BINARY NEUTRON STAR MERGERS:

Testing Ejecta Models for High Mass-Ratios

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Mentor

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Abstract

Neutron stars are extremely dense stellar corpses which sometimes exist in orbiting pairs known as binary neutron star (BNS) systems. The mass ratio (q) of a BNS system is defined as the mass of the heavier neutron star divided by the mass of the lighter neutron star. Over time the neutron stars will inspiral toward one another and produce a merger event. Although rare, these events can be rich sources of observational data due to their many electromagnetic emissions as well as the gravitational waves they produce. The ability to extract physical information from such observations relies heavily on numerical simulations of merger events. In this project, we report results of six simulations for BNS mergers having total system masses of 2.50 or 2.75 M_{sun} and with mass ratios of 1.75, 2.00, and 2.25 (the highest mass ratio simulated in the world). Our goals are to (a) test community-developed models of the ejecta produced by BNS mergers, (b) examine the gravitational waveforms for distinctive spectral characteristics, and (c) estimate the electromagnetic emissions of the merger remnants. Simulations are run using the Einstein Toolkit and employ a semirealistic seven-segment piecewise-polytrope model for the neutron stars based on the Skyrme-Lyon equation of state. We find that the community models of ejecta are robust, with some systematic overestimation of the amount of ejecta produced at extremely high mass ratios. Also, several gravitational wave and electromagnetic characteristics are identified, such as reduced gravitational spectral peaks and extended kilonova emissions in the near infrared for weeks after the merger.

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INTRODUCTION

Neutron stars are stars at supranuclear density, tending to have masses one to two times that of the sun with a radius of about 10 km. From this we determine that the maximum density of a neutron star is roughly 10^{15} g/cm^3 . The nuclear equation of state of matter at this extreme density is not known. Due to various mechanisms, two neutron stars can sometimes form a gravitationally bound pair called a binary neutron star (BNS) system. Over time these two stars will lose orbital energy and gradually inspiral toward one another until they eventually merge. This event is called a BNS merger. For a summary review, see Baiotti and Rezzola (2017). BNS mergers are especially violent and highly energetic, producing gravitational waves (Abbot et al., 2017b) and a short gamma ray burst (Abbot et al., 2017a). During the merger process neutron star material can become gravitationally unbound by several mechanisms, allowing it to escape out into the host galaxy. One such method for ejection relies on tidal interactions and shock heating to throw material outward at high velocity; this material is called dynamical ejecta (hereafter simply ejecta). Ejecta play a critical role in galactic chemical evolution including the formation of heavy elements, which due to their high velocity can be dispersed over interstellar distances. Numerical simulations typically include estimates of the ejecta characteristics, such as the mass, velocity, and geometric distribution of the ejecta. Based on results of simulations from many researchers, Dietrich and Ujevic (2017) and Radice et al. (2018) developed fitted models of ejecta properties.

Currently the total number and spatiotemporal distribution of neutron stars is not fully known, but by using population synthesis models a multitude of estimates can be made regarding the number of neutron star binary systems. These population models predict that a detectable fraction of BNS mergers will have mass ratios as high as $q = 2.00$ (Dietrich et al., 2015). However, community research has focused mostly on simulations of BNS mergers with mass ratios $q < 1.5$. Although this is understandable, since most BNS mergers are expected to have mass ratios near 1, there may be distinctive traits for high mass ratio mergers that could provide stronger insights regarding neutron star structure and remnant properties. Thus, our research seeks to explore these possibilities by focusing on extreme mass ratios $q > 1.5$, with three goals in mind. First, we aim to test the accuracy of the community-developed ejecta models. Second, we study the distinct gravitational wave characteristics

in order to test spectral features found in low mass ratio BNS mergers. Third, estimation of the electromagnetic emissions produced by high mass ratio mergers may show distinctive features relative to low mass ratio mergers.

METHODS

We conduct simulations at two different resolutions for each of six different BNS systems. The six systems have total neutron star masses of either 2.50 or $2.75 M_{\text{sun}}$ and mass ratios of either 1.75, 2.00, or 2.25. While the last of these mass ratios is perhaps unrealistically large, it is hoped that its inclusion may exaggerate and make clearer any distinguishing trends or signals that may be present but less pronounced at the lower mass ratios.

Initial models of the neutron stars for each system are constructed using the LORENE pseudospectral code (Gourgoulhon, Grandclement, Taniguchi, Marck, & Bonazzola, 2001). The neutron stars are initially placed 45 km apart, allowing several orbits before merger. We assume a Skyrme-Lyon equation of state for the neutron stars, modeled as seven-segment piecewise-polytropes. This is a standard and semirealistic assumption that is generally consistent with observations of neutron stars to date, such as seen in Abbot et al. (2017b). Our model has several flaws, including an absence of neutrinos as well as neutrino-driven winds and cooling, no modeling of neutron capture or electron fraction, and an assumption of no initial magnetization of the neutron stars. It is left to future work to alleviate these flaws.

