Computational Astrophysics - Assignment 3

Saeid Mahmoudzadeh - s2547341, Yuan Chen - s2562081
Christiaan van Buchem - s1587064

November 7, 2019

1 Introduction

It has been theorized that it took around a million years for Jupiter to form after the birth of our sun. As this is a relatively small amount of time, the protoplanetary stellar accretion disk associated with star formation was most likely still present. For this assignment we will be investigating a simplified version of this young solar system by simulating the evolution of a gaseous disk and a planet around a sun-sized star. We will also be investigating what the effect of a closely passing (unbound) star would have on this system and whether or not this would have an effect on the accretion rate upon the planet. We believe that a passing star would cause a displacement in the gas of the disk which could increase local density of the gas within the disk, which in turn would cause the planet in the system to be able to accrete more mass. In the following section the method will be presented. We will then show our results, have a discussion and finally draw our conclusions.

2 Method

We approached this project by building up the simulation in different steps. These steps are the following:

1. Build a circumstellar disk around a sun sized star
2. Build a two-body system with a sun sized star and a Jupiter sized planet.
3. Join the two-body system to the circumstellar disk.
4. Add a passing star to the simulation.

For step 1 we used Smoothed Particle Hydrodynamics (SPH) in order to simulate the evolution of a stellar disk. The SPH code that we decided to use is called `Fi`. As asked in the assignment description, we used a star mass of $1M_{\odot}$, a disk mass of 1% of the star mass, and a maximum disk radius of 100 AU. We decided ourselves that 2 AU would be a suitable size for the minimum disk radius. We tracked the disk size by looking at the 90% percent Lagrangian radius and ran the simulation for 1000 years for N = 500 SPH particles, 1000, 2000 and 4000. For step 2 we ran a simulation of a single $1M_{Jupiter}$ planet orbiting a $1M_{\odot}$ star for a 1000 years and used the integrator named `Ph4`. The initial conditions that we used were the one given in Table 1.

Table 1: The initial conditions used to initialise the two-body system. These values were taken from Portegies Zwart & McMillan (2018).

	Mass	Position $[AU]$			Velocity $[km\ s^{-1}]$		
		x	y	z	vx	vy	vz
Sun	$M_{\odot}$	0.005717	-0.00538	-2.130e-5	0.007893	0.01189	0.0002064
Jupiter	$M_{Jupiter}$	-4.9829	2.062	-0.10990	-5.158	-11.454	0.13558

For step 3 we measured the accretion onto the Jupiter by adding a sink particle to it. The sink particle swallows gas particles when they approach within the Jupiter‘s Hill radius. We then added the accreted mass to the Jupiter. We were asked to use a bridge between the gravity and the hydro integrator. However, this was causing the gas particles near the sun to disperse very quickly. This was due to the large bridge time step, but decreasing the bridge times steps makes the simulation extremely time-consuming. Therefore, we decided to use hydro code for both for the Sun and the disk in order to avoid this effect. We ran the simulation for 1000 years for N=4000 SPH particles and tracked the disk size, Jupiter's semi-major axis, eccentricity and the mass-accretion rate of Jupiter. In the 4^{th} step we added a passing star with a mass of $2M\odot$ in an unbound orbit with respect to the star-planet-disk system with an approximate pericenter distance of 200 AU and a velocity in order of 1 km/s in the y direction. The passing star's initial position is $r_{PStar} = (200, -400, 0)$ AU. For this part of the assignment we also encountered a problem with using an N-body code in this simulation. It appeared that Jupiter would get ejected from the system once the second start passed nearby. We suspected that this was due to a similar problem in the code as for step 3. Therefore we decided to also give Jupiter to the hydro code. Therefore we no longer used an N-body code which made the use of a bridge unnecessary.

3 Results

In this section we will be presenting our findings for each of the steps taken in building the model.

3.1 The circumstellar disk

First of all we needed to test the stability of the generated disk. We expected that an increased number of SPH particles used in the simulation would produce more accurate and stable result due to an increased resemblance to a physical gas. As we can see in Figure 1 this was indeed the case since the amount of fluctuation in the disk size visibly decreases as the number of particles is increased. It appears that we have a stable disk for first 300 years in the integration time. Past this point the particles in the disk start to drift outwards at an increasing rate.

