Spotting stellar-mass black holes in star clusters

Computational Physics lab

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July 2019

1 Introduction

Black holes are very dense stellar objects that even light cannot escape their gravitational field. A black hole is a final stage of an aging star, that can no longer balance between gravitational pull and core collapse.
The so called gravitational waves are ripples in the fabric of space-time due to a change in the gravitational field of massive objects. Usually when two massive objects merge or form a binary system these waves can form due to the spin of the two objects round each other and losing energy. In that case, as objects lose energy, they come closer to each other and could merge, lose a part of their combined mass as energy, which causes ripples in the space-time. The motivation behind this project is to try to detect black holes, their masses, if they are in binary system and how these black holes either as single stars or in binary systems evolve with time. The data used in the analysis is 10 data sets of an N-body simulation of star clusters.

1.1 The simulation

N-body problem is the classic problem defined by newton's laws of gravity describing interacting number [N] of bodies, the analytical solution of this problem is only known for $N = 2$ -and special cases of $N = 3$- but for larger number of bodies many numerical methods can be used. There are many methods that have been used in the provided simulation, monte carlo, fokker planck approximations.., these methods are used to perform an accurate integration of n-bodies based on Newtonian equations of motion. The N-body used simulation "6++" is descendant from many previous ones with the goal of high accuracy integration.The N-body6++ code is written in fortran77 with developing routines aimed to for higher accuracy. The code is separated by marking words that activate the code on multiprocessor machines. The specifications given by the user running the N-body code decide what kind of output is produced, such as the number of stars, the size of the cluster, a mass function, density profile, and many more. All these specifications are decided through an input file fed to the code, Then, a star cluster is created according to the user's instructions, and the bodies are moved one by one with respect to their time evolution. This star cluster output is the used data for my analysis, mainly:bdat.9_*, bwdat.19_*, sev.83_*, bev.82_*. Finally, a typical input file is shown in the guide to be as follows:

- N = 16, 000 particles distributed from a Plummer profile

- Minimum particle number =1000.0 N–body units.
- The initial mass function follows Kroupa, (2001) with mass ranging from $m_{max} = 20.0 M_{\odot}$ to $m_{min} = 0.08 M_{\odot}$
- The initial virial ratio is 0.5
- initial metallicity is 0.001

2 The problem

- what is the black holes mass function?
- how many of them are in binary systems?
- what is the evolution of such binaries?

I will try to use the given data files of each one of the ten simulation to find a mass function that the black holes might be following, I will also check if binary files to see if they contain black holes, given a count of how many black holes are in binary systems, and finally will set a measure of time and see how these black holes develop with time.

3 The Analysis

To be able to dig into the data, one has to know more information about data files, a source of this information is the user guide of the simulation [1] .

3.1 User Guide

The previously mentioned files types bdat.9_*, bwdat.19_*, sev.83_*, bev.82_* are the files I used in my analysis because they have the needed information.
To try to answer the second question regarding black holes in binary systems I had to look at three different types of files that had binary systems information, these files are bev*, bdat*, bwdat, and to try to find other black holes in general even if in single state, I used sev* files. The main difference between the three binary files is that: bdat contain hierarchical systems information i.e. -(B-S)-S binaries, while bev* contain KS stellar evolution data, which are the close binaries whose radius can be smaller than the impact parameter corresponding to a 90 degrees[2]. while the bwdat contain the so called soft binaries which are binary systems with small orbital velocities, that are disrupted by encounters with other stars or in other words wide non-KS binaries. A final point That was the main criteria in my code was the parameter that determines the type of the star, "K*" and for black holes this parameter is 14.0.

[1] `https://github.com/nbodyx/Nbody6ppGPU/tree/master/doc`

[2] The reason these binaries are separated from the soft wide binaries is that they require a different treatment than the other stars, the system is "regularized", which means it's replaced by a center of mass in the general integration routine, while the interaction between the binary is computed separately

3.2 Steps

- Data read: to be able to read the data files I used the header information in the user guide corresponding to each file type with two main points in mind, the type of separation between lines for which I used "\s+" that catches single white spaces or more between lines and the number of rows to be skipped at the beginning of each file because that may cause glitch in the lines read.

- After loading the data into a dataframe, filtering the blackholes can be done with the masking property in the pandas dataframes, with the mask: dataframe['k*'==14.0] and then extracting the points in the dataframe corresponding to this mask. For single files I use one mask while for binary files there are two mask with an or statement to check if any of the two stars in the binary systems is a blackhole.

- After extracting the masses of the blackholes I chose to load the masses into a dictionary because each file is marked with a so called crossing time [3] that I used to be the key of each dictionary resulting from each file.

