Computational Astrophysics - Assignment 3

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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 investigate 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 investigate what effect of a closely passing (unbound) star would have on this system, and whether or not this would affect 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, and 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 in which a Jupiter-sized planet orbits around a sun-sized star.
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) to simulate the evolution of a circumstellar 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% Lagrangian radius and ran the simulation for 1000 years for four different numbers of SPH particles: N = 500, 1000, 2000 and 4000. For step 2 we ran a simulation of a single $1M_{\text{Jupiter}}$ planet orbiting a $1M_\odot$ star for 1000 years and used the direct N-body integrator `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

In the 3$^{\text{rd}}$ step we measured the accretion onto the Jupiter by adding a sink particle to it. The sink particle swallows gas particles when they enter 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 the Sun and the disk in order to avoid this effect. We ran the simulation for 1000 years with N=4000 SPH particles and tracked the disk size, Jupiter's semi-major axis, eccentricity and the mass-accretion rate.

In the 4^{th} step we added a passing star with a mass of $2M\odot$ in an unbound (hyperbolic) orbit with respect to the star-planet-disk system. Its pericenter distance to the 'Sun' is 200 AU and its velocity is in order of 1 km/s in the y direction. The initial position of the passing star is $r_{PStar} = (200, -400, 0)$ AU. For this part we also encountered a problem with using bridge between a N-body code and a SPH one. It appeared that Jupiter would get ejected from the system once the exotic star passed nearby. We suspected that this was due to a similar problem in the code as for step 3. Therefore, we decided to give Jupiter to the hydro code as well, which meant that we threw away the N-body code and dealt with this step fully by SPH code.

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 using an increased number of SPH particles in the simulation would produce more accurate and stable result due to an increased resemblance to a physical gas. This is verified by Figure 1 that 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 the first **300 years** in the integration time. After this point the particles in the disk start to drift outwards at an increasing rate.

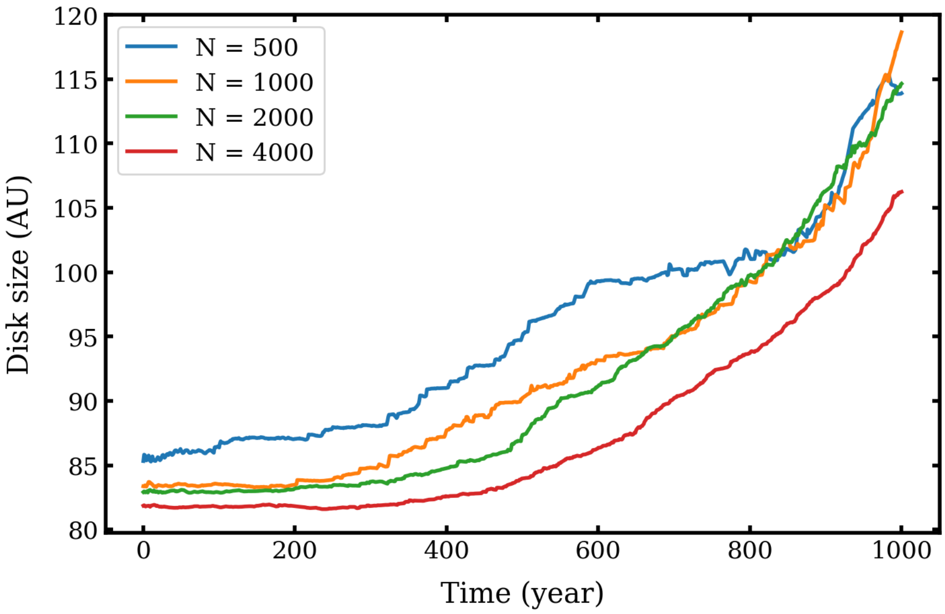

Figure 1: Size of the circumstellar disk with a total mass of $10^{-2}M_{\odot}$ around a star of $1M_{\odot}$ as a function of time using N = 500, 1000, 2000 and 4000 SPH particles in the simulation.

3.2 The two-body system

We also wanted to test the stability of our N-body simulation. As we can see in Figure 2 that the deviation from initial conditions is almost negligible (<2%) for both the semi-major axis and the eccentricity for 1000 years, which indicates the reliability of the N-body simulation within this time range.

