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BINARY-BINARY INTERACTIONS:
THE ROLE OF POST-NEWTONIAN TERMS IN FACILITATING ECCENTRIC BLACK HOLE MERGERS

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1. INTRODUCTION

Four binary black hole (BBH) systems (Abbott et al. 2016c,b, 2017; The LIGO Scientific Collaboration et al. 2017) and one BBH candidate (Abbott et al. 2016a) have currently been discovered by the LIGO/Virgo interferometer network (Aasi et al. 2013; Acernese et al. 2015). As the sensitivity of the network increases over the coming years, we expected many more systems such as these to be sensed by their gravitational wave (GW) emission (Abbott et al. 2016d).

These systems provide the best observational evidence of binary black holes, and the most direct means of uncovering their origins. Multiple formation channels for BBHs have been proposed with the ability to describe the some or all of the current catalog of GWs, and each makes different predictions for what the rate and properties of future BBHs will be (e.g., Belczynski et al. 2016; Rodriguez et al. 2016; Mandel & de Mink 2016). Therefore, by comparing the true population of BBHs to theoretical predictions, we may be able to begin constraining the relative rates and uncertain physical prescriptions that embed population models, leading to a heightened understanding of stellar evolution in general.

One route for constraining formation channels relies on sheer numbers – comparing population properties of observed BBHs to model predictions. This type of analysis has been explored primarily using the intrinsic properties of the binary, i.e. masses (Mandel et al. 2017; Zevin et al. 2017) and spins (Stevenson et al. 2017; Talbot & Thrane 2017; Farr et al. 2017). Another means in which we can distinguish the relative role of formation channels is by examining signals with system properties that are only consistent with a single formation channel (Rodriguez et al. 2016).

A physical parameter of the binary inspiral that may be useful in disentangling the various formation channels proposed for BBH mergers is the eccentricity of the binary orbit. Eccentricity appears in the GW signal because most energy is emitted in GWs at periapse than at apoapse. Highly eccentric systems will therefore look more like periodic 'bursts' of energy rather than the familiar chirp-like time-frequency evolution. As periapse passage drains more energy from the orbit, eccentric binaries also have a quicker inspiral time and will merge much quicker than their circular counterparts with identical semi-major axes. Most scenarios predict that eccentricity in systems; since GW emission is very efficient at circularizing binaries (Peters 1964) orbital eccentricities are expected to disappear by the time the binary enters the LIGO band.

However, the interplay between three or more bodies during dynamical encounters can impart larger eccentricities into BBH mergers during resonant interactions, or create hierarchical triple systems that constantly drive eccentricity into the inner binary through Lidov-Kozai cycles. Such encounters are believed to occur in the cores of globular clusters and other dense stellar environments.

N-body simulations have helped to understand the role of few-body encounters in forming tightened BBHs and building hierarchical triples (e.g., Hut & Bahcall 1983; Antognini & Thompson 2016). However, most studies do have not address post-Newtonian (pN) effects into their equations of motion, which govern effects such as GW-inspiral and apsidal precession. By performing scattering experiments and evolving the equations of motion post-encounter, Samsing et al. (2014) found that the inclusion of the 2.5-pN term in binary-single scatterings introduces a high-eccentricity peak in the eccentricity distribution of LIGO-detectable BBH systems. The detection of such a highly-eccentric binary would reveal that dynamical processes were at play in facilitating its merger.

In the study, we examine the effect of all post-Newtonian terms up to 2.5-pN order in binary-binary scatterings using an N-body code to integrate the pN equations of motion. We track the endstates of these encounters and the properties of systems in which a merger was induced, with particular interest in mergers that are facilitated during the chaotic resonant encounters and the formation of triple systems which can drive binaries to highly-eccentric mergers through Lidov-Kozai cycles. We include the 1- and 2-pN orders, which govern periapse precession, as these may alter the resultant and may play a role in the stability of hierarchical triples that are formed. Primarily, we perform scatterings on a grid of initial conditions to examine if variations in masses, mass ratios, and pre-encounter semi-major axis match analytical expectations. We then perform scattering experiments using binary-binary encounters from realistic cluster models to gauge how the inclusion of pN terms alters the merger rate and eccentricity distribution of cluster-formed BBHs.

2. BINARY-BINARY ENCOUNTERS

Interactions between more than three bodies are governed by chaos; there is no analytical expression for the equations of motion and subtle changes in the initial conditions of the system can lead to vastly different outcomes. Therefore, it is necessary to perform many scattering experiments over the possible initial configurations to understand probabilistically how variations in the initial conditions affect the binary endstate. In this study, we use Monte Carlo methods and sample over the extrinsic parameters of the system, and evolve $O(10^5)$ scatterings, determining endstates and properties of merged binaries. Here, we explain the setup of the scattering experiments we perform in our analysis.

