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Merger Rates for High-mass X-Ray Binary Systems

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Research Notes of the AAS, Volume 3, Number 1

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Received 2018 December 22

Accepted 2018 December 27

Published 2019 January 2

Sophia E. Haight *et al* 2019 *Res. Notes AAS* **3** 2

<https://doi.org/10.3847/2515-5172/aafb0e>

accretion, accretion disks; gravitational waves; stars: evolution; X-rays: binaries

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1. Background

High mass X-ray binaries (HMXBs) are potential pathways to produce compact object mergers. Therefore they are intriguing sources of gravitational waves for operational laser-interferometer detectors. In a HMXB evolution, as the main sequence donor star reaches its critical Roche lobe, it loses its outer layers, leaving behind the helium core (Tauris & van den Heuvel 2006). The mass from the outer layers transfers from the donor to accrete around its companion black hole. The mass of the remaining helium core defines the final stage of the zero age main sequence (ZAMS) star's evolution (Tauris & van den Heuvel 2006) as it explodes in a supernova, the result of which is a compact object. In many evolutions, supernovae mark the birth of neutron stars and produce a supernova "kick" of a given magnitude and direction (Kalogera 2000). A supernova kick determines the orbital properties of the system subsequent to the explosion (Kalogera 2000) and these properties determine whether the binary will merge in Hubble time due to gravitational-wave emission.

