Effect of Strong Stellar Interactions on Planetary Systems and the Formation of Hot Jupiters

Tyler Reisinger

Under the guidance of Dr. Steve McMillan and Joseph Glaser

Submitted in partial fulfillment of the requirements for the degree of Bachelor of Science in Physics

Department of Physics

Drexel University

Philadelphia, PA, United States

8th of June, 2017

Contents

1 Abstract

"Hot Jupiters" (HJs) are large planets that orbit very close to their host star. They appear to occur relatively frequently in the universe, with approximately 1% of sun-like solar systems predicted to contain one (Brucalassi et al. 2016). However, the mechanism that causes these planets to have such extreme orbital parameters is not fully understood. We aim to explore the role that star-planet and planet-planet gravitational interactions within a star cluster may have in producing Hot Jupiters. By using computational simulations of "typical" star clusters, we will attempt to probe what happens over vast periods of time in star clusters similar to those found within the Galaxy. We will run detailed simulations of close stellar encounters within these clusters and observe the resulting state of the systems after the stars have separated. Many of these system are then computationally analyzed. As a result of these simulations, we hope to observe the formation of Hot Jupiter-like orbits that match observational data as well as determine how common an occurrence they are. Additionally, we can observe what other damage might persist within the planetary orbits of the system that can be used as observational evidence for this formation scenario. Finally, we will produce a collection of code which may be used in the future to perform similar experiments.

2 Introduction

2.1 Theory

In the study of exoplanets, one interesting class of planets are the so-called "Hot Jupiters" – planets that have a Jupiter-like mass and orbits of very small radius around their host star, generally with little orbital eccentricity. Hot Jupiters are interesting as their orbits approach very close to the host star, despite the fact that most Jupiter-mass planets are believed to form much farther out, generally in the accretion disk of the forming planetary system where gases and other diffuse material can aggregate to form a new planet. If we look at our own solar system, we see that Jupiter orbits at around 5.2 Astronomical Units (AU) from the sun, where one AU is the average orbital distance of the Earth. Indeed, we see a very large gap between the orbits of the inner, small and rocky planets, and the outer gas planets, of which Jupiter is the nearest. Jupiter seems not to be an anomaly of the universe, but rather appears to be similar to many other gas giants in the Galaxy.

Hot Jupiters seen in the galaxy, however, have orbital radii of fractions of an AU, potentially approaching their star closer than even Mercury in our own solar system.

Normal planet formation theorizes that young stars are surrounded by an "accretion disk" of dust and gas that remains from the star formation process. Nearest the star, radiative pressure and energy evaporates water and other gases, as well as pushing them outward. Thus the concentration of frozen gases becomes greater some 4 AU and farther from a sun-like star. It is in this region where most gas planets are thought to form (Pollack et al. 1996).

However, in the case of Hot Jupiters, their orbit much closer to the star – beyond the accretion disk. Therefore, the formation mechanism of Hot Jupiters must be somehow different from that of "average" Jupiter planets, such as the one in our solar system.

The mode of formation for Hot Jupiters is not fully understood. Despite this, and their rather exotic orbits, they appear to be somewhat common within the universe as observations and previous models place the occurrence of Hot Jupiters at around 1% of all solar systems (Brucalassi et al. 2016).

A reasonable hypothesis for the formation of these Hot Jupiters is that they are not formed in place, but rather form much like normal gas giant planets in a gas and dust accretion disk beyond the ice line. They then migrate to their final close orbit sometime later after their formation. In order for the Hot Jupiter to move into a close orbit after it is formed, some sort of interaction must occur to change the orbital parameters. Disk migration theory postulates that the accretion of gases and solids during the planet's formation process can slowly alter the orbital parameters of the planet, pushing the planet inward towards the star (Pollack et al. 1996). This is thus a potential mechanism for the creation of these Hot Jupiters, but is not the end of the story.

New stars in the Galaxy generally form not as isolated individuals but rather in groups of stars that then gravitationally interact to form a cluster. Within one of these star clusters, there are times when two stellar systems approach very close to one another. Depending on the closeness of the approach, the effects of such an interaction may very. An encounter at a distance of a few hundred AU will likely disturb the trajectory of the two stars in the short term, but is unlikely to have other significant effects. However, if the two stars come close enough that the approaching star's gravitational attraction overwhelms that of the host star, the planets around each star may have their orbits highly disturbed. In this case, more distantly orbiting planets, such as the gas giants, have a greater chance of being disturbed than the inner planets, as the two interacting stars do not need to get as close to affect the planetary orbits.

This gravitational "push" could also have many effects on the unlucky planets caught in the middle. One likely outcome is that the planet's orbit is made more eccentric but otherwise mostly unchanged. Additionally, the planet could be ejected from the planetary system, or be captured by the approaching star – orbiting it instead of the original host star after the encounter is complete. A third possibility is that a Jupiter-like planet from the outer solar system is thrown into an eccentric orbit that approaches much closer to the star. In such a case, the orbit right after the interaction should have a highly eccentric orbit, even if it passes close to the host star.

Observed Hot Jupiter tend to have a rather circular orbit; in order for these stellar encounters to account for the observations, some process must make the orbits less eccentric. Since the Hot Jupiters are, by definition, close to the star and also, due to their eccentricity, likely pass somewhat close to the inner planets of the system (Earth in this case), tidal interactions may play a significant role in the long-term dynamics of the system. Tidal effects can be numerous, but one common feature is a slow "circularization", or decrease in eccentricity of the planet. This effect plays out in megayear scales, and so is a long term change when compared to close stellar encounters. (Rasiom et al. 1996)

Additionally, the inward movement of the larger gas planet could affect other inner planets of the solar system during its transit. This can cause the inner planet orbits to become more eccentric and could move these planets closer or farther from the star depending on the details of the interaction, or even eject them out of the system. Should this occur, then another "pair" planet could be formed in the same system which has its orbit disturbed by the migration of the gas giant rather than from the stellar encounter. This "pair" planet would likely also end up with an eccentric orbit like the outer planet. Pair planet formation would leave a second long-term impact on the system, which may provide additional observational evidence for this kind of migration having taken place.

Such an interaction also holds importance for the fate of Earth-like planets. A planet formerly in the habitable zone of a star could be knocked into a far less forgiving orbit, leading to likely fatal effects on life. Additionally, a large planet in an eccentric orbit that passes within the inner planetary orbits, even if it does not perturb these planets right away, might cause later chance encounters between the planets that lead to orbital changes.