2.1. *Pre-Encounter Setup*

Each binary system is defined by its component masses, semi-major axis, and eccentricity prior to interaction. We

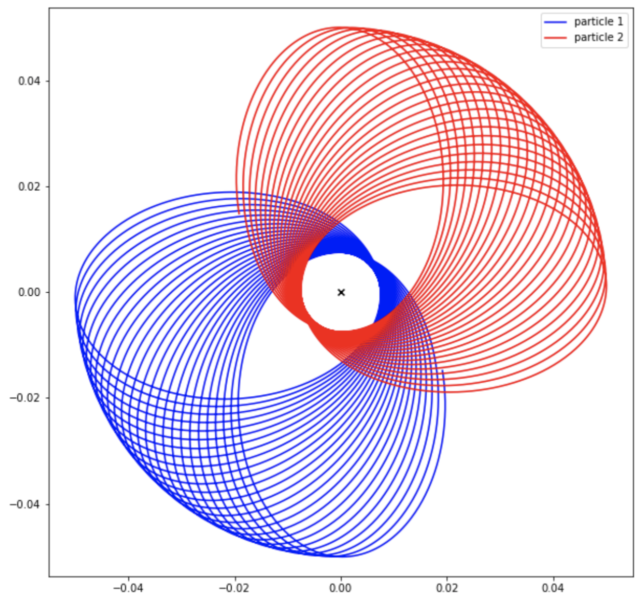

Figure 1. Apsidal precession of the numerically-integrated binary. The precession of apoapse matches with the theoretical rate.

denote these as $[m_{i1}, m_{i2}, a_i, e_i]$ where $i = [1, 2]$ refers to the binary system. We sample the location of the orbit by solving Kepler's equations numerically and sampling the mean anomaly. We randomly sample the three orientation angles of the binary: $\phi_{peri} = [0, 2\pi]$, $cos(\theta_i) = [-1, 1]$, $\phi_{ascn} = [0, 2\pi]$ where ϕ_{peri} is the angle of periapse, θ_i is the inclination, and ϕ_{ascn} is the angle of ascending node.

We then draw the offset of the velocity vectors of each incoming binary according to the impact parameters.

$$b^2 = r_{min}^2 + \frac{2GM_{tot}r_{min}}{v_{\rm inf}^2} \tag{1}$$

where $v_{\rm inf}$ is the relative velocity at infinity and r_{min} is defined as $r_{min} = m_{12}a_1/(m_{11} + m_{12})$. From the impact parameter, we can define a cross-section of interaction:

$$\sigma_i = \pi b_i^2 = \pi r_{min}^2 \left(1 + \frac{2GM_{tot}}{r_{min}v_{\rm inf}^2}\right) \tag{2}$$

We evolve the incoming binary forward using conservation of energy and angular momentum until they reach an initial separation of $30a_0$, where a_0 is the average of the two binary semi-major axes. With these initial conditions, we then numerically integrate forward the equations of motion until an endstate is reached.

2.2. *Post-Newtonian Implementation*

The resonant interactions that take place during our scattering experiments can lead to binary inspirals when dissipative pN energy terms are included in the equations of motion. As the Schwarzschild radii of BHs is extremely small, the chances for head-on collisions in minuscule and . We include the 2.5-pN acceleration term, which governs gravitational-wave emission, as this will be the primary driver for facilitating eccentric mergers during resonant interactions. For posterity, we also include the 1- and 2-pN terms, as apsidal precession may play an important role in 4-body encounters, and affect the stability of hierarchical triples that are formed in these encounters.

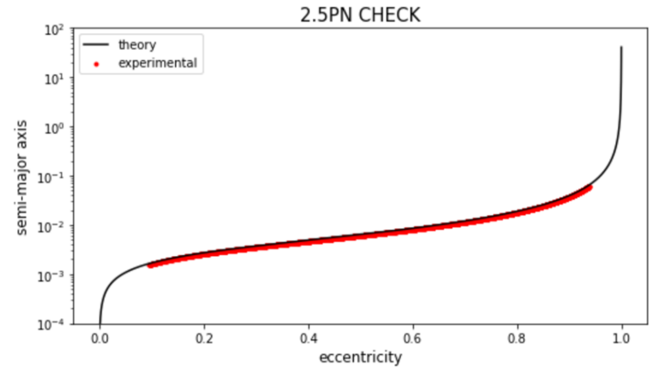

Figure 2. Evolution of the eccentricity and semi-major axis due to GW emission. The black line is the analytical expectations from Peters (1964).