Once constructed, each BNS system is evolved using the Einstein Toolkit (Löffler et al., 2012), an open-source community-developed numerical relativity package. All simulations reported here use the “Tesla” release of the Einstein Toolkit. To estimate uncertainties due to numerical rounding and resolution limitations, we evolved each system at two different resolutions. Results from the highest-resolution simulations, accurate down to 369 m, provide our best estimates. The deviations between these results and the results of identical simulations run at a lower resolution of 554 m are used to calculate the uncertainties attached to our best estimates. All simulations are conducted on the Rice cluster housed at Purdue University using 160 cores.

Once completed, the data produced from each simulation are downloaded to a local workstation for study. Visualizations of the data are produced using a publicly available software package called VisIt (Childs et al., 2016). These visualizations are used to ensure that the simulations are well behaved

and to aid interpretation of numerical analyses. Also using VisIt, ejecta are identified following the method of Dietrich and Ujevic (2017), and their total mass and energy are calculated. We created Python scripts to extract gravitational waveforms from the simulations, based on the method described in De Pietri, Feo, Maione, and Löffler (2016). Spectrograms and power spectral densities of the waveforms are then calculated to identify distinguishing features of high mass ratio systems. Finally, calculations of the light emitted from the ejecta (called a kilonova) are performed using light curve model estimates by Dietrich and Ujevic (2017).

RESULTS

Examples of the identified ejecta from the simulations are shown in the first three figures below. Figure 1 shows a snapshot from the $M = 2.75 M_{\text{sun}}$, $q = 1.75$ simulation, with surfaces representing various densities of bound matter (in shades of orange) orbiting the black hole that has formed (the small dark sphere corresponds to the apparent horizon) and other surfaces representing various densities of ejected matter (in shades of green and blue). Note that the densities of the ejected material are far lower than the densities of the bound material, and there is quite a bit of diffuse bound material not shown here for the sake of visual clarity. The background stars and nebula in the image are purely aesthetic and not part of the simulation.

The ejecta are again plotted with green surfaces in Figure 2, which is zoomed out. In general, portions of the ejecta travel as fast as 30% the speed of light, covering hundreds of kilometers in milliseconds on their way out of the system. As seen in Figure 2, the physical time for this snapshot is nearly 14 milliseconds after the start of the simulation. Figure 3 plots the density of the ejecta in both the equatorial and meridional planes at this time. The distance scales are plotted in code units ($100M = 147$ km). This shows that the ejecta is far from uniform within the spherical sector that it occupies, with greatest density occurring in a thin clump moving near the $+y$ -axis.

Estimations of the total mass, average velocity, and total kinetic energy of the ejecta are made by creating Python scripts within VisIt. These results are then compared to predictions based on the community models from Dietrich and Ujevic (2017), producing the residuals shown in Figure 4. The uncertainties on each residual are obtained by similar calculations for the ejecta produced in the corresponding lower-resolution versions of the

Figure 1. 3-D ejecta density model.

Note: $M = 2.75M_{\text{sun}}$, $q = 1.75$ simulation at time $t = 11$ milliseconds, showing diffuse ejecta material in green, with dense bound material in orange orbiting the recently formed black hole produce from the merger.

Figure 2. 3-D ejecta density model (zoomed out).

Note: The same simulation from Figure 1 at later time $t = 14$ milliseconds. The perspective has been zoomed out to include the expanding sector of diffuse ejecta material colored in green.

Figure 3. 2-D ejecta density model.

Note: The same simulation as Figures 1 and 2 at time $t = 14$ milliseconds, plotting the density of ejecta material only in both equatorial (top) and meridional (bottom) planes. The colors here do not correspond to the colors in Figures 1 or 2.

simulations, as described in the “Methods” section. It was not clear beforehand whether the tidal shearing of the lighter neutron star in each system might become more pronounced, producing more ejecta than for low mass ratio mergers, or whether the gravitational attraction of the heavier neutron star in each system might dominate, producing less ejecta than for low mass ratio mergers.

Overall, the results reinforce the community models for the total kinetic energy and average velocity of the ejecta and suggest a systematic overestimation of the ejecta mass that worsens at the highest mass ratio of 2.25. This indicates that at extremely high mass ratios the gravitational attraction of the heavier neutron star decreases the amount of ejecta by a small amount, but this effect is insignificant for ratios below roughly 2.25. Overall, the models are broadly confirmed even at these extreme mass ratios. Results for the residuals relative to the models from Radice et al. (2018) are qualitatively similar.

The gravitational waveforms are plotted in Figure 5. Inspecting this figure, we can see an increase in gravitational wave amplitude as the two stars’

Figure 4. Comparison of our results to community models.

Note: Deviations between our results and the fitted models of Dietrich and Ujevic (2017) are plotted for ejecta mass, ejecta kinetic energy, and ejecta velocity. Our results are generally consistent with these models, with some discrepancy for the ejecta mass at increasing mass ratio.

respective velocities increase. The amplitude reaches a maximum at the moment of coalescence, and then we see two different patterns depending on the total mass of the BNS system. Merger events for a total mass of $2.50M_{\text{sun}}$ result in a short-lived hypermassive neutron star (HMNS) with a smaller-amplitude “rumbling” that persists for many milliseconds until the end of our simulations. The term “hypermassive” means that these remnant neutron stars are so massive they would collapse directly to form black holes if they were stationary. However, their rapid rotation rates provide a temporary centrifugal effect that counters the gravitational attraction of the remnant and staves off black hole formation for some amount of time. The other pattern for merger events with a total mass of $2.75M_{\text{sun}}$ shows the waveforms disappear almost immediately after a black hole forms in each simulation. This is because the centrifugal effect is too weak to delay gravitational collapse.