We will focus on the star cluster interactions and their potential to cause structural changes to the planetary systems involved. Using computer simulation, we are able to probe the gravitational dynamics of these star system interactions over several thousand years of physical time in time scales much more accommodating to human lifespan. We will simulate a large number of these interactions, building up a database of information about the initial and final states of the systems. Using this data, we perform large scale analyses, finding potential Hot Jupiter formation events, as well as other significant perturbations to the planetary orbits.

By having a large database of encounter information, we also look for commonalities and frequencies of the destructive events encountered.

2.2 Orbital Elements

An important set of information for analyzing the behavior of the stellar and planetary dynamics are the orbital elements that mathematically characterize the motion of the planet relative to the host star. For our purposes, we are most interested in the eccentricity e and the semimajor axis a. The eccentricity describes how "long" the orbit is, $e = 0$ is a perfectly circular orbit whereas $0 < e < 1$ are elliptical orbits of increasingly oblong shape. Eccentricities $e > 1$ define hyperbolic orbits where bodies are no longer gravitationally bound. Additionally, these two pieces of information allow us to compute the closest and farthest points of a bound orbit by two simple relations.

The pericenter or closest distance is:

$$r_{per} = (1 - e)a \tag{1}$$

Whereas the apocenter or farthest distance is:

$$r_{apo} = (1 + e)a \tag{2}$$

The pericenter particularly will allow us to characterize orbit migration where a planet moves closer or farther from the host star.

3 Methods

3.1 Infrastructure

Our approach was entirely computational in nature. We developed a collection of tools and utilities utilizing the popular Python programming language and making use of the AMUSE (Astrophysical Multipurpose Software Environment) library [1].

AMUSE provides the underlying gravitational simulation methods, with many different integrators and utilities for different needs. With AMUSE, we were able to setup our problem and tell AMUSE to return to our code for encounter events and let AMUSE handle the rest. Additionally, AMUSE provides these features using high performance C++ and Fortran kernels, allowing us to focus on functionality without worry about the gravitational simulation details.

N-body gravitational simulations with high accuracy and over long time scales require a significant amount of computationally expensive numerical integration of the forces involved in the experiment. In order to exploit the parallel nature of the simulations, our code was run mostly on the Draco computer cluster at Drexel University. This cluster provides 24 connected nodes, each containing 12 CPU cores as well as 4-6 GPUs. Utilizing this cluster, we were able to run many simulations in parallel.

3.2 Simulation

3.2.1 Overview

The code has three logical phases forming a "pipeline" of data flow. The first phase is to run simulations of typical star clusters and to record all "close encounters" between stars in the cluster. At this stage, there are no planets around the stars, but rather we will use the parameters of the close encounters to run more detailed simulations in isolation later.

The second phase is running detailed simulations on the "close encounters". A pair of

[1] The AMUSE library can be found at http://www.amusecode.org/. See references [5]-[8]

interacting stars is placed into the simulation with the same dynamic parameters as in the cluster, and planets are added around each. A much shorter gravitational simulation is then run, allowing the systems to approach, interact and later separate. The final states of the two systems are recorded for the next phase.

The final phase is analyzing the data generated from the previous simulations. Many simulations are run in order to develop a diverse profile of interactions. At this stage, we look for interesting encounters and related patterns, what sorts of effects are most common, and the approximate frequency of certain outcomes. From here, the results can be used to verify the validity of the simulations with observation and to make predictions about these events in the universe.

3.2.2 Cluster N-Body Simulation

The N-Body simulation code is the first phase of the pipeline. In the universe, the dynamics of the star cluster and the dynamics of the interactions of planets around the containing stars are, of course, happening simultaneously. However, the dynamics of stars in a cluster are changing much more slowly than those of the planets because of the much larger distances involved. While a planet can fully rotate about a star in less than a year, only a handful of stars pass close to one another in a megayear. Accurately simulating planets around stars within a star cluster would require far more computation time, and most of this would be wasted simulating planets normally orbiting their host star far away from any other stars.

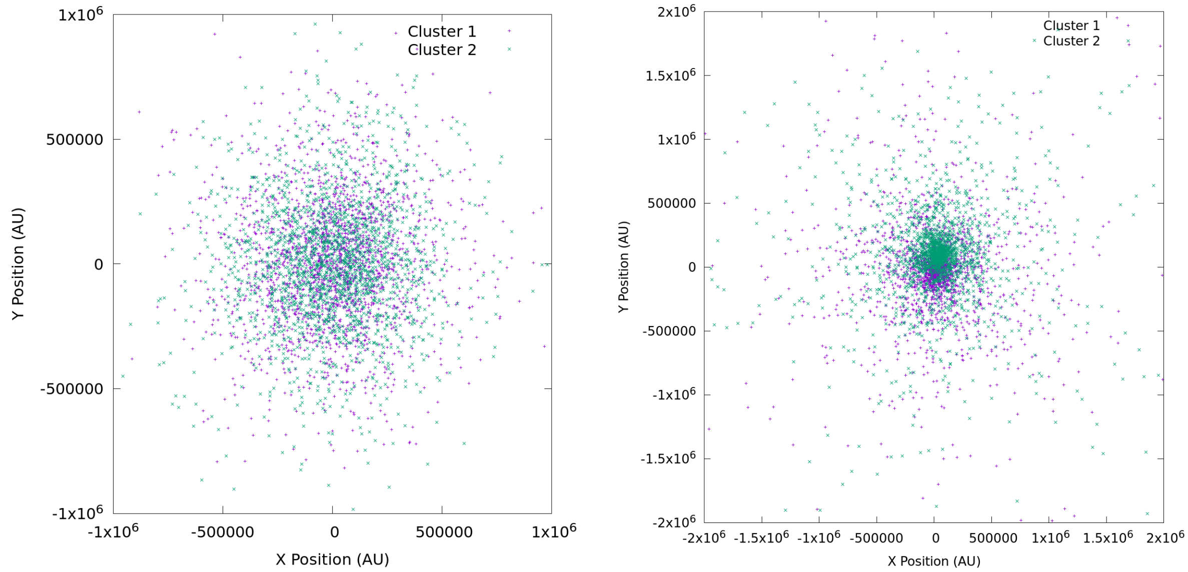
The gravitational effects of an external star on a planet's orbit only causes noticeable orbital effects if the star comes within a few times the planet's orbital semimajor axis. This means that a Jupiter-like planet with an orbit around 5 AU would only potentially be perturbed by a star that comes within approximately 30 AU of the host star. Indeed, experimentally, we observe that encounters more distant than this leave almost no visible impact on the interacting systems.

