Impact of high spins on the ejection of mass in GW170817

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ABSTRACT

Following the detection of GW170817 and the accompanying kilonova AT2017gfo, it has become crucial to model and understand the various channels through which mass is ejected in neutron-star binary mergers. We discuss the impact that high stellar spins prior to merger have on the ejection of mass focusing, in particular, on the dynamically ejected mass by performing general-relativistic magnetohydrodynamic simulations employing finite-temperature equations of state and neutrino-cooling effects. Using eight different models with dimensionless spins ranging from $\chi \simeq -0.14$ to $\chi \simeq 0.29$ we discuss how the presence of different spins affects the angular distribution and composition of the ejected matter. Most importantly, we find that the dynamical component of the ejected mass can be strongly suppressed in the case of high spins aligned with the orbital angular momentum. In this case, in fact, the merger remnant has an excess angular momentum yielding a more extended and “colder” object, with reduced ability to shed mass dynamically. We discuss how this result impacts the analysis of the recent merger event GW170817 and its kilonova afterglow.

Keywords: gravitational waves — gamma-ray burst: general — stars: neutron

1. INTRODUCTION

Following the detection of GW170817 (The LIGO Scientific Collaboration & The Virgo Collaboration 2017) and the subsequent electromagnetic counterpart (LIGO Scientific Collaboration et al. 2017), it has been possible to extract a number of different constraints and conclusions on the equation of state (EOS) of nuclear matter. Among them are the constraints on the maximum mass of isolated neutron nonrotating (Margalit & Metzger 2017; Shibata et al. 2017; Rezzolla et al. 2018; Ruiz et al. 2018) and on the possible ranges for radii of neutron stars (Annala et al. 2018; Most et al. 2018; Tews et al. 2018; Burgio et al. 2018; Raithel et al. 2018). In addition to the gravitational-wave signal, a crucial input for some of these works is the ejected mass from the merger site that has undergone nucleosynthesis and is hence responsible for the observed kilonova light curves (Kasen et al. 2017; Drout et al. 2017). Hence, having a very accurate modelling of the mass ejection and its origins is of great importance and several studies have already been made to elucidate the ejection mechanism and quantify the various ejection channels. Numerical simulations classify the ejection in terms of matter that is dynamically ejected (Hotokezaka et al. 2013; Bauswein et al. 2013; Radice et al. 2016, 2018; Palenzuela et al. 2015; Lehner et al. 2016; Sekiguchi et al. 2015, 2016; Dietrich & Ujevic 2017; Dietrich et al. 2017b,a; Bovard et al. 2017; Papenfort et al. 2018) during or shortly after the merger of the two stars, and in terms of matter that is ejected secularly (Siegel & Metzger 2017; Fernández et al. 2018; Fujibayashi et al. 2017), that is, on timescales $\gtrsim 100$ ms (see Gill et al. 2019, for a recent and extended discussion). Of these two channels, the second component is not yet very well understood, mostly due to the lack of long-term three dimensional studies, although notable exceptions exist, starting either from simplified initial conditions (Siegel & Metzger 2017; Fernández et al. 2018) or being restricted to two spatial dimensions (Fujibayashi et al. 2017). In comparison, the dynamically ejected mass component has been explored in far greater detail, using either fully consistent microphysical descriptions at finite temperature and in full general relativity (Radice et al. 2016, 2018; Lehner et al. 2016; Sekiguchi et al. 2015, 2016; Bovard et al. 2017), or in approximations of general relativity (Bauswein et al. 2013), or using a simplified microphysics treatment (Dietrich et al. 2017b,a; Hotokezaka et al. 2013; Ciolfi et al. 2017), together with analytical expressions that try to combine the abundance of data available (Dietrich & Ujevic 2017; Gill et al. 2019).

Another dynamically important parameter of the system influencing the ejection of mass is the spin of the individual neutron stars. Their magnitude or orientation are poorly
known as there are only few estimates from the limited set of binary pulsars in the Galaxy and the extraction of this information from the gravitational-wave signal of GW170817 has proved difficult so far (Zhu et al. 2018), forcing the discussion on the physical properties of GW170817 to be split between the “low-” and “high-spin” scenarios (The LIGO Scientific Collaboration & The Virgo Collaboration 2017). This uncertainty in the modelling of the dynamical mass ejection is matched by the absence of detailed studies for consistent spinning neutron-star merger simulations. Studies so far have either used inconsistent initial conditions (Kastaun et al. 2013, 2017) or a simplistic model for the description of matter (Dietrich et al. 2017a). More specifically, although Dietrich et al. (2017a) have studied in great detail the effect of spin on the gravitational-wave signal and on the mass ejection, only small dimensionless spins $\chi \simeq 0.1$ were used. Furthermore, the absence of neutrino interactions makes it difficult to classify the reasonable amount of shock heating and composition of the ejected matter.

