Astrophysics Projects: The Formation of Binary Black Holes

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, most of them interpreted as the merger of two black holes. By studying the properties of such systems, we can reconstruct the formation and evolution of binary black holes, i.e. binary systems composed of two black holes.

The data provided in these two short research projects come from simulations of binary black hole formation. The main features of the data and the goals of the two projects are described as follows.

PROJECT 1: Binary star evolution and binary black holes

A binary black hole 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 binary black hole.

GOAL OF THE PROJECT:

Understand the differences between binary black hole mergers whose progenitors evolved via common envelope and binary black hole mergers whose progenitors evolved via stable mass transfer, by looking at a set of simulated binary black holes.

The data

You can retrieve the data from this link. The tar file stable_MT_vs_CE.tgz contains 4 folders (A0.5, A1, A3 and A5). Each of them corresponds to the outputs of a set of simulations of binary black holes, which differ only by one parameter: the value of the parameter alpha (alpha=0.5,1,3,5) associated with the efficiency of common envelope.

Inside each folder, there are 12 files, named MTCE_BBHs_*.txt, where * is a number ranging from 0.0002 to 0.02 and represents the stellar metallicity at which the black holes where produced in our simulations.

Finally, each file is structured as follows:

- row 0: header for row 1.
- row 1: two columns, the first one being the total stellar mass that was simulated (in solar masses, Msun = 1.989e33 g), the second being the number of binary black hole mergers obtained from that population
- row 2: header of the rows >2
- rows >2 (to the end of the files): each row contains the properties of one simulated binary black hole. In particular (the columns highlighted in boldface are the most important ones for this analysis):
  - Column 0: identifier of the binary
  - **Column 1: initial mass (ZAMS mass) of the primary member of the binary system in Msun.**
  - **Column 2: initial mass (ZAMS mass) of the secondary member of the binary system in Msun.**
  - **Column 3: mass of the black hole that forms from the primary member (Msun)**
  - **Column 4: mass of the black hole that forms from the secondary member (Msun)**
  - Column 5: mass of the merger remnant of the two black holes (Msun). In these simulations, it is just the sum of the masses of the two black holes.

- **Column 6: delay time, i.e. time elapsed from the formation of the binary system to the merger of the two black holes (in Myr)**
- **Column 7: semi-major axis of the binary system at the formation of the second-born black hole (in solar radii, Rsun = 6.95e10 cm)**
- **Column 8: orbital eccentricity of the binary system at the formation of the second-born black hole**
- Column 9: magnitude of the supernova kick (km/s) associated with the primary member
- Column 10: magnitude of the supernova kick (km/s) associated with the secondary member
- Column 11: cosine of the tilt angle between the orbital angular momentum of the binary system before and after the supernova explosion of the primary member
- Column 12: cosine of the tilt angle between the orbital angular momentum of the binary system before and after the supernova explosion of the secondary member
- Column 13: x component of the centre-of-mass velocity of the binary system after the supernova explosion of the primary component
- Column 14: y component of the centre-of-mass velocity of the binary system after the supernova explosion of the primary component
- Column 15: z component of the centre-of-mass velocity of the binary system after the supernova explosion of the primary component
- Column 16: x component of the centre-of-mass velocity of the binary system after the supernova explosion of the secondary component
- Column 17: y component of the centre-of-mass velocity of the binary system after the supernova explosion of the secondary component
- Column 18: z component of the centre-of-mass velocity of the binary system after the supernova explosion of the secondary component
- Column 19: time at which the primary component undergoes a supernova
- Column 20: time at which the secondary component undergoes a supernova
- **Column 21: Boolean variable indicating whether the binary system undergoes a common envelope (True). If column 21 is False, the binary goes via stable mass transfer instead of a common envelope.**

Methodology:

- Divide the data based on Column 21: systems which underwent common envelope (True) and systems which have only done stable mass transfer (False).
- Plot and compare the main properties of the two “families” of binary black holes.
- Run some simple machine learning algorithm (e.g., a random forest) to figure out what features have the highest impact on the fate of a binary black hole, that is to decide if the binary system evolves via mass transfer or common envelope.

SOME BACKGROUND:

To better understand the process of mass transfer and common envelope, and what kind of simulations these data were obtained from, you might want to read the first 25 pages of this review https://arxiv.org/abs/2106.00699

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

PROJECT 2: Hierarchical mergers of binary black holes

Alternatively, a binary black hole can form via close encounters of black holes in a dense stellar environment, such as a nuclear star cluster, a globular cluster or a young star cluster. In this case, the two black holes may be single objects at birth, and pair up dynamically at some point in their "life". When two stellar-born black holes merge via gravitational wave emission, their merger remnant is called second-generation (2g) black hole. The 2g black hole is a single object at birth. However, if it is retained inside its host star cluster, it may pair up dynamically with another black hole. This gives birth to what we call a second-generation (2g) binary black hole, i.e. a binary black hole that hosts a 2g black hole . If a 2g binary black hole merges again, it gives birth to a third-generation (3g) black holes, and so on.