The clusters created for this simulation are composed of one-thousand, two-thousand or four-thousand stars. For all three cases, the masses of all stars are set equally to $M = 1M_{\odot}$. The simulations are run for a time directly proportional to the size, 250 Myr, 500 Myr and 1000 Myr respectively. During the simulations, any time two stars come close enough to strongly interact, the simulation is briefly halted so that the dynamical and orbital parameters can be recorded. The simulation is then resumed and this process repeats. At the end, a file is generated with all close encounters observed during the simulation, as well as the initial cluster bodies and information about the simulation itself.

A "close encounter" as defined by this part of the code is when two stars come close enough to have a strong encounter between them. AMUSE decides this distance itself and notifies the simulation when this occurs. For planetary effects, we are generally uninterested in the majority of these encounters, however we choose to record all of these encounters for later filtering based on the planets being studied.

The clusters generated for the simulation are uniquely created each time at the beginning of the simulation using a pseudo-random number generator. The star properties are sampled from a standard statistical model for globular clusters called a King Model, with a fixed parameter $W_0 = 3.0$ (King, 1966). All stars added to the cluster are given a fixed mass $M = M_{\odot}$ and do not include any binary star systems.

Figure 1: Two 2000-star clusters generated and simulated. The left plot shows the clusters at the start of the simulation. The right plot shows the same two clusters after 500 Myr of simulation time.



Each 100 megayears of simulation time for one of these clusters yields a few hundred encounters on average. The close encounters given to us by AMUSE are based on the distance of the two stars at the time in the simulation when the two stars first get close enough to interact, around 400 AU. Since we are interested in planetary effects, only events where the stars then approach very near one another are interesting to us. In order to ignore more distant events in the future without having to run an expensive planetary simulation for each, we compute the orbital elements of the two interacting stars, and use this with equation 1 to compute the approximate distance of closest approach. The closest approach distance, as well as the orbital elements, are saved along with the encounter data for the later stages to use.

Each of the three cluster sizes are simulated for the same total number of years. For the smallest configuration, one-thousand stars simulated for 250 megayears, 800 total clusters were simulated. For the two larger configurations, 400 and 200 clusters were simulated respectively. All cluster simulations results are systematically saved independently with information about the status and parameters of the run. This allows for taking subsets or samples of the data in the next stage, while still being easy to use all the results at once.

The cluster simulations in this step require a considerable amount of clock time to perform, and the time required tends to increase by a factor of four for each doubling of the number of stars and simulation time. The 4000-star clusters each required around 60 to 120 minutes to perform. Even running up to twenty clusters at once, it required a few days to simulate all of the clusters.

In figure 2, we see the spectrum of closest approach distances observed in all encounters within the 1000-star clusters. The distribution is biased slightly toward the more distant encounters, which are the least likely to cause planetary effects. In this sample of data, there are 57,351 total encounters with a closest approach distance under than 30 AU, out of 1,831,075 total encounters. This is just over 3% of total encounters recorded.

Figure 2: Closest approach of all recorded encounters in 800 1000-star cluster simulations and 200 4000-star clusters. The larger clusters have more close encounters than the small ones. For Jupiter-Earth simulations, we are primarily interested in those below 30 AU.

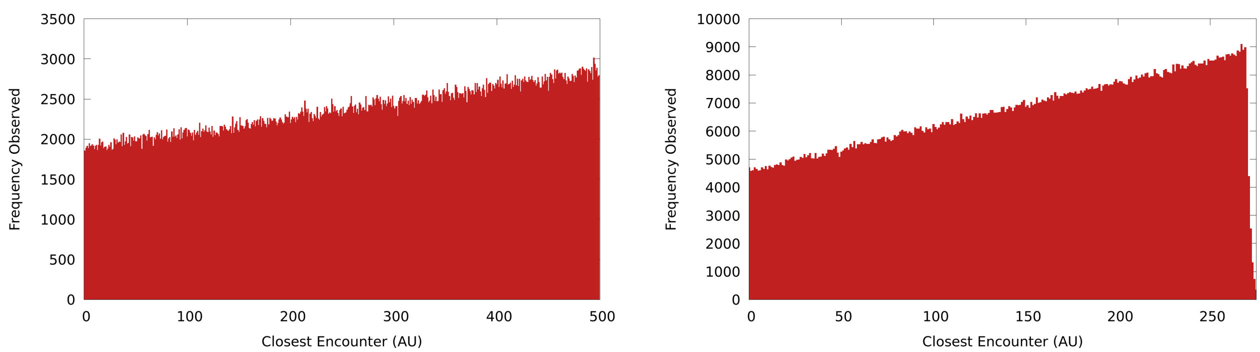


Table 1: Encounter statistics from the three sizes of clusters run. The total number of encounters observed as well as the number within two thresholds is listed.

Cluster Size	# Encounters	# Below 100 AU	# Below 30 AU
1000	1,831,075	198,952 (10.89 %)	57,351 (3.13 %)
2000	1,896,763	327,972 (17.29 %)	92,461 (4.87 %)
4000	1,869,983	534,999 (28.61 %)	144,231 (7.71 %)

3.2.3 Planetary System Simulation

The second stage of pipeline uses the cluster encounter data to do detailed analysis of individual encounters. From the cluster simulation, a list of star encounters for any number of clusters may be generated. The next step is to read these encounters and simulate just the two stars involved for each in isolated from the environment. In addition, planets are placed in orbit around both stars in the encounter before they are added to the simulation. The initial positions, velocities and physical parameters of the stars are identical to what they were at the moment AMUSE identified them as interacting.

Once the stars are setup with their planets, their gravitational dynamics are simulated. As the stars have just started interacting, the stars should move toward each other, reach a point of closest approach and then separate again in hyperbolic orbits. When the two stars separate to a distance farther than apart than they started, the simulation is stopped and the final states of the two systems are recorded.