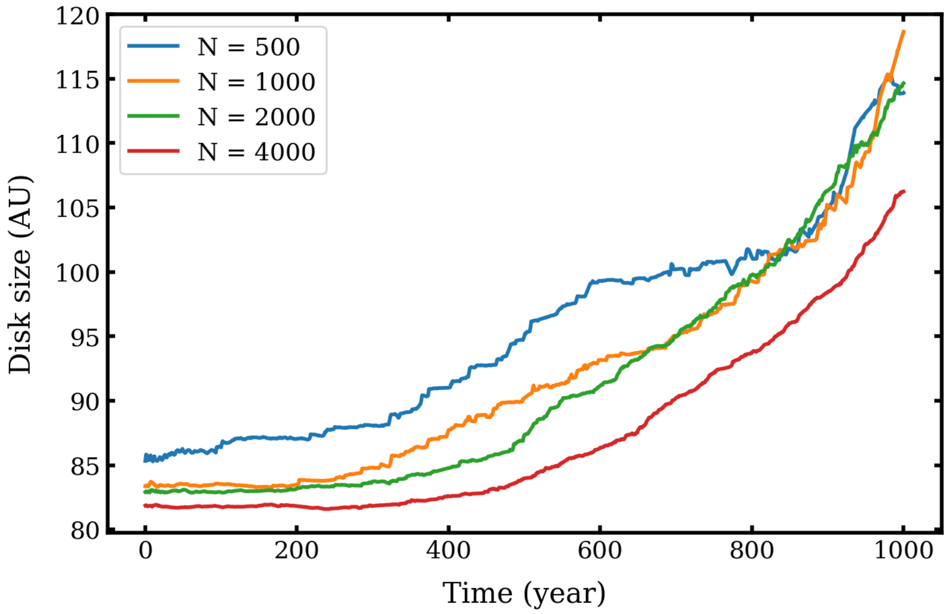

Figure 1: Size of the circumstellar disk with a total mass of $10^{-2}M_{\odot}$ around a star of $1M_{\odot}$ as a function of time using N = 500, 1000, 2000 and 4000 SPH particles in the simulation.

3.2 The two-body system

We also wanted to test the stability of our N-body simulation. As you can see in Figure 2 the deviation from initial conditions is almost negligible for semi major axis and less than 2 percent for eccentricity over 1000 years. So the N-body simulation is also reliable for first 1000 years in the integration time.

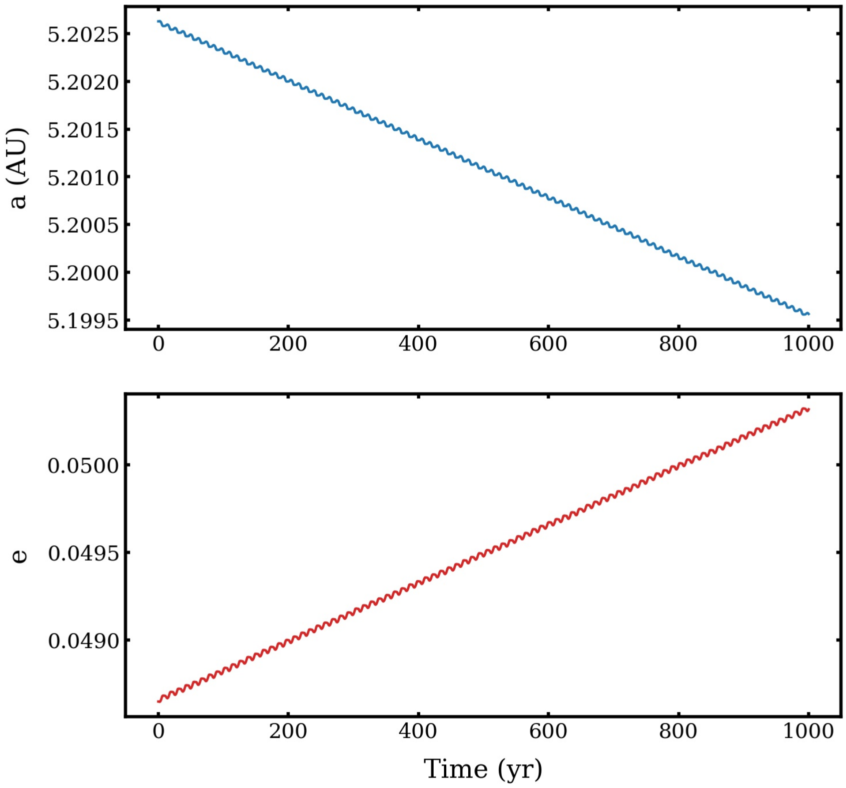

Figure 2: Semi-major axis and eccentricity of the Jupiter orbits the Sun as a function of time tracked using the N-body simulation.

3.3 The two-body system and the disk

Now that we know both hydro and gravity code are reliable in the first 300 years, we can use them together to evolve the system of Sun, Jupiter and the disk and track the accreted mass on Jupiter. In Figure 3 we can see what the system looks at $t = 0$. The change in the parameters of Jupiter's orbit is interesting however. This could be due to the slightly heterogeneous initialisation of the gas particles affecting its orbit.