In this way, repeated black hole mergers in star clusters can give birth to hierarchical chains of mergers, leading to the formation of more and more massive black holes.

GOAL OF THE PROJECT:

Understand the differences between hierarchical binary black hole mergers in nuclear star clusters, globular clusters and young star clusters, by looking at a set of simulated binary black holes. Nuclear star clusters are very massive (~1e5 – 1e8 solar masses) star clusters lying at the center of some galaxies, including the Milky Way. Globular clusters are old (~12 Gyr) massive (~ 1e4 – 1e6) stellar clusters lying in the halo of almost every galaxy. Young star clusters are young (<100 Myr) stellar clusters forming mostly in the disk of a galaxy.

The data

You can retrieve the data from this link. The tar file fastcluster_comp_physA.tgz contains three main directories:

NSC_chi01_output_noclusterevolv/ for nuclear star clusters (NSC)
GC_chi01_output_noclusterevolv/ for globular clusters (GC)
YSC_chi01_output_noclusterevolv/ for young star clusters (YSC)

Each of these main directories contains a subdirectory Dyn/. Inside each directory Dyn/ there are twelve sub-directories named
0.0002/ 0.0004/ 0.0008/ 0.0012/ 0.0016/ 0.002/ 0.004/ 0.006/ 0.008/ 0.012/ 0.016/ 0.02/
These numbers refer to the metallicity of the star cluster.
Inside each directory with the name indicating the metallicity, there is just one file nth_generation.txt, which contains the information about the simulated hierarchical mergers for a given metallicity (from 0.0002 to 0.02) and for a given stellar cluster (YSC, GC, NSC). The files nth_generation.txt are organized as follows (the columns highlighted in bold face are the most important ones for your project):

- row 0: header
- row >=1: each row contains the properties of one simulated binary black hole. In particular (the columns highlighted in boldface are the most important ones for this analysis):
    - **Column 0: identifier of the binary**
    - **Column 1: mass of the primary black hole in solar masses (Msun = 1.989e33 g)**
    - **Column 2: mass of the secondary black hole (Msun)**
    - **Column 3: dimensionless spin magnitude of the primary black hole**
    - **Column 4: dimensionless spin magnitude of the secondary black hole**
    - Column 5: angle theta between the spin of the primary black hole and the angular momentum vector of the binary system
    - Column 6: angle theta between the spin of the secondary black hole and the angular momentum vector of the binary system

- Column 7: initial semi-major axis of the binary black hole in solar radii (Rsun = 6.95e10 cm)
- Column 8: initial orbital eccentricity of the binary black hole
- **Column 9: time requested for the dynamical pair up of the binary black hole in Myr**
- Column 10: semi-major axis of the binary black hole after hardening in Rsun (ignore this column)
- Column 11: eccentricity of the binary black hole after hardening in Rsun (ignore this column)
- Column 12: time for hardening and gravitational wave shrinking in Myr (ignore this column)
- **Column 13: time elapsed from the formation of the first-generation progenitors of this nth-generation binary black hole to the merger of the nth-generation binary black hole.**
- Column 14: magnitude of the gravitational wave recoil in km/s (a GR kick the merger remnant receives at birth)
- **Column 15: mass of the black hole remnant resulting from the merger of the binary black hole (Msun). It accounts for GR mass loss.**
- **Column 16: magnitude of the dimensionless spin of the black hole remnant, accounting for GR effects.**
- **Column 17: escape velocity from the star cluster.**
- Columns 18 – 24: internal diagnostic flags of the code. Ignore them.
- **Column 25: total mass of the stellar cluster in Msun**
- Column 26: binary black hole eccentricity when the orbital frequency is 10 Hz. Ignore it.
- **Column 27: number of the generation. If it is equal to 2, 3, 4, .. it means that the binary black hole is second, third, fourth, … generation.**

Methodology:

- Plot the main properties of hierarchical black holes in different star clusters. Compare nuclear star clusters, globular clusters and young star clusters. I suggest you consider the masses of the black holes (cols. 1,2, 15), the spin magnitudes (cols. 3,4,16), the escape velocities col.17), the total masses of the star clusters (col.25) and the number of generation (col.27).
- Run some simple machine learning algorithm (e.g., a random forest) to figure out what features have the highest impact on the fate of a binary black hole in the three different kinds of star clusters.

SOME BACKGROUND:

To better understand the process of hierarchical pair up, and what kind of simulations these data were obtained from, you might want to read this recent paper https://arxiv.org/abs/2103.05016. Of course, you are welcome to ask questions. Do not hesitate to contact Michela Mapelli michela.mapelli@unipd.it