To ensure the correct implementation of pN terms, we evolve a single BBH system to see if the evolution of semi-major axis and eccentricity match the analytical expectations from Peters (1964). We find our evolution to be consistent with theoretical expectations.

2.3. *Endstates*

We identify a variety of endstates to the binary-binary encounters. During the resonant encounters, many variations in the orbital configurations of the binaries can occur. For example, inspirals can occur during the encounter, single BHs can be ejected, BBHs can swap partners, stable triples can form, etc. We track all the possible endstates for the interactions, so that cross-sections and for various interactions can be produced. This allows for the likelihood of a particular outcome given a set of initial conditions to be understood.

3. SCATTERING EXPERIMENTS

We first perform scatterings on a grid of intrinsic parameters of the binaries. Though this is not motivated by the true distribution of initial conditions, it allows for the cross-sections of particular endstates as a function of a single initial condition to be targeted and comparisons to analytical expectations. We perform these experiments over two binary parameters: total mass and semi-major axis of one of the binaries. During the scatterings, we hold all other intrinsic initial conditions fixed and sample over the extrinsic parameters describing the initial system. In addition, we vary the pN terms that are included in the equations of motion to see

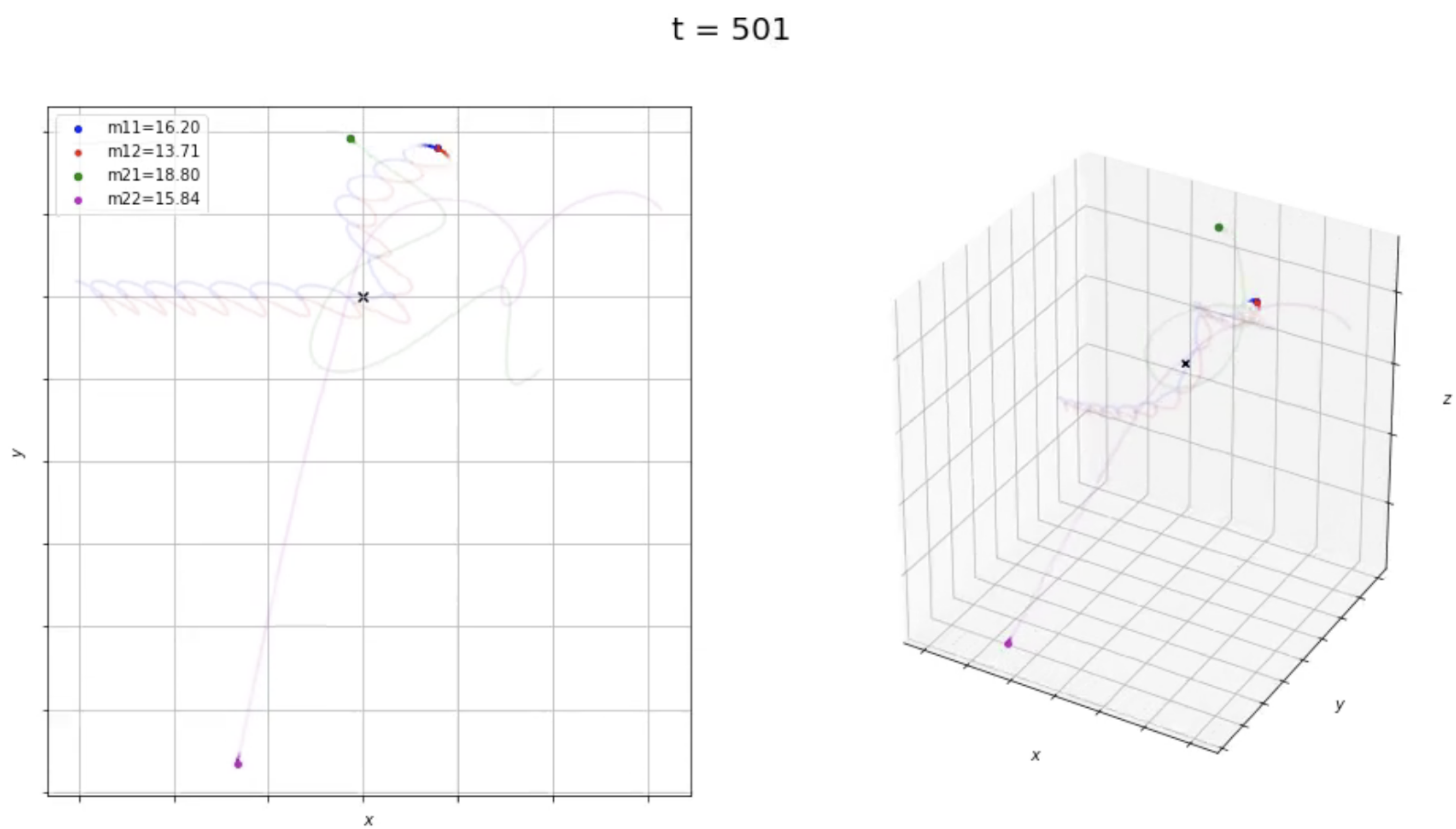

Figure 3. Example scattering, where resonant encounter led to a BBH inspiral.

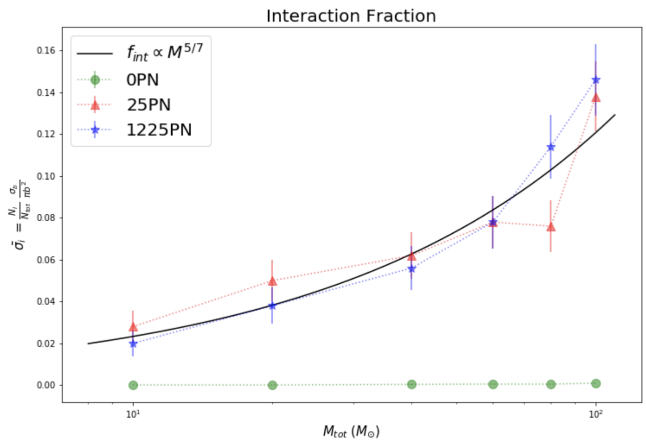