3.4 The planetary system, the disk and the encountering star

In Figure 5 we can see the results of adding a passing star to the system. It is quite clear that the amount of accreted mass by the planet is larger than it was without a passing star by about $0.01 M_{Jupiter}$. Furthermore the disk size clearly starts increasing from after the star has passed the point of closest approach. Lastly we can also see that the general trend in Jupiter's orbit is that it moves closer to the sun.

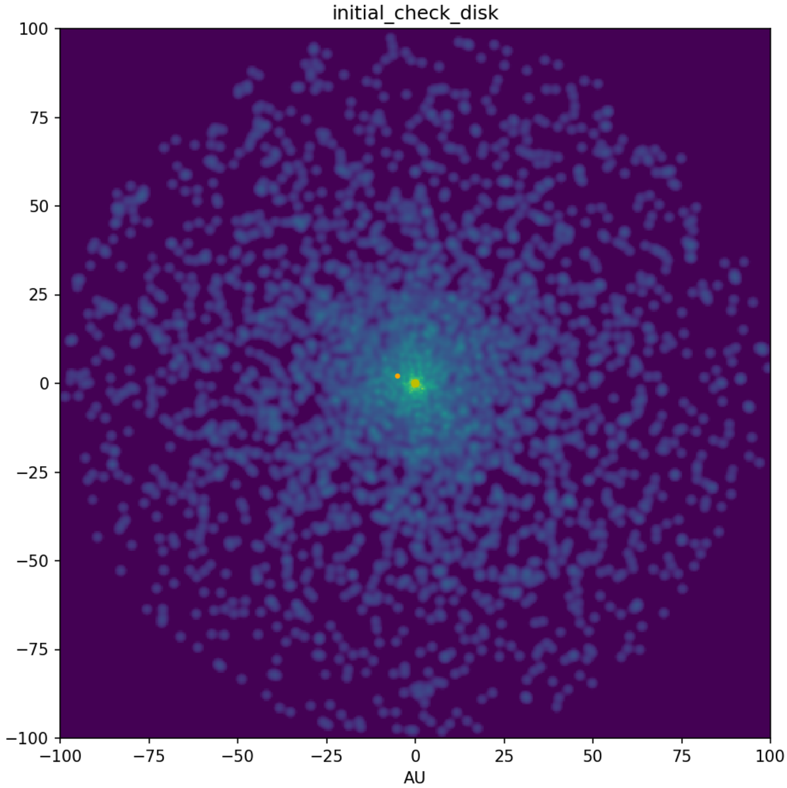

Figure 3: Here we see the initial conditions for the two-body system with a disk. The yellow dot in the center represents the Sun, the orange dot represents Jupiter.

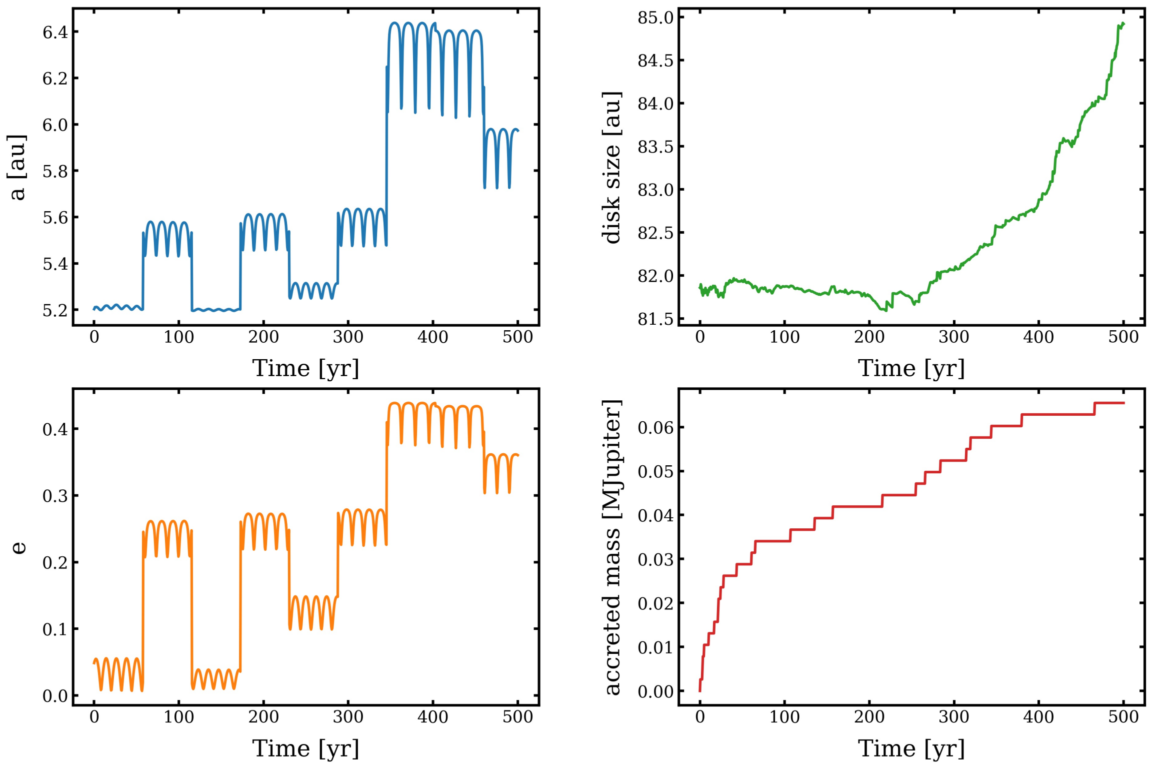

Figure 4: (plots for question 3)