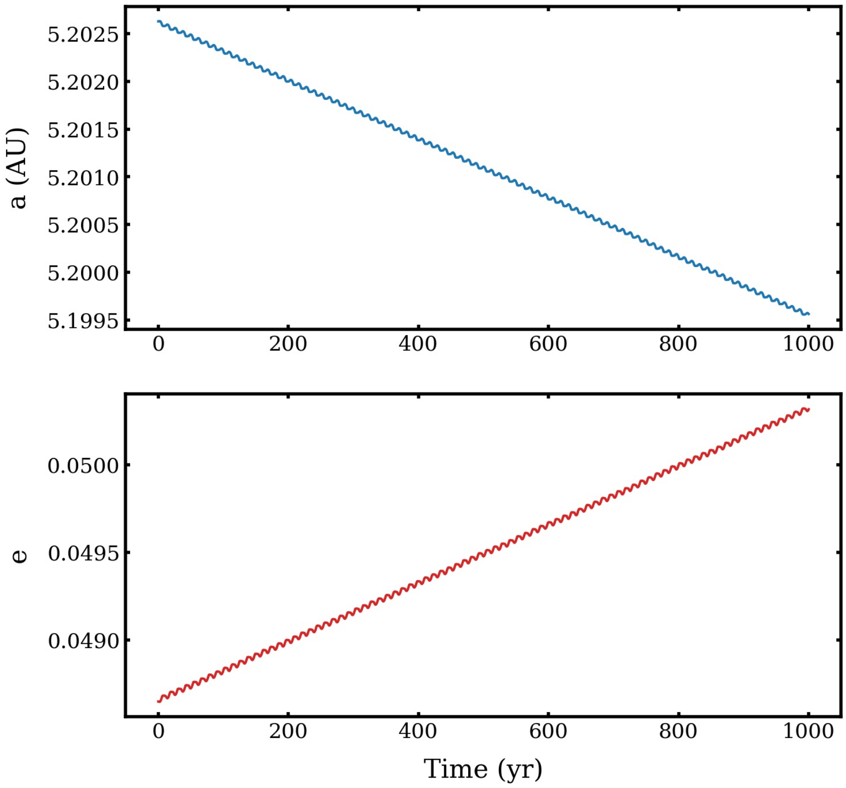

Figure 2: Semi-major axis and eccentricity of Jupiter's orbit as a function of time in the N-body integration.

3.3 The two-body system and the disk

Now that we know both the SPH and the 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. Figure 3 shows what the system looks at $t = 0$.

In Figure 5 we present how the four parameters evolve as a function of time: the semi-major axis, eccentricity, and accreted mass of the planet, as well as the disk size. The evolution of the Jupiter's orbit is interesting: the pattern of the semi-major axis seems like a harmonic function with increasing amplitudes, and the eccentricity shows a 'beat' pattern which usually results from a superposition of two harmonic functions with different resonant frequencies. This is probably caused by the interaction between the planet and the disk. Since we fixed the random seed before the initialization, we cannot rule out the effects from initialization.

From the upper-right panel we can see that the disk size increases dramatically after 250 years. This time stamp is a bit earlier than that of the case without a accreting planet. Taking all of the four plots into account, we deduce that the existence of the planet and the disk will add chaos to (reduce the stability of) the stellar system.

3.4 The planetary system, the disk and the encountering star

In Figure 5 we display the same plots as Figure 4 but for the system with a passing star. It is clear that the amount of accreted mass by the planet is larger than it was without a passing star by about $0.01M_{\text{Jupiter}}$, which verifies our hypothesis in the Introduction. Furthermore, we can see from the top-right panel that the disk size clearly starts increasing after the star has passed the pericenter to the Sun. This is reasonable since the passing star is quite massive ($2\ M_{\odot}$) and close (200AU) to the Sun-Jupiter-disk system, therefore its influence should be significant. An interesting point to notice is that the Jupiter's orbit becomes more stable than in the previous case. This is likely to because of the distortion of the disk by the passing star, which breaks the circular shape and dilutes the density of the outer part of the disk, and hence reduce some resonant effects to the planet's orbit. We highly recommend readers to take a look at the movies that visually show how these processes are going.