In this Letter we attempt to fill this gap and study the mass ejection of high spin systems up to $\chi > 0.29$ for two finite-temperature EOSs, representing both high and low compactness, with the latter being favoured by the detection (Annala et al. 2018; Most et al. 2018; Abbott et al. 2018).

| $\chi$ | $\Omega \times 10^{-3}$ $[M_\odot^{-1}]$ | $J_{ADM}$ $[M_\odot^2]$ | $P$ $[\text{ms}]$ | $M_{ej} \times 10^{-3}$ | EOS |
|-------|-----------------|-----------------|-------------|-----------------|-----|
| $-0.148$ (↓↓) | 8.77 | 6.89 | -3.34 | 4.41 | TNTYST |
| $-0.002$ (00) | 8.75 | 7.37 | -258 | 2.73 | TNTYST |
| 0.106 | 8.74 | 7.72 | 4.49 | 0.31 | TNTYST |
| 0.287 (↑↑) | 8.81 | 8.39 | 1.75 | 0.24 | TNTYST |
| $-0.142$ (↓↓) | 8.76 | 6.90 | -4.35 | 1.45 | BHBAΦ |
| $-0.001$ (00) | 8.75 | 7.37 | -619 | 0.64 | BHBAΦ |
| 0.156 | 8.75 | 7.90 | 3.93 | 0.62 | BHBAΦ |
| 0.194 (↑↑) | 8.75 | 8.04 | 3.18 | 0.37 | BHBAΦ |

Table 1. Initial binary configurations. Reported are: the dimensionless stellar spin $\chi$, the period $P$, the orbital angular frequency $\Omega$, the ADM angular momentum $J_{ADM}$, and the ejected mass $M_{ej}$. All binaries have $M_{ADM} = 2.700$ and are at an initial separation of 45 km. The labels (↓↓), (00) and (↑↑) refer to reference binaries.

Figure 1. Distribution of dynamically ejected matter $M_{ej}$ during and shortly after the merger, with $\chi$ referring to the dimensionless spin of the neutron stars in the binary. The upper panel shows the absolute value of the ejected mass the lower panel the relative value normalised to the irrotational case $M_{ej}^{(00)}$. The dashed lines refer to lower bound reference values in the literature.
to $\simeq 1500$ km and using a total of seven levels with a highest resolution of $\simeq 250$ m.

The final important ingredient is the description of nuclear matter at finite temperatures. In light of recent studies on EOSs and neutron-star properties following the detection of GW170817 (Annala et al. 2018; Most et al. 2018; Abbott et al. 2018), we select two temperature-dependent EOSs: TNTYST (Togashi et al. 2017) and BHBA$\Phi$ (Banik et al. 2014), to representing the bounds on small and high tidal deformabilities.

Every star in the binary systems is initially endowed with a poloidal magnetic field of $10^{15}$ G at its center. While magnetic fields are very important to study secular outflows, the impact they have on the dynamical mass ejection are small and we will not discuss them here for compactness.

3. RESULTS

To study the effect of spin on the dynamical mass ejection, we consider a total of eight systems modeled using two EOSs and having either spins aligned or misaligned with the orbital spin angular momentum. Since we are interested in studying the most pronounced impact that spins have on the ejection, we do not consider systems where only one of the stars is spinning (Dietrich et al. 2017a), nor do we take into account unequal-mass binaries, despite GW170817 has an associated mass ratio of $\simeq 0.85$ (The LIGO Scientific Collaboration et al. 2019). While we plan to consider these effects in future work, we note that unequal-mass binaries are expected to yield systematically larger matter outflows, so that the constraints pointed out here can only become stronger.

Depending on the spin orientation and starting from a separation of $45$ km, the two stars inspiral for several orbits before they merge. The systems with large aligned spins take longer to radiate away the orbital angular momentum and will hence merge later than the systems with misaligned spin Kastaun et al. 2013, (see also Dietrich et al. 2017a; Ruiz et al. 2019, for a detailed description). After the merger, we record the mass that is unbound according to the geodesic criterion (Bovard et al. 2017) and crosses a sphere at a radius of $600$ km, thus obtaining the dynamically ejected mass by an integration over roughly $15 - 20$ ms, when the mass flux drops significantly in all cases.

Before focussing on three fiducial cases – misaligned high spins (↓↓), no spins (00), and aligned high spins (↑↑) – we give an overview of the amount of dynamically ejected matter for all models listed in Table 1. This is shown in Fig. 1, which reports the amount of dynamically ejected mass depending on the dimensionless spin $\chi$. The upper panel refers to the absolute value of the ejected mass, while the lower
panel emphasizes the difference with the respect to the irrotational case, which is the most common in merger simulations.

