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Black-hole formation in mergers of spinning neutron stars

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The mergers of neutron star (NS) binary systems are multi-messenger events and provide a wide range of observables, which can be used to explore and constrain the incompletely known Equation of State (EoS) at very high densities as well as stellar properties of neutron stars. These events can result in the formation of a black-hole (BH) due to a gravitational collapse. For a sufficiently high total binary mass the gravitational collapse to a BH occurs immediately after merging. This is called a prompt collapse and occcurs if the total mass exceeds a so called threshold mass. The threshold mass depends on the EoS and parameters of the binary systems like the mass ratio and intrinsic spin. In NS merger simulations the NSs are often assumed to be irrotational since their spin period are considered slow compared to the orbital period at merging of about 2 ms. But spins of NSs in binary system have been measured in the range of a few tens of milliseconds and therefore should also be included in simulations to study the effect of such spins. The rotation of the NSs in binary systems changes the total angular momentum of the system depending on the orientation of the spin angular momentum relative to the orbital angular momentum. Spin of NSs can have an significant impact on the observables and dynamics of the merger like the gravitational wave (GW) signal, dynamical ejecta, kilonova emission as well as properties of the remnant and thus also affect the threshold mass. To systematically investigate this influence on the threshold mass we discuss simulations of NS mergers with multiple spin configurations for equal-mass systems and different EoSs. We find a linear dependence of the threshold mass on the spin and observe an increase of 0.2-0.25 $M_\odot$ for the considered parameter space.

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1. Introduction

Neutron stars (NSs) are compact objects from supernova explosions of stars with a mass of more than 8 solar masses and have a mass of ~ 1-2 $M_\odot$ and radius between 10-15 km [1]. This leads to supra-nuclear densities, which is why neutron stars provide the opportunity to study the Equation of State (EoS) at high densities. The merger of binary NS systems are multi-messenger events that can be observed with the detection of gravitational waves (GWs) and their electromagnetic counterpart [2–4]. They provide a wide range of information, which can be used to constrain the EoS and stellar properties of NSs. Furthermore, they are thought to be a source for the formation of heavy elements through the rapid neutron-capture process (r-process) and short gamma-ray bursts, as discussed in e.g. Ref. [5]. So far two NS-NS merger events have been observed with GWs: GW170817 [2] and GW190425 [4].

2. Threshold mass

Mergers of binary NS systems result in either a massive NS remnant or a black hole (BH) through gravitational collapse while the outcome dominantly depends on the total mass of the system $M_{\rm tot} = M_1 + M_2$ with the mass of the heavier NS M_1 and the mass of the lighter NS M_2. Here, mass refers to the gravitational mass in isolation and the mass of the binary is the sum over the gravitational masses of the binary components at infinite separation. To quantify the collapse behaviour the so called threshold mass $M_{\rm thres}$ is used and if $M_{\rm tot} > M_{\rm thres}$ the system will undergo a direct gravitational collapse, which is also called a prompt collapse, and form a BH. For systems with $M_{\rm tot} < M_{\rm thres}$ a massive NS remnant results from the merger, which might collapse to a BH through a delayed collapse at a later time. The threshold mass systematically depends on the EoS and the mass ratio $q = M_2/M_1$ and decreases with higher mass asymmetry as discussed in Ref. [6]. Furthermore, the dependence of $M_{\rm thres}$ on q itself depends on the EoS.

3. Spin in NS binary systems

Generally, for neutron stars in binary systems the spin period is estimated to be in the order a few seconds to milliseconds [7, 8]. The spin of the individual neutron stars depends on the origin and evolution of the binary system. The heavier NS in the binary system usually possess a higher spin since it can be spun up through the accretion of matter and angular momentum from its companion star [8, 9]. The spin also depends on the duration of this accretion process and spin periods in the range of a few milliseconds are possible. Due to the spin-down effect the NSs slow down but the heavier NS shows a slow spin-down, which can lead to spin periods in the range of milliseconds at the time of the merger depending on the accretion process and spin period thereafter. The lighter NS spins-down faster to a final spin period of a few seconds. Further details about the spin-down effect of the NSs are discussed in Ref. [7–9].
The spin of the individual neutron stars is defined with the dimensionless spin parameter $\chi_i = J_i/M_i^2$ using its spin angular momentum J_i and mass M_i, note that $c = G = 1$. Furthermore, the effective spin $\chi_{\rm eff}$ of the system is the spin parameter that can be measured from the inspiral phase of the GWs, which is the mass weighted sum of the components of the spins χ_i along the axis of orbital