Last but not least, we only run the simulation for 500 years instead of the required 1000 years. Besides the affordable time cost, the reason of doing this is that the system becomes quite chaotic

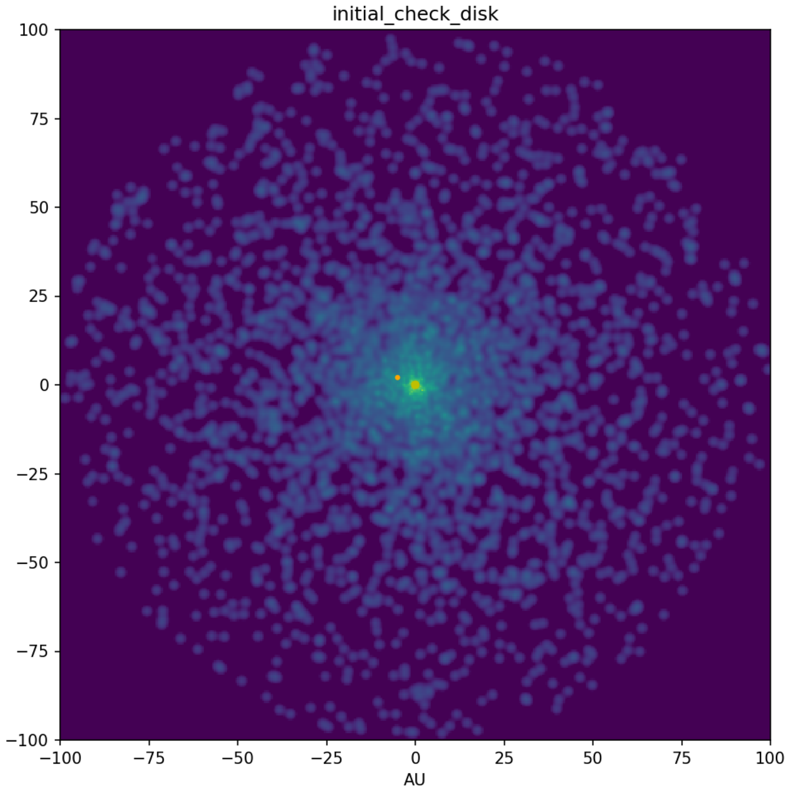

Figure 3: Here we see the initial conditions for the two-body system with a disk. The yellow dot in the center represents the Sun, the orange dot represents Jupiter.

