The delay time distribution of binary compact objects with the SEVN code

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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.

GOALS OF THE PROJECT:

1. Calculate the delay time distribution for a set of binary black hole simulations. The **delay time is the time between the formation of a binary star and the merger of the two black holes that form from the binary star**. The merger is caused by gravitational-wave emission. The delay time depends on the black hole masses, semi-major axis and eccentricity.
To calculate it, you have to **integrate the following systems of two ordinary differential equations**:

$$\frac{da}{dt} = -\frac{64}{5}\,\frac{G^3\,M\,m\,(M+m)}{c^5\,a^3\,(1-e^2)^{7/2}}\,\left(1+\frac{73}{24}\,e^2+\frac{37}{96}\,e^4\right)$$

$$\frac{de}{dt} = -\frac{304}{15}\,e\,\frac{G^3\,M\,m\,(M+m)}{c^5\,a^4\,(1-e^2)^{5/2}}\,\left(1+\frac{121}{304}\,e^2\right)$$

where *a* is the semi-major axis, *e* the orbital eccentricity, *M* the primary mass (the mass of the most massive black hole), *m* the secondary mass (the mass of the least massive black hole), *G* is the gravity constant and *c* is the speed of light.
You can do the integration with a user-provided script (best option, I can explain you why it is the best option and how to do it) or with a scipy library.

2. Once you have obtained the delay times, plot their distribution.

3. Obtain a fitting formula for the resulting distribution.

[4. Optional, to be discussed if there is time, don’t worry: train a random forest to learn the delay time distribution given a number of features.]

THE DATA

The data are stored in the centerba server at the following path (more details on how to reach it will be provided during the next meeting):

/tank1/iorio/pessoa_wdns/paper_run_mtrand/mtrad_reduced/fiducial_S3fix_Hrad/

Folder tree

In the main folder, there are several sub-folders with the names: sevn_output_ZxAyL1
Where x indicates the metallicity of the simulation and y is the value for the Common Envelope efficiency (0.5, 1, 3, 5).

START BY ANALYZING THE DATA IN ONE OF THESE SUB-FOLDERS, YOU DO NOT HAVE TO ANALYZE ALL OF THEM.

For example, start from

/tank1/iorio/pessoa_wdns/paper_run_mtrand/mtrad_reduced/fiducial_S3fix_Hrad/sevn_output_Z0.002A1L1/

Simulation files

Inside each of the above folders you find (among the others) the file **BHBH.csv**
It is a csv (comma separated) file containing the properties of a sample of simulated binary black holes.
The columns are (the ones indicated in red are the most important ones):

- ID: [long int] unique ID identifying the binary system, it also indicates the initial position of the binary in the input file
- name: [long int] unique binary identifier randomly drawn at the beginning of the evolution
- **BWorldtime: [double] age of the system in Myr**
- **Mass_0/Mass_1: [double] mass of the star in Msun, the suffixes 0 and 1 indicate the first and second black hole, respectively.**
- Radius_0/Radius_1: [double] radius of the black hole in Rsun.
- Zams_0/Zams_1: [double] will not be used

- Phase_0/Phase_1: [int] SEVN stellar phase (see Appendix)
- **RemnantType_0/RemnantType_1: remnant type (see Appendix)**
- **Semimajor: [double] orbital semimajor axis in Rsun**
- **Eccentricity: [double] orbital eccentricity**
- **Gwtime [double]: very approximate estimate of the delay time [you can use it for comparison with the more accurate values you will find]**
- EventsAll [string]: it will not be used
- Events [string]: it will not be used
- EventsPlus [string]: it will not be used
- Mzams_0 [double]: it will not be used
- Mzams_1 [double]: it will not be used
- Semimajor_ini [double]: it will not be used
- Eccentricity_ini [double]: it will not be used
- Z [double]: metallicity

IMPORTANT DOCUMENTATION:

additional details on the SEVN files can be found in the SEVN tutorial:

https://www.giulianoiorio.eu/data/SEVN2_tutorial.pdf

The analysis of the outputs of SEVN has been thoroughly described in these previous videos (from the lectures of the Lab of Computational Physics 2020/2021)

https://mediaspace.unipd.it/media/Comp+Phys+Astro+2021/1_wpt2p66s

https://mediaspace.unipd.it/media/Comp+Phys+Astro+2021/1_f61cs5uw

TOOLS

The Python module Pandas provides very powerful tools to handle csv files. Pandas can also be used to merge different dataset based on some common keys. For example, the output and evolved columns can be joined in a single dataset using the pandas function merge (https://pandas.pydata.org/docs/reference/api/pandas.DataFrame.merge.html) based on the columns ID and name.

There are other Python modules, as Dask (https://docs.dask.org/en/stable/dataframe.html), that can be interfaced with Pandas dataset, but can naturally work with "split" files as the one produced by the (parallel) SEVN simulations.

APPENDIX (with supplementary material)

Stellar Phases

The SEVN stellar phases are the following

- Phase 1: *Zero age main sequence*, the star is burning Hydrogen in the core
- Phase 2: *Terminal main sequence*, the stars has developed an He-core
- Phase 3: *H-shell burning*, the star is burning hydrogen in a thin shell around the He-core
- Phase 4: *Core-He burning*, the star is burning He in the core
- Phase 5: *Terminal Core-He burning*, the star has developed a Carbon-Oxygen (CO) core
- Phase 6: *He-shell burning*, the star is burning He in a thin shell arounce the CO core
- Phase 7: *Remnant*, final product of the stellar life, it could be a black hole, a neutron star or a white dwarf (see section below)

Remnant Types

- Type 1: *Hydrogen White Dwarf*
- Type 2: *Helium White Dwarf*
- Type 3: *OxygenNeon White Dwarf*
- Type 4: *Electron capture Neutron Star*
- Type 5: *Core collapse Neutron Star*
- Type 6: Black hole

Concerning this project, type 4 and type 5 can be considered as the same remnant type (Neutron Star).

Enjoy