As previously stated, each hundred megayears of a cluster simulation yields over one hundred encounters, but most of these encounters are completely uninteresting in their planetary dynamics. So for these simulations, the list of encounters is first filtered so “uninteresting” interactions are removed. For an Earth-Jupiter system, a closest approach of 30 AU was chosen as the farthest periastron to be worth considering. With this cut in place, only ten to twenty encounters, on average, are left per 100 megayears of cluster simulation.

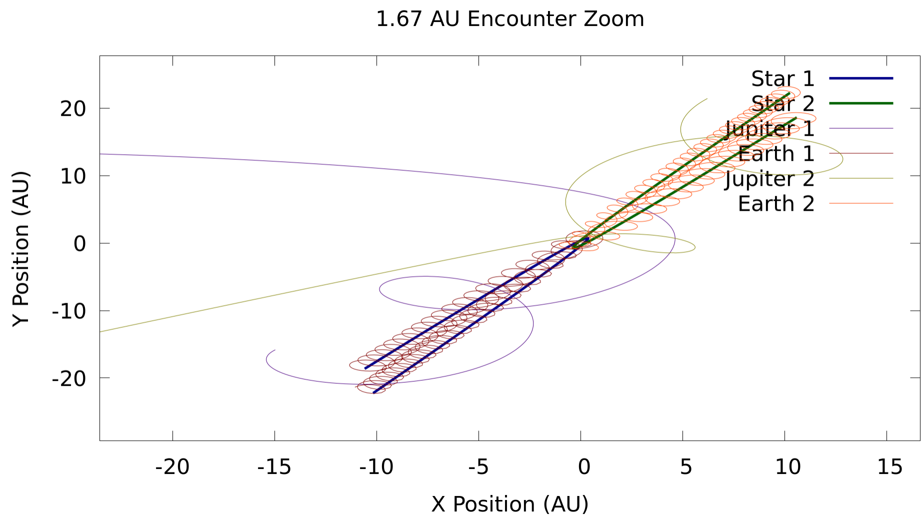
Each individual two-system simulation requires only twenty to thirty seconds of clock time to run on the computational cluster. This can be parallelized easily and we were able to run as many as fifty planetary simulations at once. With the 30 AU cut, all relevant encounters in a single cluster simulation can be simulated within ten minutes.

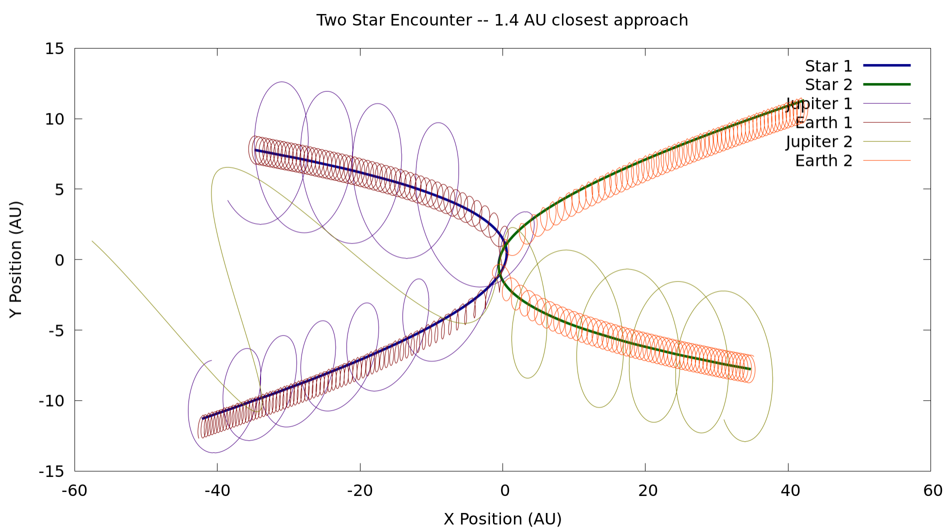
The planets added to the stars were kept consistent throughout, thus each star in each simulation was made to have one Earth and one Jupiter orbiting with the approximate physical and orbital parameters as the respective planets in our solar system. In this way, all variation will occur through variations in the clusters, not the planetary systems. All planets are placed in circular orbits (with $e = 0$), making it easy to analyze any changes after the interaction.

When the simulation is finished, the data important for later analysis is saved. The most important of this data is the starting and ending orbital elements, as well as the initial and final positions of each of the bodies. Additionally, the trajectory of all bodies may be saved in detail. The trajectories are useful for replaying an individual encounter or plotting the interaction to manually analyze some of the particularly interesting encounters.

We analyzed 55,000 close encounters for each cluster size. Figure **??** illustrates two examples of close encounter events. These two examples are chosen from the thousands of simulations that were run in the database. The large hyperbolic trajectories are the two stars interacting while the helices around them are the planets. In these interactions, the stars approach extremely close, within 2 AU in both cases, and the planets are significantly affected. These two samples represent only a snapshot of the full set of interactions that occur within the simulations.

Figure 3: Two examples of close encounter events. On the top, we see an ejection of two planets from the systems. On the bottom, one planet in the first system is captured by the second and approaches within 0.5 AU of the star. In both cases, the orbits of the remaining planets become more eccentric.





3.2.4 Data Analysis

The final stage of the pipeline is to actually analyze the encounter data output by the previous simulations. After a few days of running simulations, we are able to obtain nearly one-thousand close encounters simulated for analysis. The database constructed for this process allows all of the encounters to be loaded and related back to their originating clusters.

There are numerous potentially interesting trends or situations to look for in the output, some of which are beyond the scope we explored.

One very simple analysis we perform is to look at the output eccentricities. Since all planets were given $e = 0$ initial orbits, any deviation from zero in the output is an effect of the interaction. This shows not only the approximate amount an orbit was disturbed, it also shows planets that were ejected from their original system. Additionally, by computing the eccentricity between each planet and *both* stars, we are able to determine how many planets are captured by the approaching star.

A second analysis is to look at the final periastron for all planets that are still gravitationally bound (that is, final $e < 1$). Jupiters with a periastron of only a fraction of an AU are prime candidates to become Hot Jupiters. Additionally any significant periastron change in the Earth may have significant consequences to the sustainability of life.

4 Data Pipeline and Storage

4.1 Database

One pervasive problem in running a large number of simulations for analysis is that there is a large amount of data created and all of this data needs to be organized in order to perform detailed analysis. For instance, different simulations needs to be kept separate and the parameters used to create the clusters initially needs to be known. Additionally, if changes are made to any part of the process, it is necessary to keep that data apart from the previous data.

