expect that effects of the conformal flatness approximation are small, it would be desirable to perform similar simulations with a fully relativistic treatment. These simulations should also include an even larger sample of temperature-dependent EoSs and should explore the effects of asymmetric binaries.

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[64] We compared models for the ALF2, SLy4 and APR4 EoSs, using a “hybrid” treatment for thermal effects, and found the same behavior as in [20] for all cases except for APR4, for which we obtained prompt collapse for a 1.42-1.42 M⊙ binary instead of a 1.4-1.4 M⊙ system.

[65] We found that similar quasi-linear relations also hold for C_max and for any other C∗ = (GM_max)/(c²R_NS), in which NS radii R_NS different from those of 1.6 M⊙ are used as EoS characterization, e.g. C_{1.4} = (GM_{max})/(c²R_{1.4}).

[66] The hybrid treatment of thermal effects employed in [20], with a relatively small value of Γ_{th} = 1.357, is likely to underestimate thermal pressure support [35]. This should be taken into account in a direct comparison of the k values.