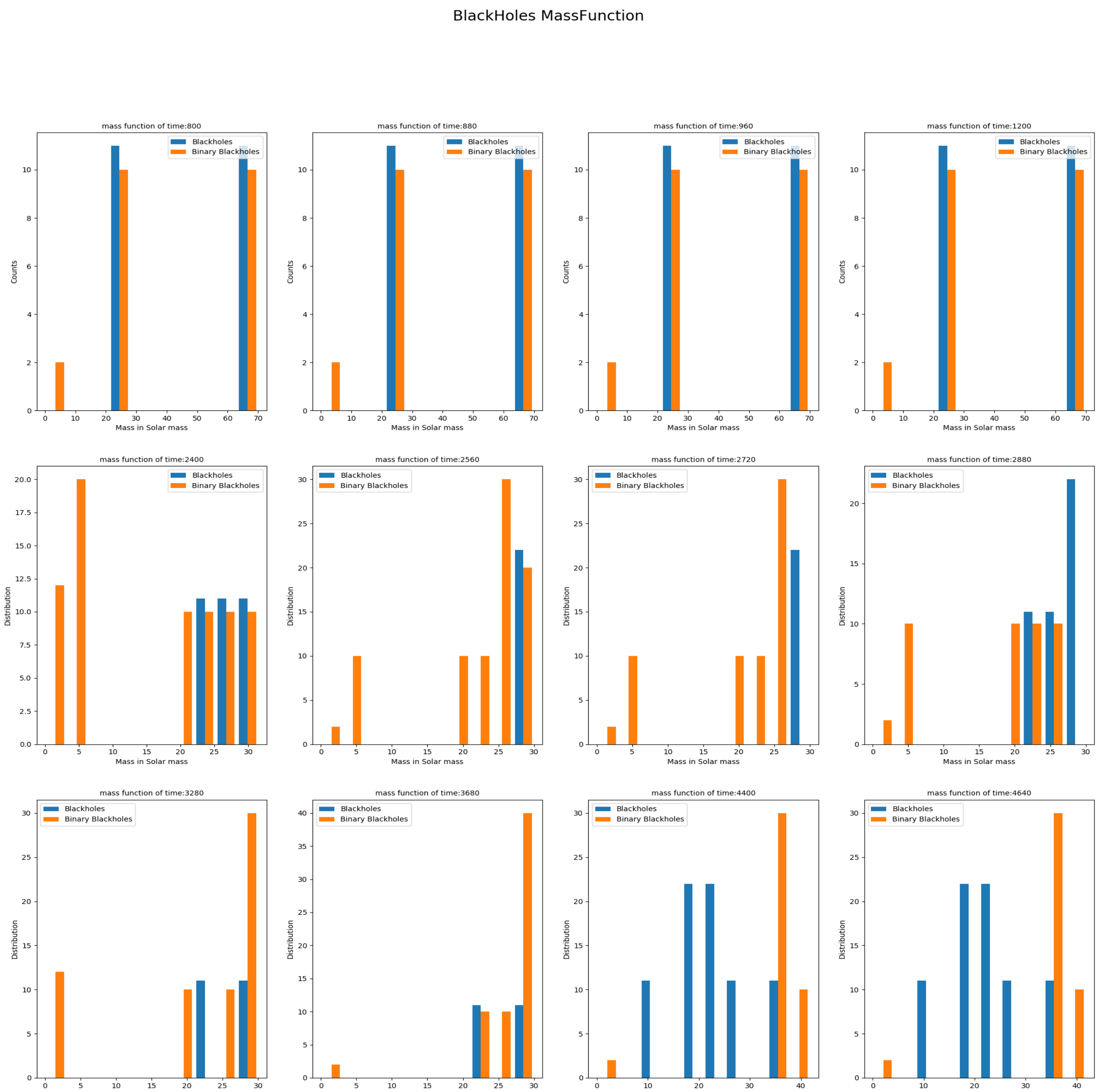
- Because the number of blackholes is small in each simulation I decided to create a dictionary of dictionaries containing all the previously loaded dictionaries then eventually stacking all the masses at each time step to know the black holes masses distribution at known times for the ten simulations.

[3] A concept used for checking the stability of a group of mass such as a cluster of galaxies or a star cluster.It loosely measures the time needed for a star to cross the cluster once. It's directly correlated with the relaxation time and it provides an appropriate timescale for studying the stellar dynamics. The crossing time is given by tc = R/V, where R is the average projected radial distance of group members from the center of mass and V the Gaussian dispersion in internal velocity.

4 Results

4.1 Mass Distribution

The number of black holes I found in the ten simulations is still relatively small and is only spanning very discrete values that's why we can see in the figure I extracted from three different points in time give a very discrete distribution for both single blackholes and those in binary systems.