A second important consideration for this project is that the simulations themselves can be run in parallel and in large numbers. Big runs take a long time to run and thus it would be highly beneficial to be able to simultaneously run cluster simulations, run planetary system encounter simulations and analyze all of the completed simulations without worrying about the processes interfering with one another or using only partially complete data.

In order to address all of these concerns, we developed a python library for writing, maintaining and reading a database of this information. This database creates one directory for each cluster that is simulated. Within each directory, there is a table of all encounters, a table of the initial states of all stars and a set of details about the run itself. These directories are separated into clusters of the same initial cluster parameters for easy segregation if needed.

When simulations of the individual encounters are performed, each encounter creates a subdirectory inside of the originating cluster's directory for the results. The initial and final parameters of each body in the simulation are stored, along with trajectories for the particles during the encounter. When all simulations in some cluster are complete, overall statistics about which encounters were simulated and which were skipped due to data cuts are generated.

In each of these processes, the program first creates a "lock" file before it writes any data to the database. This lock file signifies that the cluster or encounters within are being actively simulated by some program at the time and should not be touched by anything else until it is removed. This allows us to safely achieve the high level of parallelisation desired without risk of data corruption. The lock file stores the time it is created so if a program crashes, power is lost or some other event that causes the program to end without proper termination, a lock can be identified as old automatically which signals that the data contained within is likely incomplete and the program writing it was unable to properly complete.

One final data management feature is the inclusion of a database version number in each summary file produced. This allows for the data format to be modified, additional features to be added and backward incompatible changes to be introduced without making all old data unusable.

It is our hope is not only that this makes our data analysis tasks easier, but that it is usable by future researchers who want to perform similar experiments.

4.2 Analysis

As hundreds of thousands of encounter simulation results can be stored in the database, and a few kilobytes of data is stored for each, it can take as long as a half-hour to load, parse process each set of 100,000 results. In order to promote modularity, each analysis should be able to run independently of all others, but running each analysis independently over all the data would result in as much as an order of magnitude slow down as the data would be parsed again and again. However, on the opposite side, throwing all analyses into a single function or module makes it very difficult for future scientists to define their own analyses without understanding everything already done or replacing it all entirely. Additionally, it becomes extremely difficult for multiple people to collaboratively write analyses.

To remedy the problem without losing modularity, the analysis module takes a set of analysis tasks to run. Each analysis task has a coroutine that accepts a single encounter result at a time, and incrementally processes that data into its isolated state. This technique (called an "online algorithm") allows any number of analyses to be performed in one pass over the input data. The complexity of writing an analysis using this approach is slightly higher, and requires code be written to understand this model, but the end result is a fast and modular processing framework.

5 Results

To draw conclusions and generate plots, we used exactly 55,000 close encounters from each set of parameters.

We first analyze the final planet eccentricities. Figure 4 shows the resulting spectrum of eccentricity values after the simulation. The eccentricity values are divided into 100 bins, each 0.01 wide. The top pair of plots is for 1000-star clusters, followed by 2000-star and 4000-star clusters. The green plots show Earths while the blue plots show Jupiters. The Jupiters are clearly more easily perturbed than the Earths, however a measurable number of Earths, at least a few hundred, are perturbed to have an eccentricity greater than 0.5. In both cases, the vast majority of planets are hardly perturbed at all, with tens of thousands of final states having $e < 0.1$.

Figure 4: Final orbit eccentricity frequencies for the planets after the two systems interact. The left plots are for the Earth and the right are for the Jupiter. The frequency scale is base-10 logarithmic. Planets that were ejected from their systems are not included.