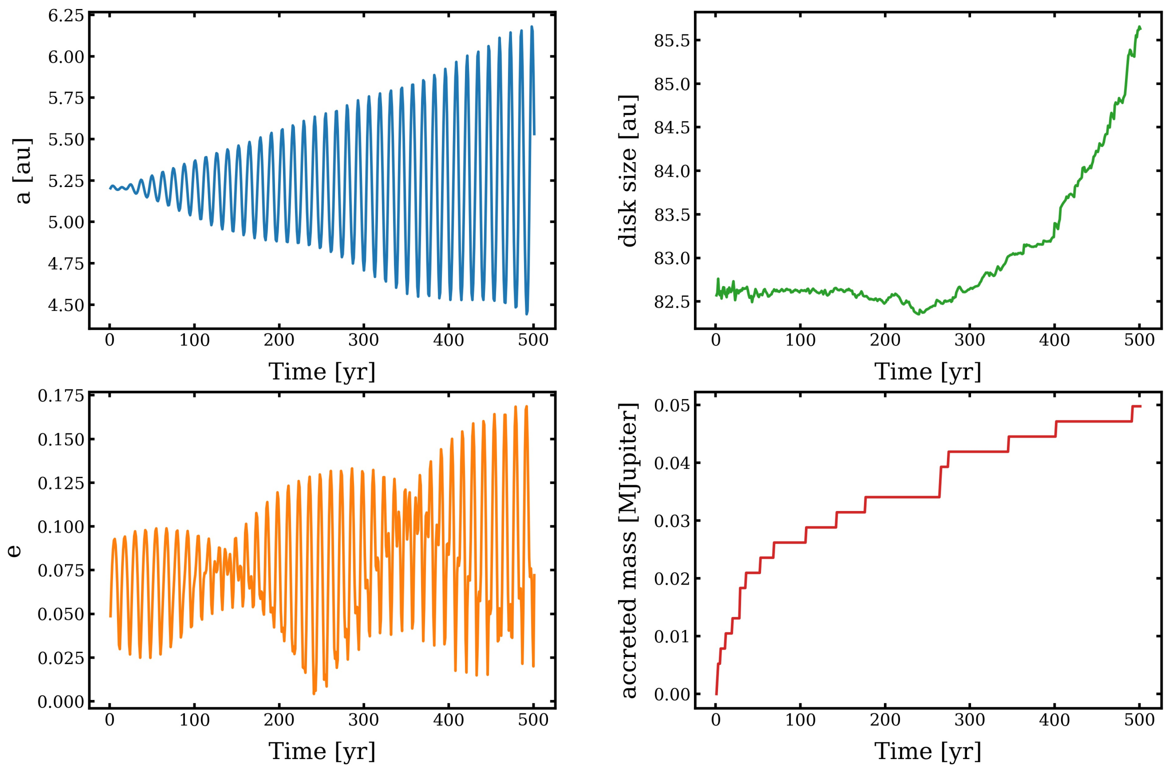

Figure 4: (plots for question 3)

or disturbed after 500 years and it is not very meaningful to investigate its evolution to a very far time stamp. And technically, it will be very time-consuming to simulate such a system, so we just stop our running at 500 years for the last two tasks.

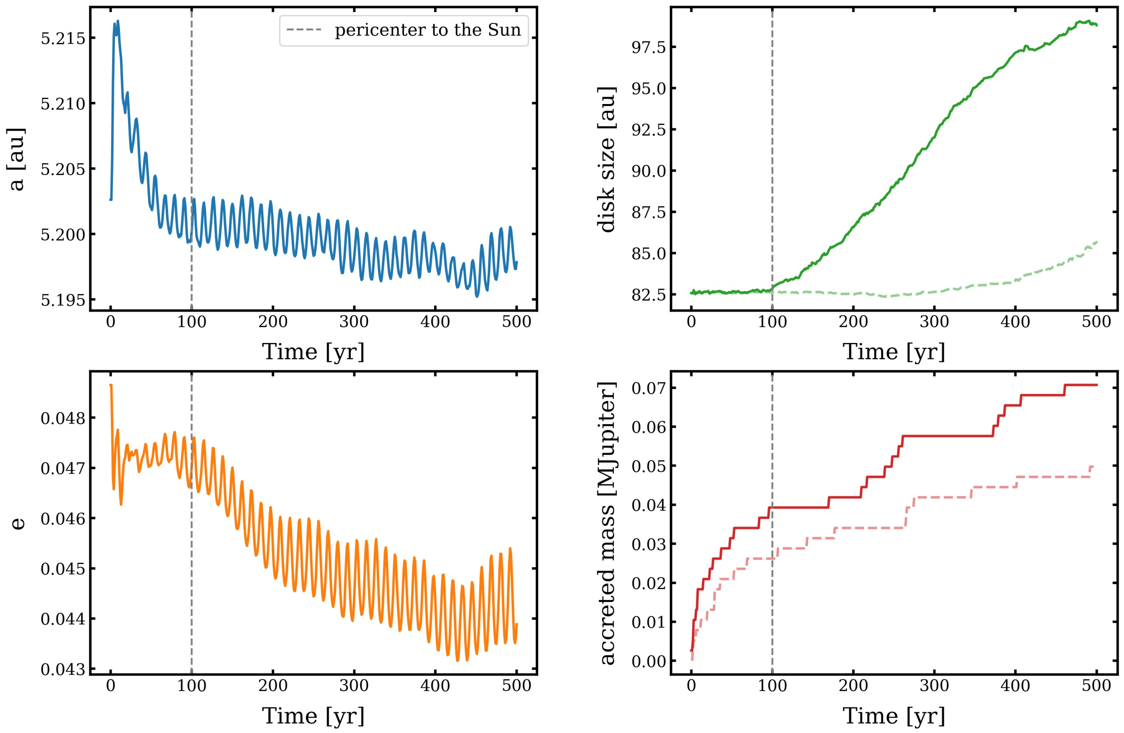

Figure 5: Semi-major axis, eccentricity, accreted mass of the Jupiter, and the disk size as a function of time. The translucent dashed lines in the right panels illustrate the same data as Figure 4 and serve as a comparison.

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 of increasing the accreted mass by the planet. 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. Besides, a higher resolution and therefore a more accurate 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 'step by step', 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