angular momentum. It is defined as $\chi_{\rm eff} = (M_1\chi_1\cos\Theta_1 + M_2\chi_2\cos\Theta_2)/(M_1+M_2)$ with the angles Θ_i between the axis of the spin and orbital angular momenta. For the merger event GW170817 the effective spin was determined to $\chi_{\rm eff} \approx 0$ [2, 3]. It should be noted that the effective spin is degenerate with the mass ratio, which complicates accurate measurements of both parameters, more details can be found in Ref. [3]. Spin periods in the 10 millisecond range affect the dynamics of NS binary mergers and have been observed multiple times for pulsars in binary NS systems in recent years [10–13]. The highest spin observed so far in a binary NS system is of the pulsar PSR J1946+2052 with a spin period of 17 ms [9, 14]. This systems is expected to merge in 46 Myr, its chirp mass was measured to $1.0882\,M_\odot$ and the total mass is estimated with $(2.50 \pm 0.04)\,M_\odot$. Zhu et al. (2018) estimated the spin χ of this pulsar to be about 0.031 to 0.043 at merging depending on the model for the spin-down and assuming the mass of the pulsar as $1.25\,M_\odot$ [9]. The spin of this pulsar is still considered slow compared to the orbital period of ~ 2 ms before merging but so far spin periods less than 10 ms have only been observed in pulsars outside of NS binary systems. For example, the pulsar PSR J1748-2446ad is the fastest detected pulsar to date with a frequency of 716 Hz and a dimensionless spin of $\chi \lesssim 0.4$ [2, 15].

4. Impact of spin on the threshold mass

Intrinsic rotation of the neutron stars in binary systems impacts the dynamics and observables of merger events. This is due to the change of total angular momentum in the system as it increases for spins aligned with the orbital angular momentum and decreases for anti-aligned spins. Therefore, the dynamics are impacted by the spin, which can be observed by various observables like the GW signal, dynamical ejecta, lifetime and disk size of the remnant and kilonova emission (see Ref. [10–13, 16] for further information). Furthermore, the remnant is directly influenced through the additional angular momentum in the system since it further stabilizes the remnant against gravitational collapse, which in turn changes the threshold mass. Additionally, the dominant postmerger frequency decreases for aligned spin as the remnant oscillates at a lower frequency since it is less compact due to the higher angular momentum compared to an irrotational system with the same total mass [11, 13]. These effects are stronger with faster rotation and become observable for spin periods of a few milliseconds. For this range the spin angular momentum is roughly more than 1% of the total angular momentum. Previously, the impact of spin on the threshold mass was studied by Tootle et al. (2021) and they found an increase of $M_{\rm thres}$ for spins aligned with the orbital angular momentum and a decrease for anti-aligned spins considering a maximum value for the effective spin of $\chi_{\rm eff} = \pm 0.2$ [17]. For systems with one rotating NS they considered one aligned and one anti-aligned spin setup for each configuration of mass ratio and EoS.

To further study the impact of spinning neutron stars in binary systems and to quantify the impact of spin on the threshold mass we consider various aligned spins for binary systems with one rotating neutron star. Similar to Ref. [6], for a given configuration of mass ratio q, EoS and spin χ_i the threshold mass is determined by increasing the total binary mass stepwise by $0.05\,M_\odot$ to find the heaviest stable and the lightest unstable mass configuration. The merger of systems with stable mass configurations ($M_{\rm tot} = M_{\rm stab}$) result in a massive NS remnant, which might undergo a delayed collapse, and systems with unstable mass configurations ($M_{\rm tot} = M_{\rm unstab}$) yield a prompt collapse. This defines the threshold mass with $M_{\rm thres} = 0.5\,(M_{\rm unstab} + M_{\rm stab})$ and leads to an accuracy of