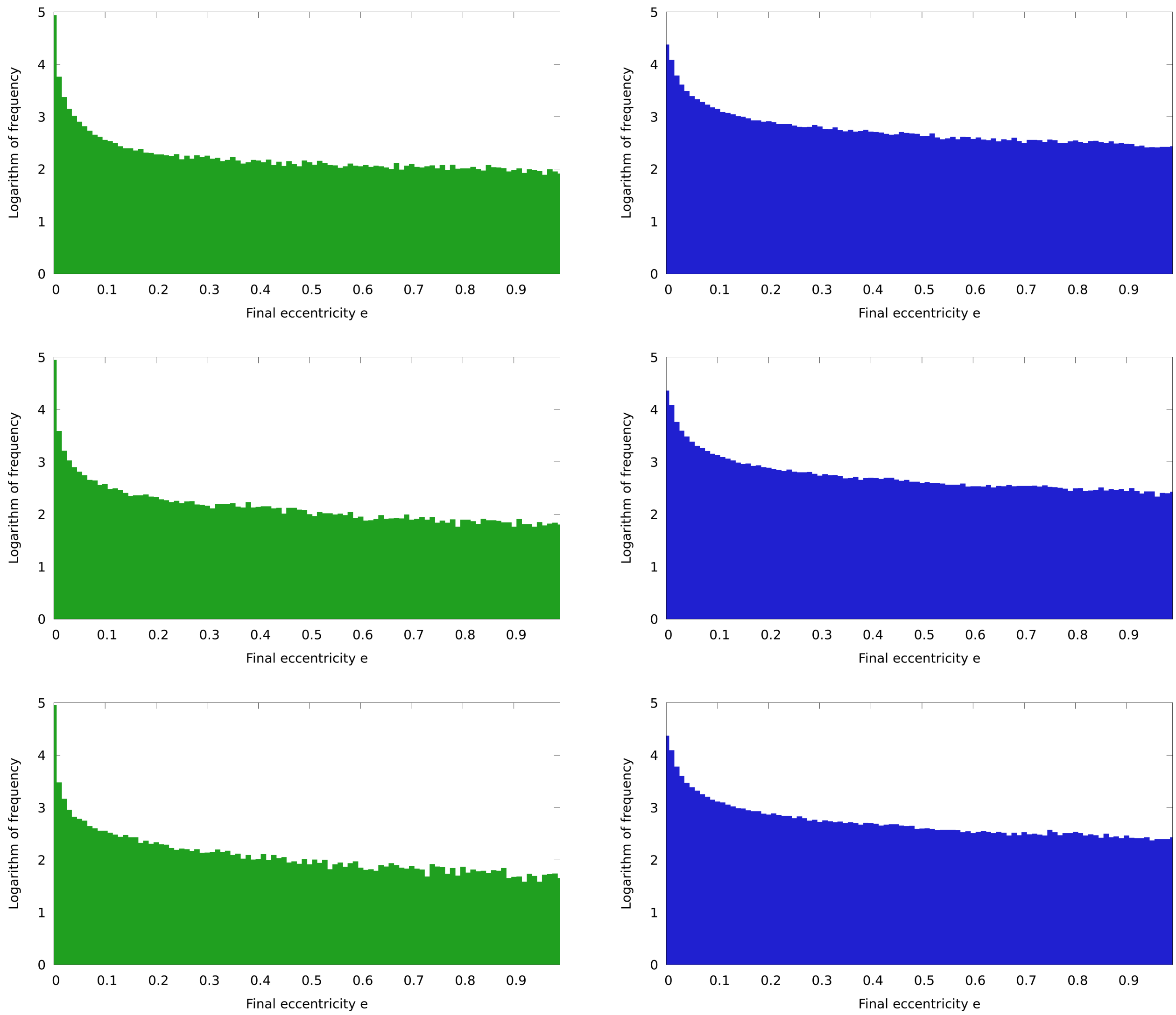


Figure 5 shows the final distributions of closest approaches. The top plots are 1000-star clusters, while the bottom are 4000-star clusters. There is a decrease in very close periastron distance with increasing cluster size, especially in the Earths. We find several hundred

Jupiters with a periastron less than 0.1 AU. The bottom-most plot is a zoom of the closest Jupiters for a 1000-star cluster.

Figure 5: Closest approaches of all Earth and Jupiter planets after the encounter that have not escaped. On all plots, there is a peak at the unperturbed orbital distance (5.1 AU for Jupiter, 1.0 AU for Earth) and then a tail of closer approaches representing orbits that were more severely perturbed. Jupiter planets below 1.0 AU come into the inner planet orbits and could continue to interact further. The extremely close orbits potentially could become Hot Jupiters after orbit decay.

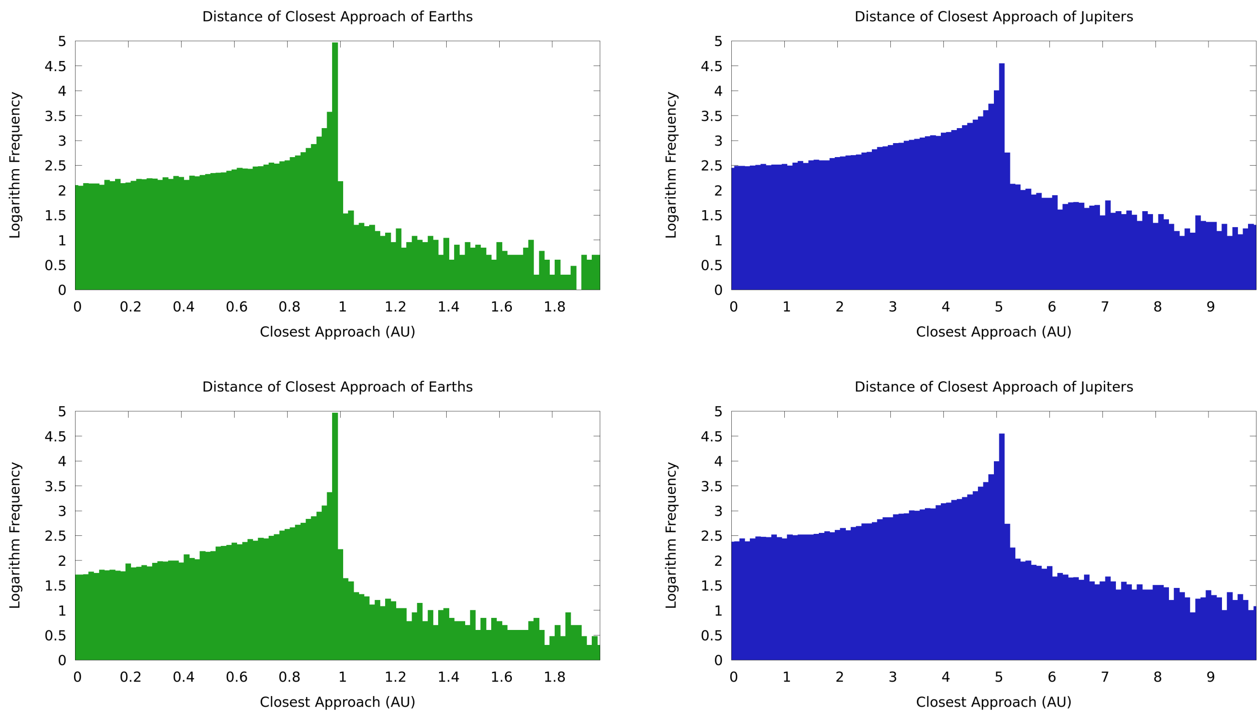
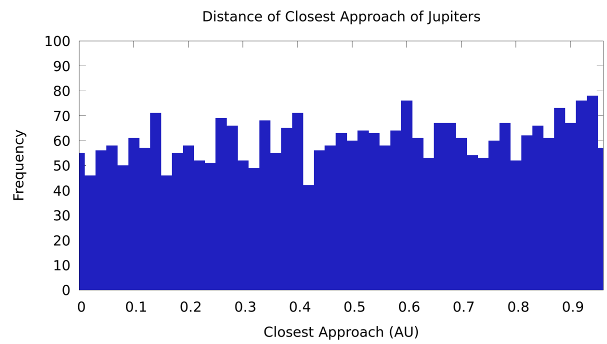