Mass Distribution of blackholes

4.2 Black holes in binary systems

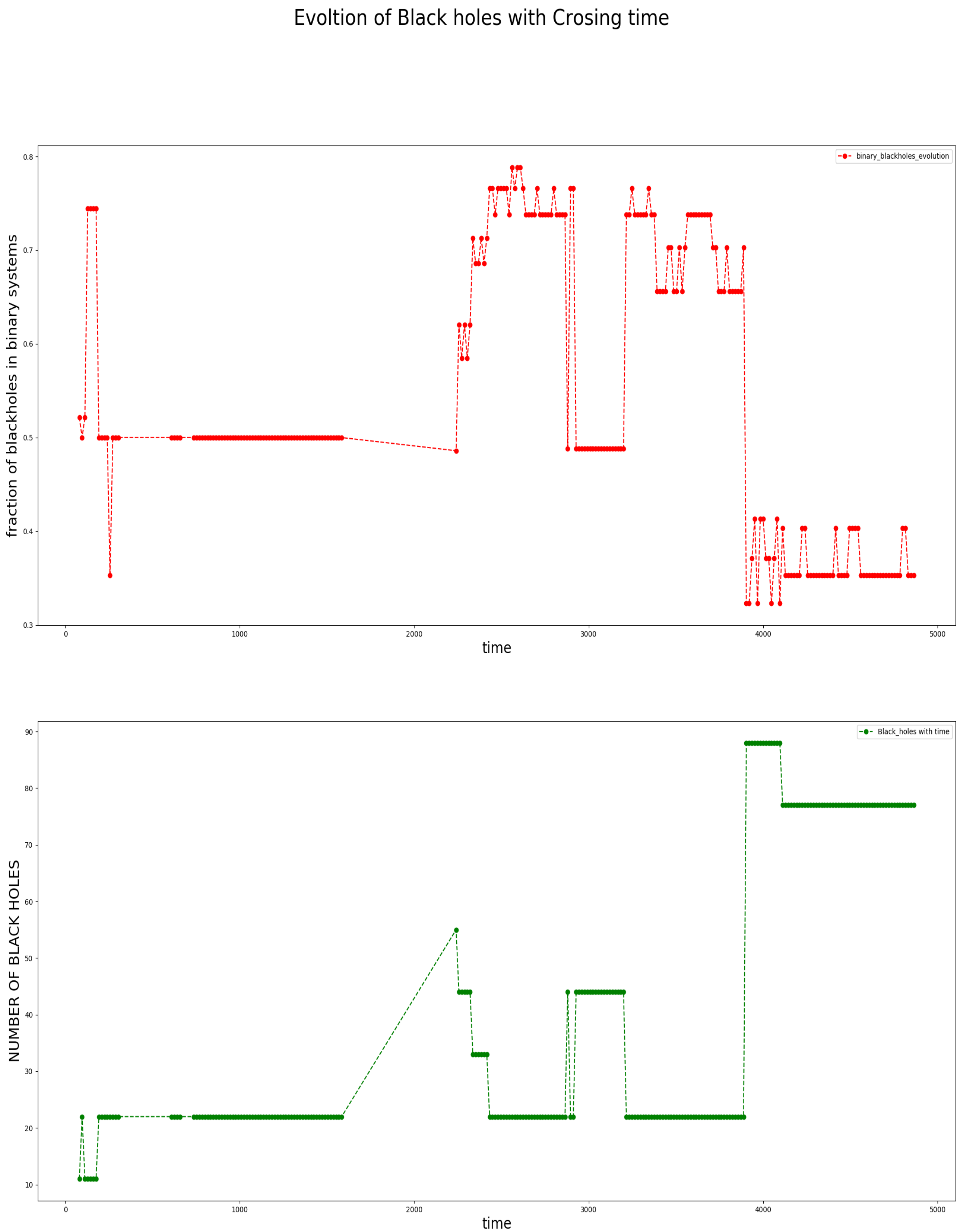
In order to quantify how many of the blackholes available in the simulation is in binary system with another star I used the following simple formula to have a fraction of these binaries, since an absolute number won't give a meaning or an understanding about how many binary systems are there but a fraction give a more profound idea.

$$fraction = \frac{N^{BH}_{Binary}}{N^{BH}_{Binary} + N^{BH}_{Single}} \tag{1}$$

The values of these fractions are automatically printed when the code is run, the fractions range from (0.32307692:1.0) where the 1.0 value corresponds to the case that: at that time step all blackholes are in binary systems. The number of time steps is 305 and the number of time steps where the black-holes in binary systems are dominating is 67.

4.3 Evolution of binaries

To show the evolution of black holes in binary systems In time I plotted the fractions extracted in the previous with the 305 time steps marking the files in all the data sets, I also plotted the number of blackholes in single files to have a vision about how single blackholes svolve as well, but the reader much note that the evolving values in the first plot is fractions with time while in the seond one they are absolute numbers.



Evolution with crossing time

5 Conclusion

- In a simulated star cluster, the number of blackholes in binary systems usually dominate over the number of blackholes in single state.
- number of blackholes in binary systems can increase with time as binaries might form and as time evolves these binaries could form mergers and their number will decrease.
- Since the main motivation behind this project is the trial of detection of gravitational waves, A decrease in the number of blackholes in binary systems might imply the probability of gravitational waves.
- Blackholes are not of the most abundant tars in star clusters so investigation of blackholes might need a huge amount of data.

6 References

– Di Carlo, U. N., Giacobbo, N., Mapelli, M., Pasquato, M., Spera, M., Wang, L., Haardt, F. (2019). Merging black holes in young star clusters. Monthly Notices of the Royal Astronomical Society, 487(2), 2947–2960. doi: 10.1093/mnras/stz1453

– NBODY6++ Manual for the Computer Code

– https://www.mpifr-bonn.mpg.de/4171741/Maria$_Stanescu.pdf$