Note that intermediate misaligned spins $\chi \sim -0.14$ lead only to a small twofold increase compared with the irrotational case, while for high aligned spins $\chi \lesssim 0.29$ we find that large aligned spins can significantly reduce the mass ejection by about a factor of two in the case of the stiff BHBΛΦ EOS and even of about one order of magnitude in BHBΛΦ especially in the case of the softer TNTYST EOS – and are distributed to higher latitudes. This is due to the fact that the misaligned binaries not only have the smallest amount of angular momentum after merger, and so higher radial velocities in the ejecta (see also Fig. 4), but also the largest plunge velocity at merger. Indeed, these binaries inspiral with fewer orbits and merge with a radial velocity for the TNTYST (BHBAΦ) EOS that – in units of the speed of light – is $\simeq 0.042 (0.035)$; these plunge velocities should be compared with $\simeq 0.028 (0.027)$ for the aligned case. On the other hand, when considering aligned high-spin binaries (top row in Fig. 2), we find that mass ejection is significantly suppressed, up to one order of magnitude for the TNTYST EOS. Furthermore, the ejection is strongly beamed towards the equator, a clear indication that the origin of the mass ejection is purely tidal, consistent with the fact of the two stars having a significantly reduced relative velocity at merger, in analogy with what happens in eccentric mergers (Radice et al. 2016; Papenfort et al. 2018). An important difference with respect to the other two cases is that the ejecta are mainly neutron rich and even the polar regions feature significantly smaller electron fractions.

Much of the phenomenology discussed above is reflected in the gravitational-wave emission from the merger remnant. Figure 3 reports the amplitude of gravitational-wave strain ($\ell = 2 = m$ mode of the $h_{+}$ polarization) for the three reference systems described by the TNTYST EOS. To aid the visual comparison, the amplitudes of the signals are shown in the inset.

When contrasting the irrotational binaries with the misaligned-spin ones (bottom row in Fig. 2), it is clear that in this case most of the ejecta is driven by strong shock-heating – especially in the case of the TNTYST EOS – and are distributed to higher latitudes. This is due to the fact that the misaligned binaries not only have the smallest amount of angular momentum after merger, and so higher radial velocities in the ejecta (see also Fig. 4), but also the largest plunge velocity at merger. Indeed, these binaries inspiral with fewer orbits and merge with a radial velocity for the TNTYST (BHBAΦ) EOS that – in units of the speed of light – is $\simeq 0.042 (0.035)$; these plunge velocities should be compared with $\simeq 0.028 (0.027)$ for the aligned case. On the other hand, when considering aligned high-spin binaries (top row in Fig. 2), we find that mass ejection is significantly suppressed, up to one order of magnitude for the TNTYST EOS. Furthermore, the ejection is strongly beamed towards the equator, a clear indication that the origin of the mass ejection is purely tidal, consistent with the fact of the two stars having a significantly reduced relative velocity at merger, in analogy with what happens in eccentric mergers (Radice et al. 2016; Papenfort et al. 2018). An important difference with respect to the other two cases is that the ejecta are mainly neutron rich and even the polar regions feature significantly smaller electron fractions.

1 The fitting formulas of Radice et al. (2018) and of Dietrich & Ujevic (2017) yield negative values when considering the TNTYST EOS for our binary configuration.
larger ejection of high-$Y_e$ matter. As expected, the irrotational binary is intermediate between these two cases.

Finally, we report in Fig. 4 the relative distributions of $Y_e$, of the entropy $s$ per baryon and of the velocity $v$ of the ejecta. For both EOSs, the behaviour is qualitatively the same: the misaligned and the irrotational binaries have similar compositions peaking around $Y_e \approx 0.1$ and then rapidly falling off until about $Y_e \approx 0.35$. Most of these ejecta have small entropies $s < 20 k_B / \text{baryon}$, with $s < 80 k_B / \text{baryon}$ almost everywhere. The material for these two systems also has outflow velocities reaching up to 0.6. On the other hand, the aligned spinning binaries have large amounts of ejecta around $Y_e < 0.05$ and almost no material is present with $Y_e > 0.3$; a cut-off in the electron fraction is present in both EOSs. Similarly, the velocity $v$ of the ejecta in the aligned binaries peaks around small values $v \approx 0.1$, pointing to the absence of strong shock heating in most of the matter, with a cut-off velocity of $v \approx 0.35$ for both EOSs.