Figure 4. Interaction fraction for inspiraling binaries as a function of total mass (M_{tot}). The black line corresponds to the expected scaling relation expected, $f_{int} \propto M^{5/7}$. The blue, red, and green lines represent the inclusion of all pN terms (1,2,2.5), the inclusion of energy-dissipative pN terms (2.5), and no pN terms (0). As expected, the fraction of inspirals and mergers when no pN terms are included is 0.

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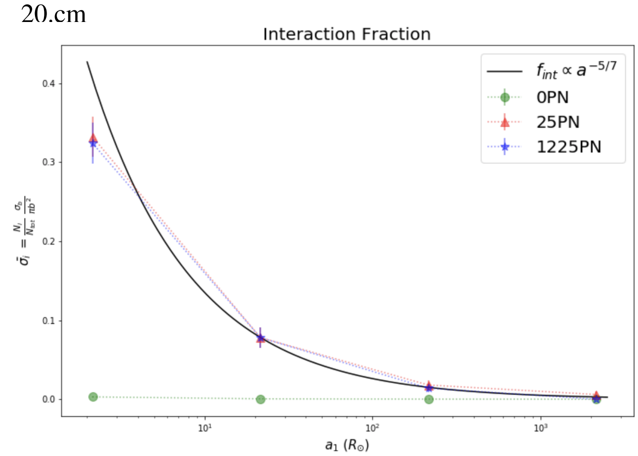

Figure 5. Interaction fraction for inspiraling binaries as a function of semi-major axis of binary 1 (a_1). The black line corresponds to the expected scaling relation expected, $f_{int} \propto M^{-5/7}$. The blue, red, and green lines represent the inclusion of all pN terms (1,2,2.5), the inclusion of energy-dissipative pN terms (2.5), and no pN terms (0). As expected, the fraction of inspirals and mergers when no pN terms are included is 0.

the affect that higher-order terms have on outcomes. We find our experiments to be consistent with analytical expectations derived in Samsing et al. (2014).

In addition, we also examine the effect that pN terms have on the eccentricity distribution of merging binaries. Our preliminary results show a peak at high-eccentricity mergers in our scattering experiments, driven by the inclusion of pN terms in our equations of motion.

4. ENCOUNTERS IN REALISTIC ENVIRONMENTS

After running the scattering experiments on a grid to determine scaling relations for different outcomes, we plan to run scatterings for binary BBH encounters that were produced in CMC cluster models (Chatterjee et al. 2010). These models maintain the pertinent information for setting up the binary encounters, such as initial masses, semi-major axes, eccentricities, impact parameters, and relative velocities. We will gauge the effect that pN terms has on the resultant eccentricity distribution of merged binaries, and formulate a rate of occurrence of highly-eccentric binaries.