These results are different from what is observed for low mass ratio mergers having the same total mass as in De Pietri et al. (2016), where systems with total masses as high as $3.0M_{\text{sun}}$ show delayed black hole formation despite using the same nuclear equation of state as our simulations. This is likely due to the greater rotational velocity achieved by low mass ratio systems. High mass ratio systems show a prompt merger due to the extended size of the lightweight neutron star and the greater tidal effect across it that is produced from the heavier neutron star. By causing the merger to occur more rapidly, the inspiral is unable to last as long, and the stars do not reach as high an orbital velocity, weakening the

Figure 5. Gravitational waveforms for each of the 6 simulations.

Note: Wave amplitudes for the dominant mode of gravitational wave emission—called the (2,2)-mode—are shown as functions of time.

centrifugal effect that helps to prop up the neutron star remnant against gravitational collapse.

Figure 6 displays spectrograms that illustrate how the energy of the gravitational waves was distributed over frequencies up to 5500 Hz, while Figure 7 shows the associated power spectral densities. Using the $M = 2.50M_{\text{sun}}$, $q = 1.75$ simulation as an example, after the merger the distinct “rumbling” can be seen as a continuing high-frequency signal near 1800 Hz in Figure 6. Examination of the power spectral density for this simulation in Figure 7 shows a well-defined peak near this frequency, with associated secondary peaks on either side of it at roughly 1000 Hz and 2600 Hz.

The primary frequency is produced by the bar-deformed remnant spinning after the merger, consistent with results from lower mass ratio simulations such as De Pietri et al. (2016). However, the primary frequencies are far lower, and the amplitudes for each peak are also smaller, again

likely due to the tidal effects that drive our high mass ratio systems to quick mergers. The origins of the secondary peaks are not well understood, although the lower-frequency peak may be due to the one-armed spiral pattern of material orbiting the hypermassive neutron star remnant that was formed from shearing of the low-mass neutron star during inspiral. The higher-frequency peak near 2600 Hz is less understood and may be produced by pulsating oscillations in the shape of the remnant itself.

Finally, the estimated light curves for the kilonova produced by ejecta are calculated and several illustrative results are shown in Figure 8. For each of the two total system masses ($M = 2.50, 2.75M_{\text{sun}}$), light curves for the lowest mass ratio (1.75) are plotted as solid lines, and those for the highest mass ratio (2.25) are plotted as dashed lines. The light curves for the intermediate mass ratio (2.00) lie between these two and are not plotted for the sake of visual clarity.

Figure 6. Gravitational wave spectrograms for each of the 6 simulations.

Note: Powers are color-coded for frequencies up to 5500 Hz as functions of time, with yellow indicating high-intensity emission at a particular frequency during a particular instant of time and purple indicating low intensity.

Figure 7. Gravitational power spectral density plots for each of the 6 simulations: Difference in $M = 2.50M_{\text{sun}}$ and $M = 2.75M_{\text{sun}}$ merger events.

Note the dominant peak for $M = 2.50M_{\text{sun}}$ simulations near 1800 Hz due to postmerger emissions.

Figure 8. Kilonova light curves for mass ratios.

Note: $q = 1.75$ (solid lines), and $q = 2.25$ (dashed lines).

These light curves suggest that the kilonova for each of these six BNS mergers would peak in the near-infrared bands (J, H, K) after 7–10 days. These bands correspond to wavelengths of 1.25 μ , 1.65 μ m, and 2.2 μ m, respectively. The near-infrared emissions would persist for nearly three weeks before dimming significantly, making for particularly long-lived kilonova. In contrast, near-infrared emissions from low mass ratio mergers are expected to fade after roughly two weeks.

CONCLUSION

Our results broadly confirm the community models for mass ejecta from BNS mergers with only a weak suggestion of overestimation for the ejecta mass at BNS mass ratios near or exceeding 2.00. For ejecta velocity and kinetic energy, our results strongly confirm community models even for extreme mass ratios. Our results for gravitational wave patterns are consistent with simulations of BNS merger events for lower mass ratios but demonstrate significantly lower peak frequencies and amplitudes due to tidal shearing of the low-mass neutron star in each case. Kilonova light curve results predict persistent near-infrared radiation emission for at least three weeks, which is significantly longer than community models expect for low mass ratio mergers.

FUTURE RESEARCH

In continuation of our research, we will build on our previous results and begin to study the effects that magnetization has on mass ejecta and gravitational wave characteristics. Simulations of magnetized BNS mergers with mass ratio $q = 1.75$ at total masses of 2.50 and 2.75 M_{sun} will be conducted. Results from this future research will then be compared to community models and the results described above.

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