2. Methods

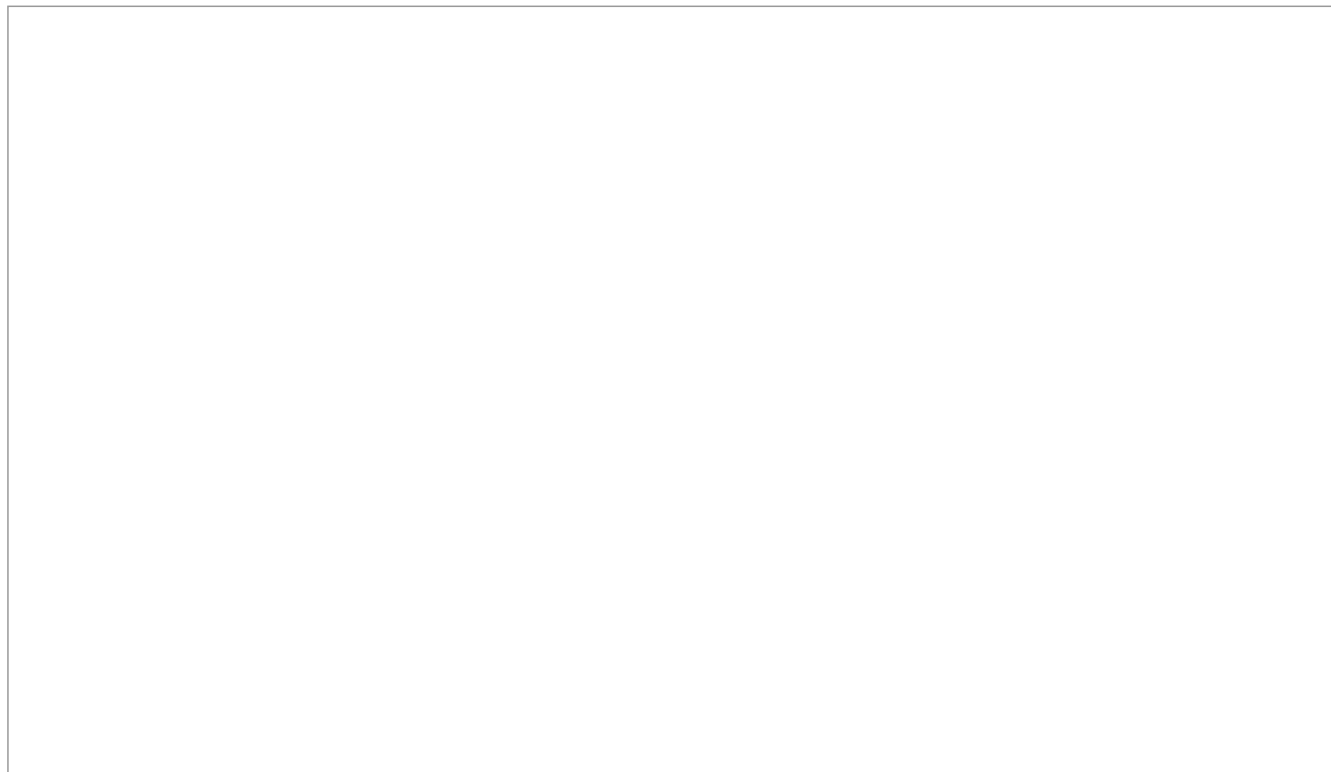
To evolve HMXB systems we use Modules for Experiments in Stellar Astrophysics (MESA) (Paxton et al. 2018). MESA is a one-dimensional hydrodynamic module which we use to evolve a ZAMS star in a binary system. We vary physical properties like mass, temperature, orbital separation, etc. to estimate the resultant evolutionary state of the system. We explore both the initial metallicity of the ZAMS companion star along with mass ratios -chosen to develop a grid of masses across the viable uncertainty range of the masses in the system- to obtain a range of evolutions. MESA outputs final masses and orbital separations for each evolution. We evolved three systems, LMC X-1, M33 X-7, and Cygnus X-1 and found only Cygnus X-1 would produce a compact merger. The final masses indicate the ZAMS star would evolve either into a black hole or neutron star. However, due to the significant mass loss we observed during supernova, it is unlikely the star would produce a black hole. Thus we assume the system evolves into a black hole neutron star binary. This type of system has yet to be observed with gravitational-wave instruments. With this information, we aim to determine a merger rate for this system post-supernova. We note that we have few methods to constrain this merger rate from previous models of binary black hole, binary neutron star, and neutron star black hole merger rates. In Abadie et al. (2010), many of these rates were extrapolated from observations of other astronomical phenomena.