5. CONCLUSIONS & FUTURE PROSPECTS

Though our preliminary results are promising, we plan to do a more comprehensive analysis of how parameters of the binary affect encounter cross-sections. In particular, we plan to reproduce the analysis of Antognini & Thompson (2016), where extensive binary-binary scatterings were performed without the inclusion of pN terms in the equations of motion. By performing scattering experiments using cluster-formed binaries, we will also identify the properties of clusters that best facilitate highly-eccentric mergers. Furthermore, we will investigate the phase-space of various endstates from binary-binary encounters. Lastly, we will explore the creation of hierarchical triples systems in globular cluster environments, and determine the effect that pN terms have on their long-term stability and inducing highly-eccentric mergers.

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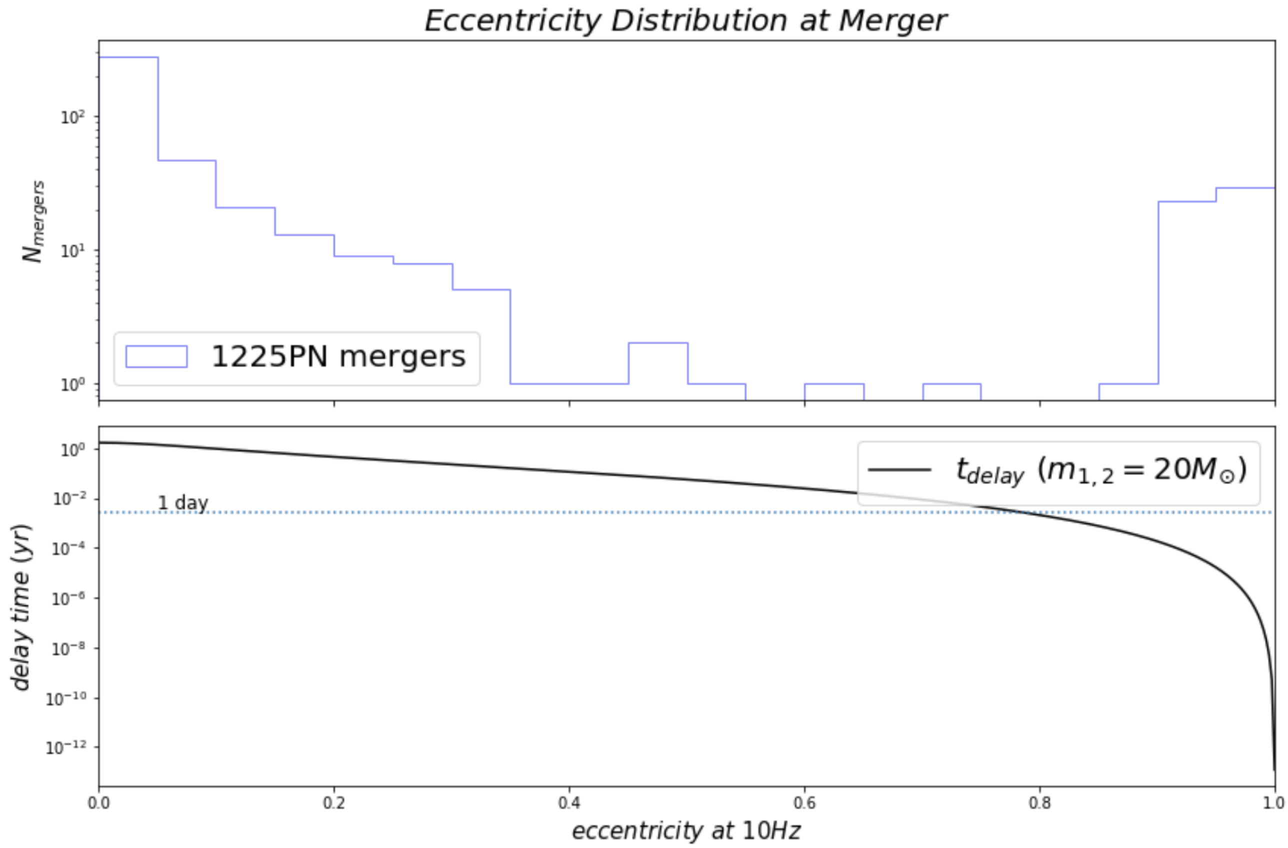

Figure 6. Top: eccentricity distribution of binaries that merged during resonant interactions of binary BBH encounters. Higher-order pN terms are included. We find a peak at high eccentricities. Bottom: inspiral time for a nominal binary configuration as a function of eccentricity.

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