Following the approach by Abbott et al. (2017), we can make simple estimates of the spin-induced differences in the kilonova emission from the dynamical ejecta of our models. Employing the simplest model used by Abbott et al. (2017), which is the semi-analytical model from Wollaeger et al. (2018) in the grey-opacity approximation, we can express the ratio of the peak epoch of the kilonova emission $t_p$, and of peak bolometric luminosity $L_p$, as

$$
\frac{t_p^{\uparrow \uparrow}}{t_p^{\downarrow \downarrow}} \approx \left( \frac{\langle v \rangle^{\uparrow \uparrow}}{\langle v \rangle^{\downarrow \downarrow}} \right)^{0.60} \left( \frac{M_{ej}^{\uparrow \uparrow}}{M_{ej}^{\downarrow \downarrow}} \right)^{0.32}, \tag{1}
$$

$$
\frac{L_p^{\uparrow \uparrow}}{L_p^{\downarrow \downarrow}} \approx \left( \frac{\langle v \rangle^{\uparrow \uparrow}}{\langle v \rangle^{\downarrow \downarrow}} \right)^{0.78} \left( \frac{M_{ej}^{\uparrow \uparrow}}{M_{ej}^{\downarrow \downarrow}} \right)^{0.43}, \tag{2}
$$

where $\langle v \rangle$ is the mass-averaged velocity of the ejecta.

In the case of a soft EOS such as TNTYST, the simplified estimates in (1) lead to significant difference in the peak time, $t_p^{\uparrow \uparrow} / t_p^{\downarrow \downarrow} \approx 2.2$, and luminosity $L_p^{\uparrow \uparrow} / L_p^{\downarrow \downarrow} \approx 4.3$ of the kilonova emission from the dynamical ejecta. Two important implications follow from this result. First, a careful consideration of spin effects needs to complement any study of the kilonova emission. Second, by measuring the basic features of the kilonova emission – peak time and luminosity – it is in principle possible to extract information on the spins of the binaries, a property that has been elusive so far.

4. CONCLUSIONS

We have presented GRMHD simulations of neutron-star mergers having high component spins and employing two temperature-dependent EOSs representing the soft and stiff limits of current constraints (Annala et al. 2018; Most et al. 2018; Abbott et al. 2018). By varying the orientation as well as the magnitude of both stellar spins, we were able to reveal a strong impact on dynamical mass ejection and highlight the changes in the nuclear composition of the material. In particular, binaries with high spins aligned with the or-
bital angular momentum lead to a strong suppression of the ejected mass when compared to the standard case of irrotational binaries. At the same time, misaligned configurations show only a modest increase. We found that this effect was most pronounced for the soft TNTYST EOS, where it lead to a suppression of one order of magnitude compared with the non-spinning case.

The physical origin of this behaviour lies with an increased total angular momentum at merger of the binaries with aligned spins and consequently with the decreased plunge velocities when the two stars collide. In turn, this process leads to a merger remnant that is more extended and “colder” than in the case of irrotational binaries, thus with a reduced ability to shed mass dynamically, but more efficient in radiating gravitational waves. In contrast, binaries with large misaligned spins collide with larger velocities and yield, for the same EOS, a remnant that is more compact, “hotter” and less luminous in gravitational waves.

Our simulations have also shown that the spatial distribution and composition of the ejected matter vary with spin. Most notably, we have demonstrated that binaries with high aligned spins eject extremely neutron-rich material and at lower average velocities. The contrary is true for binaries with large misaligned spins. Finally, we have highlighted how neglecting the effects of high spin on the dynamical ejecta overestimates the amount of ejected mass and can in principle lead to significant deviations in the modelling of the resulting kilonova emission, in particular in the peak epoch and peak bolometric luminosity of the red component. If the remnant disk mass after collapse will be similarly and consistently suppressed as the dynamically ejected mass, then by measuring the peak time and magnitude of the luminosity of the red component compared to the blue component of the kilonova it would be possible to obtain a constraint on the spin configuration of the system that is tighter than what can be inferred from the gravitational-wave emission during the inspiral by current detectors.

Our simulations inevitably cover only a small but representative portion of the space of parameters spanned by the EOSs, masses, mass ratios, and spin configurations. Further studies, and the development of new temperature-dependent EOSs, will be needed to set tighter constraints on how the dynamically ejected matter relates to the stiffness of the EOS and to the spin configuration. These simulations will also be able to confirm an implicit assumption in our work, namely, that the secular ejection of matter follows the same dependence on spin as that of the dynamical ejection. Thus, expect that a difference in angular momentum and compactness of the remnant directly translates to different lifetimes and disk masses after collapse to a black hole. Only long-term self-consistent simulations accounting for magnetically and neutrino driven winds will be able to validate or confute this assumption.

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