Using a Monte Carlo simulation to model a supernova kick, we sample kick velocity magnitudes from a Maxwellian distribution described by Hobbs et al. (2005) (Abbott et al. 2017) while the kick direction is chosen isotropically over the sphere surrounding the ZAMS star.

We input the supernova kick parameters and pre-supernova masses and separation into equations from Kalogera (1996), describing the post-supernova orbital properties. The resulting orbital separation and eccentricity are inputted to Equation 5.14 derived in Peters (1964) to find resulting inspiral time distributions and to identify systems that remain bound post-supernova.

3. Data and Analysis

For each MESA simulation in the set, via the supernova kick Monte Carlo, we calculate the fraction of systems which remain bound. Then we find the percent merging in Hubble time. From these systems we derive a distribution of orbital separations, eccentricities, and inspiral times describing the orbital parameters. We also find distributions of kick velocities and values of the two angles theta and phi, indicating the magnitude and direction of the supernova kick, and show distributions of these in Figure 1.



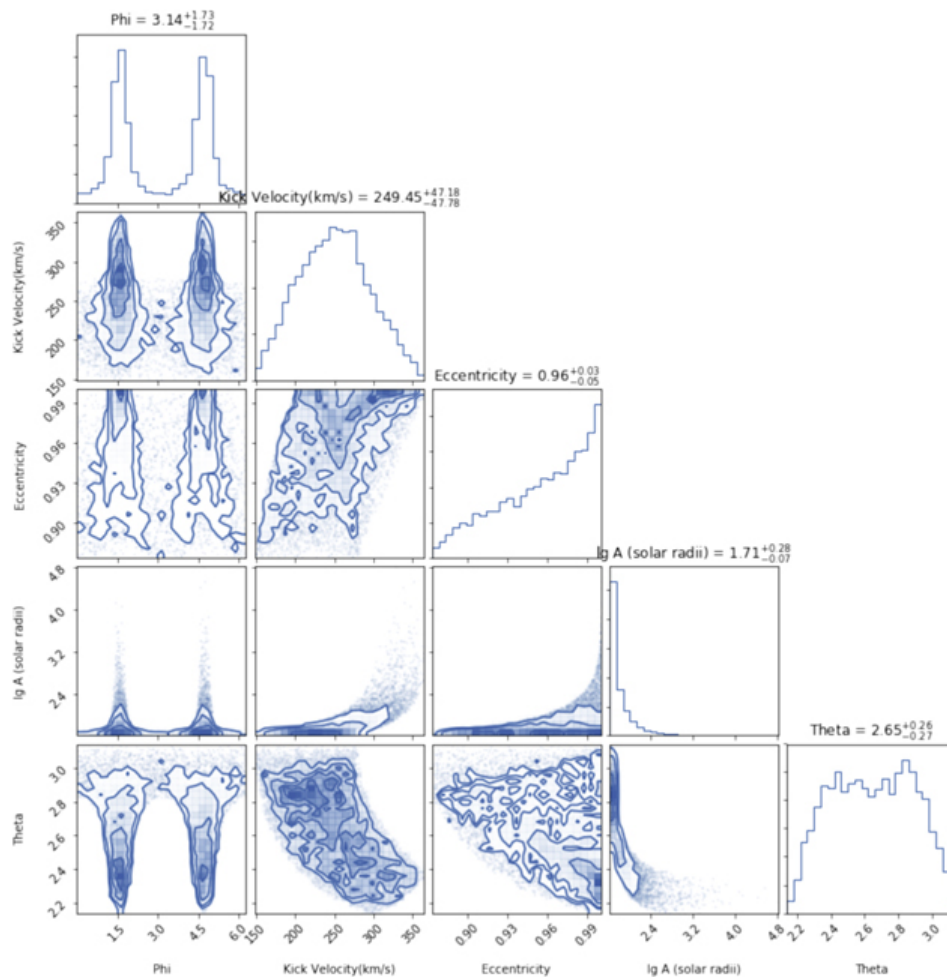


Figure 1. One and two-dimensional histograms of supernova kick parameters and orbital parameters. Angular distributions give a visualization of kick direction in three-dimensional space. While kicks are distributed isotropically, the kicks which lead to merging systems produce a bimodal distribution in the phi coordinate. We also note that systems merging in Hubble time tend to be extremely eccentric.

4. Conclusions

We find that, across variations of Cygnus X-1, roughly 85% of systems do not remain bound following a supernova kick. Therefore, 15% of systems remain bound and, relative to the bound fraction, about 8% of systems will coalesce in Hubble time. From this we derive a merger rate (within Hubble time) of about 1.4% (per Myr) for HMXBs with parameters similar to that of Cygnus X-1.

The first step toward expanding on this work is to calculate and obtain a distribution for the orbital tilt relative to the pre-supernova orientation, the angle between the pre-supernova angular momentum and post-supernova angular momentum. Due to the minor effect of the supernova kick, the object's spins are tilted. Kalogera (2000) identifies that the misalignment of the "spin tilt angle" has an effect on the imprint of the emissions pattern. Additionally, we would take more steps to vary over a system's evolution in MESA to confirm final evolutions truly are black hole neutron star binaries and investigate whether a black hole binary could form. Furthermore, we assume a neutron star mass of 1.4 solar masses, so using a range of neutron star masses in orbital equations from Kalogera (1996) could theoretically produce different results. Lastly, to obtain an overall merger rate, we would need to consider the star formation, metallicity, etc. in galaxies which are not the Milky Way.

This material is based upon work supported by the National Science Foundation under grant No. AST-1757792.

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