The Delay Time Distribution of Binary Compact Objects

Michela Mapelli, Laboratory of computational physics, mod B, 2022

The first direct detection of gravitational waves in 2015 has opened a new window on the physics and astrophysics of compact objects (see e.g. https://www.ligo.caltech.edu/). Now, we know of several ten gravitational wave events, all of them interpreted as the merger of two compact objects (black holes or neutron stars). By studying the properties of such systems, we can reconstruct the formation and evolution of binary compact objects, i.e. binary systems composed of two compact objects (black holes or neutron stars).

A binary compact object can originate from the evolution of a massive binary star. During its life, a tight massive binary star undergoes several complex physical processes: the two stars can exchange mass either via stable mass transfer or via a common envelope. This has a profound impact on the final masses and orbital properties of the two compact objects.

The data provided in this research project come from simulations of binary compact object formation. The main features of the data and the goal of the project are described as follows.

GOAL OF THE PROJECT:

Understand which physical processes affect the delay time distribution. The delay time is the time between the formation of a binary star and the merger (via gravitational-wave emission) of the two compact objects produced by the collapse of these stars. In the literature, the delay time is commonly assumed to scale as t^-1, but dedicated simulations show that there are significant deviations from this scaling, especially at short values of t (<100 Myr). In this project, the students will analyze a set of simulations of binary compact object formation and merger, in order to assess the impact of different physical parameters (common envelope efficiency, accretion efficiency, metallicity, mass of the progenitor stars) on the distribution of delay times. The project is structured in two parts:

- part 1: make a fit of the delay time for the different set of data;
- part 2: with a machine learning algorithm (e.g., random forest), figure out which of the aforementioned parameters has the main impact on the delay time distribution.

The data

You can retrieve the data from this link (if it does not work, copy and paste the following: https://drive.google.com/file/d/120_l93SjQE4WDgvjdDB5HyJfh41ygeFg/view). The tar file tau_data.tgz contains 20 folders (vnew_delayed_fMT*, with *=005, 01, 015, 02, 025, 03, 035, 04, 045, 05, 055, 06, 065, 07, 075, 08, 085, 09, 095, 1). Each of them corresponds to a different value of f_MT=0.05, 0.1, 0.15, 0.2, 0.25, 0.3, 0.35, 0.4, 0.45, 0.5, 0.55, 0.6, 0.65, 0.7, 0.75, 0.8, 0.85, 0.9, 0.95, 1, which is the accretion efficiency (the fraction of mass lost from a primary star that can be accreted by a secondary star during a mass transfer episode).

Each of these folders contains 11 sub-folders: A0.5, A1, A2, A3, A4, A5, A6, A7, A8, A9, A10. Each of them corresponds to one different value of the common envelope efficiency: Alpha=0.5, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10.

Finally, each of the sub-folders contains 36 files, named

data_BHBs_*.txt → files corresponding to binary black holes (BHBs)
data_BHNS_*.txt → files corresponding to black hole – neutron star binaries (BHNS)
data_DNSs_*.txt → file corresponding to double neutron stars (DNSs)

with * = 0.0002, 0.0004, 0.0008, 0.0012, 0.0016, 0.002, 0.004, 0.006, 0.008, 0.012, 0.016, 0.02 indicating 12 different metallicities (Z) of the stellar progenitors of the binary compact objects.

Finally, each file is structured as follows:

- line 0: header. Column 0: total stellar mass in the initial simulation, Column 1: number of binary compact object mergers in the file.

- lines >= 1: each line contains the information on a different binary compact object, namely

    - Column 0: identifier of the binary
    - **Column 1: initial mass (ZAMS mass) of the primary member of the binary system in Msun (1 Msun= 1.989e33 g). This is the initial mass of the most massive stellar progenitor.**
    - **Column 2: initial mass (ZAMS mass) of the secondary member of the binary system in Msun. This is the initial mass of the least massive stellar progenitor.**
    - **Column 3: mass of the compact object that forms from the primary member (Msun)**
    - **Column 4: mass of the compact object that forms from the secondary member (Msun)**
    - Column 5: mass of the merger remnant of the two compact objects (Msun). In these simulations, it is just the sum of the masses of the two compact objects.
    - **Column 6: delay time, i.e. time elapsed from the formation of the binary system to the merger of the two compact objects (in Gyr = 1e9 yr)**
    - Column 7: semi-major axis of the binary system at the formation of the second-born compact object (in solar radii, Rsun = 6.96e10 cm)
    - Column 8: orbital eccentricity of the binary system at the formation of the second-born compact object.

Methodology:

1. Choose one of the families of binary compact objects first. I suggest you start from the binary black holes (files ***BHBs***) and consider the other families (BHNS and DNS) only if you have time, at the end of the project.

2. Plot the distribution of the delay times (column 6) for different values of
    - the common envelope parameter Alpha (folders with different A values)
    - the accretion efficiency fmt (folders with different fMT values)
    - the metallicity Z (files with different metallicity from 0.02 to 0.0002)
    - the masses of the progenitor stars (columns 1 and 2) or a combination of them
    - the masses of the two compact objects (columns 3 and 4) or a combination of them

3. Choose an algorithm to fit the data and apply it to at least some of the combinations listed above

4. Choose a machine learning technique (e.g. random forest) and apply it to the data above. For example, you can divide the data into **systems with delay time > 1 Gyr and systems with delay time < 1 Gyr** and see which FEATURES (e.g., metallicity, accretion efficiency, common envelope parameter, masses of the progenitor stars, masses of the two black holes) are more important to determine whether a system ends up with delay time shorter or longer than 1 Gyr.

There is a lot of freedom in the organization, so if you prefer to start from point 4. and do point 3. after point 4, you are more than welcome. Independence of decisions and implementation will be a part of the final evaluation of the project.

SOME BACKGROUND:

To better understand the process of mass transfer and common envelope, and what kind of simulations these data were obtained from, **we will organize some preliminary discussion** and you might also want to read the first 25 pages of this review https://arxiv.org/abs/2106.00699
These data have already been presented in Bouffanais et al. 2021: https://arxiv.org/abs/2010.11220

Of course, you are welcome to ask questions. Do not hesitate to contact Michela Mapelli michela.mapelli@unipd.it