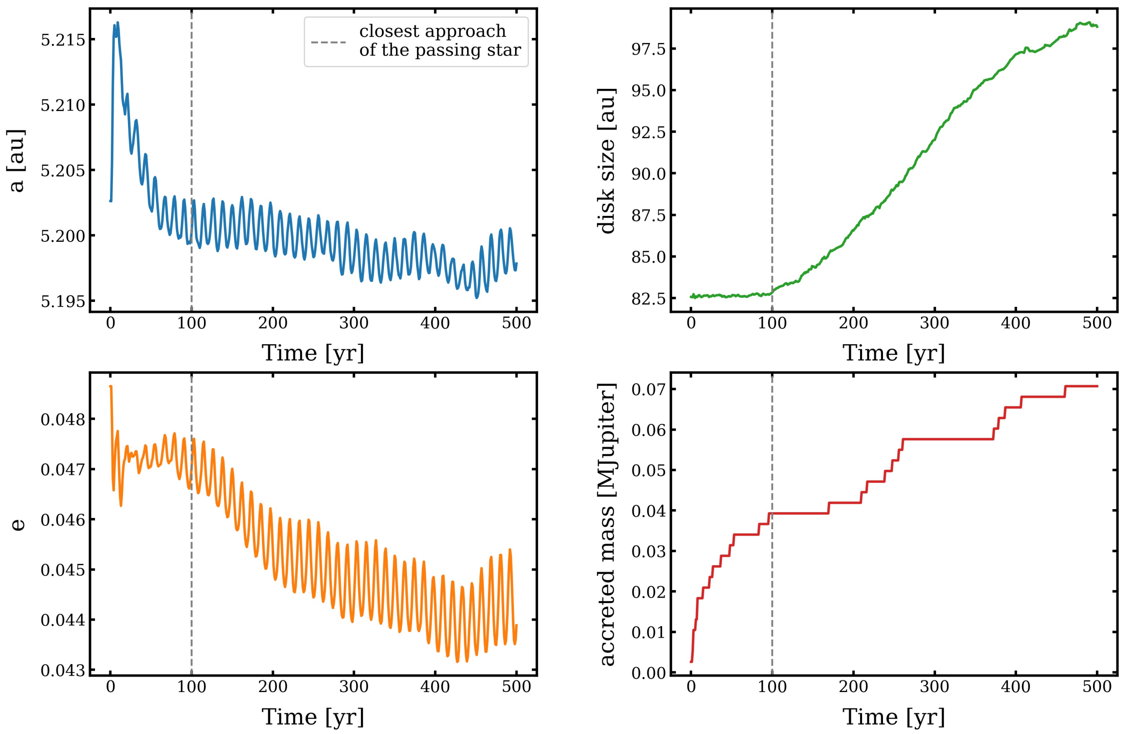

Figure 5: Semi-major axis and eccentricity of the Jupiter as a function of time tracked using the N-body simulation.

4 Discussion and conclusion

By comparing the results from Figure 1 with Figure 4 that adding a planet to the sun-disk system does not have a very large effect on the growth of the accretion disk. It mostly appears to slightly increase the size fluctuation but the overall growth trend is similar. However, we do see a significant increase in disk size growth a passing star. The passing star also has a visible effect on the amount of accreted mass by the planet. Although the accretion rates initially appears to decrease, it eventually increases up to a point were the final total accreted mass is greater than without a passing star. This experiment therefore supports the hypothesis that we stated in our introduction.

For further more in depth analysis of this problem we would could investigate what the effect would be of having the passing star move against the direction of the rotation of the disk as opposed to along with it. Furthermore a higher resolution and therefore more accurate version of this simulation could be run by increasing the number of `SPH` particles in the simulation. As we can see in the accretion plots, the mass increases are incremental which is due to the fact that the gas is grouped in relatively large particles. This could potentially tell us more about the exact rate of increase or decrease in accretion. Finally we could also investigate the effect of the star on the accretion as a function of its point of closest approach.

References

Portegies Zwart S., McMillan S., 2018, Astrophysical Recipes: The art of AMUSE. IOP Publishing, Bristol, doi:10.1088/978-0-7503-1320-9