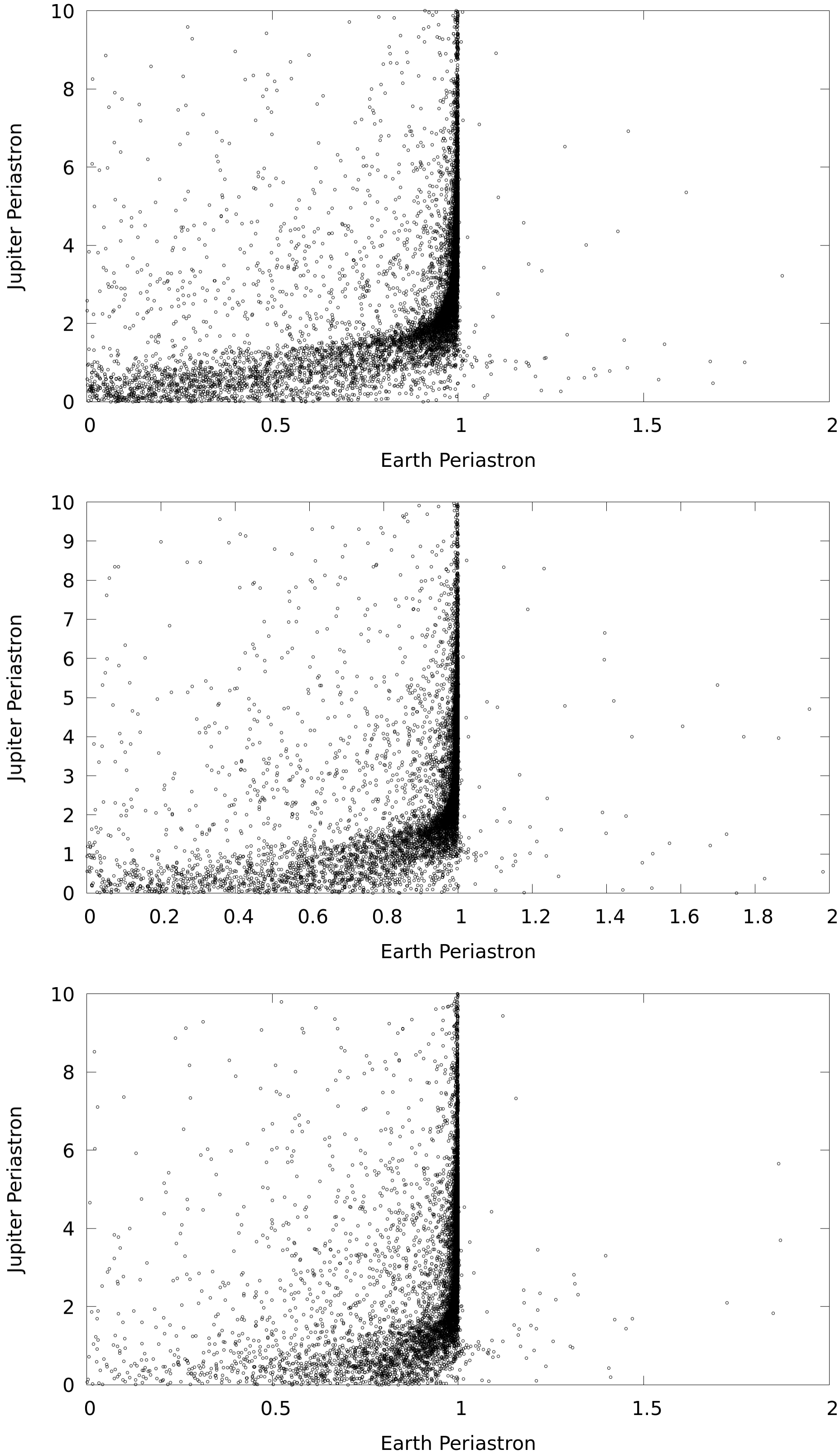
Figure 6: Closest approach of Jupiter for 1000-star clusters, zoomed into the closest 1 AU of the star. The scale is linear.



To determine how much of an effect Jupiter migration had on the fate of the Earths, we plot the periastron of the two planet classes together. There is a very clear trend showing that relatively few Earths are perturbed significantly when the corresponding Jupiter is not perturbed significantly. However, once the Jupiter migrates to within less than about two AU of the star, the corresponding Earth has a much larger chance to be perturbed. Furthermore, there is a clear trend showing that as the Jupiter periastron gets closer to the star, on average, so does the periastron of the Earth. By the time Jupiter comes closer than 1 AU from the star, the Earth rarely survives unharmed.

Interestingly, as the mass of the cluster increases, the Earths appear to be less strongly affected by the Jupiter migration. Figure 5 shows that the average frequency of close Jupiters does not significantly decrease in these more massive clusters, while the frequency of close Earths decreases by as much as half an order of magnitude in the closest cases.

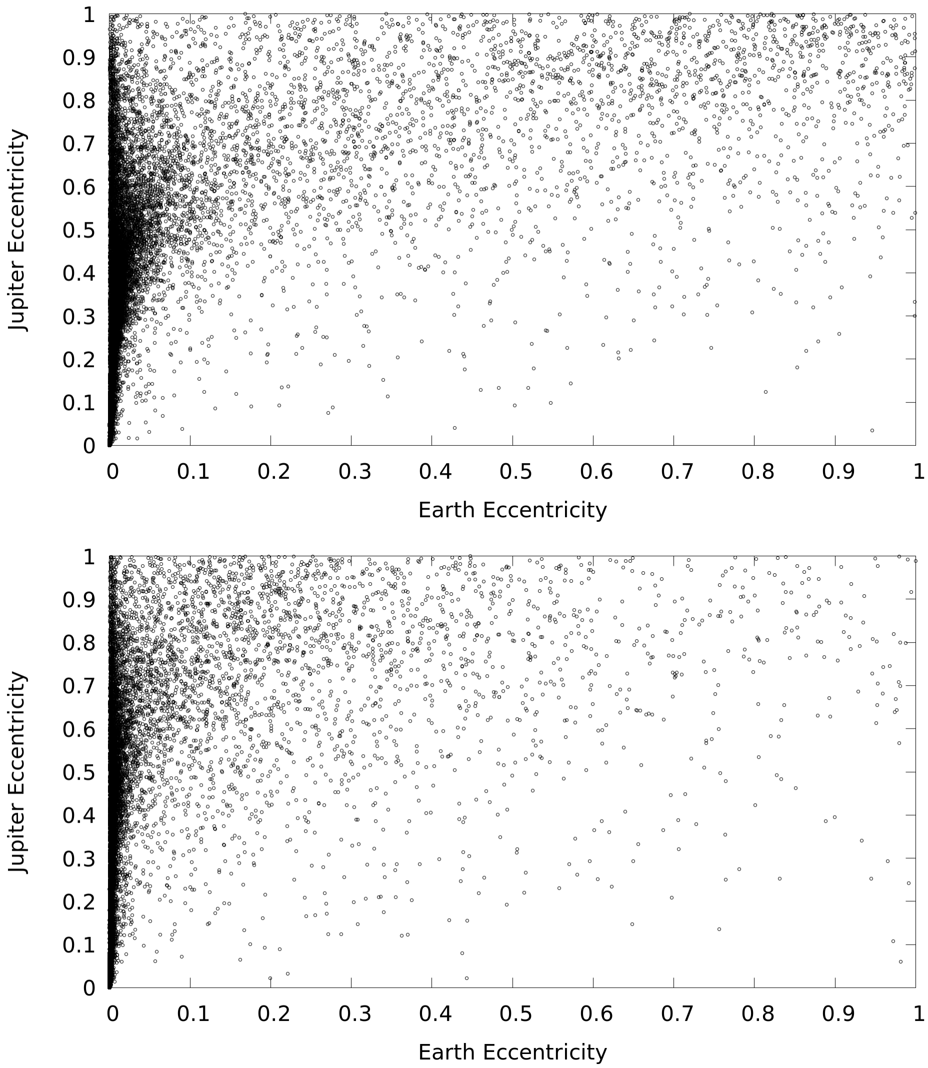
Figure 7: Periastron of Earth vs Jupiter for all encounters in each cluster group where neither planet escaped. From the top, the plots are for 1000-, 2000- and 4000-star clusters.