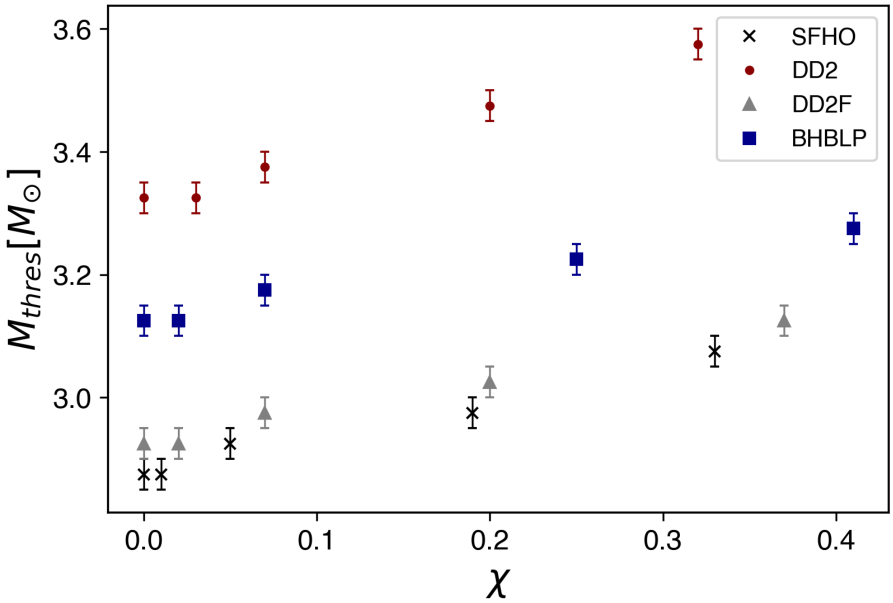

Figure 1: Threshold mass in dependence of the dimensionless spin χ of the rotating NS in equal-mass systems including an irrotational configuration for four EoSs.

$\Delta M_{\rm thres} = \pm 0.5\,(M_{\rm unstab} - M_{\rm stab}) = \pm 0.025\,\rm M_\odot$. To determine the outcome of the merger we consider the minimum lapse function $\alpha_{\rm min}$ and for a prompt collapse $\alpha_{\rm min}$ continuously decreases while for the formation of a massive NS remnant $\alpha_{\rm min}$ shows several bounces after the merger. The NS binary mergers are simulated using a general-relativistic smooth particle hydrodynamics (SPH) code, which solves the Einstein equations using the conformal flatness condition [18–20]. In Figure 1 the threshold mass is shown for configurations with $q = 1$ and different spins χ of the rotating NS for a set of four EoSs, which includes the SFHO [21], DD2 [22, 23], DD2F [23–25] and BHBLP EoS [26]. The threshold mass displays a linear increase for aligned spins for all four EoSs. The increase to the highest considered spin χ of $\sim$ 0.3-0.4 is 0.2-0.25 $\rm M_\odot$. This corresponds to an increase of $\sim$ 7% compared to the threshold mass for the irrotational system with $\chi = 0$. These data show no change of the threshold mass for spin periods in the range of the observed spins in binary systems with about 17 ms, which equals to a spin of $\chi \approx$ 0.01-0.03 depending on the EoS and exact spin period.

5. Conclusion

The spin of NSs in binary systems impacts the dynamics and observables of NS mergers due to the change in total angular momentum. We showed that the threshold mass increases with aligned spins in the system and found an increase of 0.2-0.25 $\rm M_\odot$ for the threshold mass for spins χ between 0.3 and 0.4 compared to $M_{\rm thres}(\chi = 0)$ for the considered set of EoSs. Our data suggests a linear increase of the threshold mass with spin considering equal-mass mergers and the rotation of one NS in the system. To further quantify and study this effect more configurations of q, EoS and χ should be considered in the future including asymmetric mergers and anti-aligned spins.

References

[1] N.K. Glendenning, *Compact Stars*, Springer US (1996), 10.1007/978-1-4684-0491-3.

[2] B. Abbott, R. Abbott, T. Abbott, F. Acernese, K. Ackley, C. Adams et al., *GW170817: Observation of gravitational waves from a binary neutron star inspiral*, *Phys. Rev. Lett.* **119** (2017) .

[3] B. Abbott, R. Abbott, T. Abbott, F. Acernese, K. Ackley, C. Adams et al., *Properties of the binary neutron star merger GW170817*, *Phys. Rev. X* **9** (2019) .

[4] B. Abbott, R. Abbott, T. Abbott, S. Abraham, F. Acernese, K. Ackley et al., *GWTC-1: A gravitational-wave transient catalog of compact binary mergers observed by LIGO and Virgo during the first and second observing runs*, *Phys. Rev. X* **9** (2019) .

[5] D. Eichler, M. Livio, T. Piran and D.N. Schramm, *Nucleosynthesis, neutrino bursts and γ-rays from coalescing neutron stars*, *Nature* **340** (1989) 126.

[6] A. Bauswein, S. Blacker, G. Lioutas, T. Soultanis, V. Vijayan and N. Stergioulas, *Systematics of prompt black-hole formation in neutron star mergers*, *Phys. Rev. D* **103** (2021) .

[7] X.-J. Zhu and G. Ashton, *Characterizing astrophysical binary neutron stars with gravitational waves*, *ApJL* **902** (2020) L12.

[8] T.M. Tauris, M. Kramer, P.C.C. Freire, N. Wex, H.-T. Janka, N. Langer et al., *Formation of double neutron star systems*, *ApJ* **846** (2017) 170.

[9] X. Zhu, E. Thrane, S. Osłowski, Y. Levin and P.D. Lasky, *Inferring the population properties of binary neutron stars with gravitational-wave measurements of spin*, *Phys. Rev. D* **98** (2018) .

[10] S.V. Chaurasia, T. Dietrich, M. Ujevic, K. Hendriks, R. Dudi, F.M. Fabbri et al., *Gravitational waves and mass ejecta from binary neutron star mergers: Effect of the spin orientation*, *Phys. Rev. D* **102** (2020) .

[11] L.J. Papenfort, E.R. Most, S. Tootle and L. Rezzolla, *Impact of extreme spins and mass ratios on the post-merger observables of high-mass binary neutron stars*, *Monthly Notices of the Royal Astronomical Society* **513** (2022) 3646.

[12] R. Dudi, T. Dietrich, A. Rashti, B. Brügmann, J. Steinhoff and W. Tichy, *High-accuracy simulations of highly spinning binary neutron star systems*, *Phys. Rev. D* **105** (2022) .

[13] W.E. East, V. Paschalidis, F. Pretorius and A. Tsokaros, *Binary neutron star mergers: Effects of spin and post-merger dynamics*, *Phys. Rev. D* **100** (2019) .

[14] K. Stovall, P.C.C. Freire, S. Chatterjee, P.B. Demorest, D.R. Lorimer, M.A. McLaughlin et al., *PALFA discovery of a highly relativistic double neutron star binary*, *ApJ* **854** (2018) L22.

[15] J.W.T. Hessels, S.M. Ransom, I.H. Stairs, P.C.C. Freire, V.M. Kaspi and F. Camilo, *A radio pulsar spinning at 716 Hz*, *Science* **311** (2006) 1901.

[16] A. Bauswein, N. Stergioulas and H.-T. Janka, *Exploring properties of high-density matter through remnants of neutron-star mergers*, *EPJ A* **52** (2016) 1.

[17] S.D. Tootle, L.J. Papenfort, E.R. Most and L. Rezzolla, *Quasi-universal behavior of the threshold mass in unequal-mass, spinning binary neutron star mergers*, *ApJL* **922** (2021) L19.

[18] J.R. Wilson, G.J. Mathews and P. Marronetti, *Relativistic numerical model for close neutron-star binaries*, *Phys. Rev. D* **54** (1996) 1317.

[19] R. Oechslin, S. Rosswog and F.-K. Thielemann, *Conformally flat smoothed particle hydrodynamics application to neutron star mergers*, *Phys. Rev. D* **65** (2002) .

[20] R. Oechslin, H.-T. Janka and A. Marek, *Relativistic neutron star merger simulations with non-zero temperature equations of state*, *A&A* **467** (2007) 395–409.

[21] A.W. Steiner, M. Hempel and T. Fischer, *Core-collapse supernova equations of state based on neutron star observations*, *ApJ* **774** (2013) 17.

[22] M. Hempel and J. Schaffner-Bielich, *A statistical model for a complete supernova equation of state*, *Nuclear Physics A* **837** (2010) 210.

PoS(FAIRness2022)020

[23] S. Typel, G. Röpke, T. Klähn, D. Blaschke and H.H. Wolter, *Composition and thermodynamics of nuclear matter with light clusters*, *Phys. Rev. C* **81** (2010) .

[24] S. Typel, *Relativistic model for nuclear matter and atomic nuclei with momentum-dependent self-energies*, *Phys. Rev. C* **71** (2005) .

[25] D. Alvarez-Castillo, A. Ayriyan, S. Benic, D. Blaschke, H. Grigorian and S. Typel, *New class of hybrid EoS and Bayesian M - R data analysis*, *Eur. Phys. J. A* **52** (2016) .

[26] S. Banik, M. Hempel and D. Bandyopadhyay, *New Hyperon Equations of State for Supernovae and Neutron Stars in Density-dependent Hadron Field Theory*, *ApJS* **214** (2014) 22.