Looking at the correlation of eccentricities of the final Earth and Jupiter systems, we see similar trends. In the 1000-star clusters, more high eccentricity Earths are in systems with high eccentricity Jupiters. Additionally, there appears to be a "bulge" around $e = 0.5$ for the Jupiter where a large number of Earths are at least partially affected.

Again, as with the periastron plots, we see many fewer high eccentricity Earths, though the general correlation between Earth and Jupiter periastron still exists.

Figure 8: Eccentricity of Earth vs Jupiter for all encounters in each cluster group where neither planet escaped.The top plot is with 1000-star clusters while the bottom is with 4000-star clusters.



One final interesting analysis is to look at ejections and captures of planets. An ejection can be easily detected by searching for an $e \geq 1.0$ for a planet around both stars, whereas a capture can be detected by looking for $e \geq 1.0$ in the host star but $e < 1.0$ in the approaching star.

We see over 10% of all Jupiters are ejected, and around 2.5 % of Earths are as well. Captures are a bit rarer, but they still occur with an appreciable frequency. The size of the cluster seems to have no effect on these statistics.

Table 2: Final states of Jupiter planets. Each row sums to 55,000.

Cluster Size	**Remaining Planets**	**Ejected Planets**	**Captured Planets**
1000	46,935	6,472	1,593
2000	46,925	6,528	1,548
4000	47,146	6,343	1,511

Table 3: Final states of Earth planets. Each row sums to 55,000.

Cluster Size	**Remaining Planets**	**Ejected Planets**	**Captured Planets**
1000	53,427	1,245	328
2000	53,489	1,229	282
4000	53,413	1,299	288

6 Conclusion

We explored a potential formation scenario for the formation of Hot Jupiter planets using computational simulations to probe the physical universe. These planets have been observed in the universe with some frequency, but their exact method of formation remains debated. We theorize that strong interactions between two planetary systems in a star cluster could perturb the orbit of a normal gas giant to make it approach very close to its host star.

Our simulations show that this scenario is indeed a possibility, and that very close interactions on the order of a few AU can frequently throw Jupiter-mass planets into highly eccentric orbits with very close approaches to their host star. This may also drastically impact the orbits of other Earths in the system, with Jupiters migrating close to their host star being correlated with Earths also being perturbed. This provides support for the idea that a Hot Jupiter may often have another pair planet that was thrown into an extreme orbit by the same process that affected the Jupiter's orbit. Thus, observation of these pair planets may provide reason to search for a Hot Jupiter nearer the star.

Further long-term simulation will be needed to determine if the highly eccentric Jupiter orbit could decay into a more circular orbit, similar to the many observed Hot Jupiters observed in our Galaxy, through tidal forces. Additional experiments may also determine how more distantly orbiting planets such as Neptunes differ from Jupiter in their behavior and whether they are more likely to form Hot Jupiters.

References

[1] James B. Pollack, Olenka Hubickyj, Peter Bodenheimer, Jack J. Lissauer, Morris Podolak, Yuval Greenzweig, Formation of the Giant Planets by Concurrent Accretion of Solids and Gas, Icarus, Volume 124, Issue 1, 1996, Pages 62-85, ISSN 0019-1035, http://dx.doi.org/10.1006/icar.1996.0190. (http://www.sciencedirect.com/science/article/pii/S0019103596901906)

[2] A. Brucalassi, L. Pasquini, R. Saglia, M. T. Ruiz, P. Bonifacio, I. Leo, B. L. Canto Martins, J. R. de Medeiros, L. R. Bedin, K. Biazzo, C. Melo, C. Lovis, S. Randich, Search for giant planets in M67 - III. Excess of hot Jupiters in dense open clusters A&A 592 L1 (2016) DOI: 10.1051/0004-6361/201527561

[3] Foreman-Mackey, D., Morton, T. D., Hogg, D. W., Agol, E., & Schölkopf, B. 2016, arXiv:1607.08237

[4] Shara, M. M., Hurley, J. R., & Mardling, R. A. 2014, arXiv:1411.7061

[5] Eisenstein, DJ, Hut, P, HOP: A new group-finding algorithm for N-body simulations, ApJ 498 (1998)

[6] Portegies Zwart, S. et al., 2013, Multi-physics Simulations Using a Hierarchical Interchangeable Software Interface, Computer Physics Communications 183, 456-468 [2013CoPhC.183..456P]

[7] Pelupessy, F. I. et al., 2013, The Astrophysical Multipurpose Software Environment, Astronomy and Astrophysics 557, 84 [2013A&A...557A..84P]

[8] Portegies Zwart, S. et al., 2009, A multiphysics and multiscale software environment for modeling astrophysical systems, *New Astronomy*, **Volume 14**, **Issue 4**, 369-378 [2009NewA...14..369P]

[9] F. A. Rasio, C. A. Tout, S. H. Lubow and M. Livio, "Tidal decay of close planetary orbits," Astrophys. J. **470**, 1187 (1996) doi:10.1086/177941 [astro-ph/9605059].

[10] King, I. R. 1966, "The structure of star clusters. III. Some simple dynamical models", The Astronomical Journal 71, 64 doi:10.1086/109857 (http://adsabs.harvard.edu/abs/1966AJ.....71...64K)