Common envelope outcome of the inner Solar System

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1 Introduction

The Sun plays a special role for us on Earth. It provides the major part of the energy needed by the life on Earth through radiating the energy as visible and ultraviolet light and infrared radiation. This energy is generated by the nuclear fusion reactions in the core of the Sun. A lot of research has been done to understand our Sun's history and interior structure [2][4][3]. The current Sun has an age of 4.6 Gyr and is around halfway through its main sequence phase. After its main sequence lifetime the Sun will go into the red giant phase where its mass will change (besides other solar parameters). Previous studies show that the mass loss rate of the Sun would potentially give a significant expansion to the orbit of the Earth [24]. The future of the Sun and how it will influence the Earth's orbit is a fascinating research topic for us. It may give some insight of the human's future and could also help us understand observations from a planetary system with a host star that is already in the red giant phase. Previous studies which also examined the fate of the Earth as the Sun evolves using simulations have had conflicting results: Sackman et al (1993) found that the Earth would survive, but Schröder & Smith (2008) concluded that it did not [24][25].

In this project, the framework AMUSE [17][19][20][21], a Astrophysical Multipurpose Software Environment to explore whether the Earth can survive after the Sun moves into its red giant phase and beyond.

2 Theory

2.1 Evolution of the Sun

As mentioned in the introduction, our simulations are concerned with the interactions between the Sun and Earth, as well as the latter's final fate, as the Sun's expanding envelope closes in on the Earth. This will involve the evolution of the Sun through the red giant branch. The following processes determine the growth of the solar radius while the Sun is still on the main sequence:

1. As hydrogen is converted to helium in the core, the mean molecular weight μ increases. This in turn leads to an increase in luminosity as $L \propto \mu^4 M^3$.

2. As the luminosity increases and the amount of hydrogen decreases, the core temperature has to increase by a small amount in order to keep up with energy production. Note that the nuclear energy generation rate is very temperature dependent: $\epsilon_{pp} \propto T^4$.

So while the Sun is evolving along the main sequence, its core temperature is near-constant, but its mean molecular mass is increasing. Using the ideal gas law:

$$\frac{P_c}{\rho_c} \propto \frac{T_c}{\mu} \tag{1}$$

this leads to either an increase in core density or a decrease in the pressure on the core. The latter of these forces the layers around the core to expand, as is evidenced by the fact that

$$P_c = \int_{m_c}^{M} \frac{Gm}{4\pi r^4} dm \tag{2}$$

However, in lower mass stars like our Sun, the temperature dependence of the nuclear energy generation rate is much lower than that of stars for which $M > 1.3M_{\odot}$, as lower mass stars do not use the CNO-cycle. This leads to larger increases in T_c and ρ_c, resulting in less expansion of the outer layers [18].

The situation is quite a bit different, however, once the Sun enters the red giant branch. Here the Sun will have exhausted the hydrogen burning in its core, with the core now consisting of degenerate helium. In the shell surrounding this core, hydrogen is still being burned. As this happens, more mass is added to the core. With the core now becoming more massive, its degeneracy pressure needs to increase to counteract gravity. This causes the core to contract [18].

In order for thermal equilibrium to be sustained, the temperature of the hydrogen burning shell must remain at a near constant temperature. If the shell were to contract, this would bring about heating. As such, the radius of the shell must also be approximately constant.

So when the core contracts, the density ($\rho_{shell} \propto \frac{M_{shell}}{R_{shell}^3 - R_{core}^3}$) must therefore decrease. With a decrease in density comes a decrease in the pressure of the shell, which in turn means the pressure of the envelope must decrease. This final decrease in pressure leads to the expansion of the layers above the shell, and so an increasing radius.

If the Sun is approximated as a spherical black body source, then its luminosity can be assumed to be:

$$L = \sigma 4\pi R^2 T^4 \tag{3}$$

Here R is the outer radius, T the temperature in Kelvin and σ the Stefan–Boltzmann constant. This implies that more energy is radiated away as the solar radius increases. So by conservation of energy, the hydrogen burning in the shell has to increase as the radius grows. But this burning is also what is causing the radius to grow in the first place. Consequently, increased burning leads to larger growth of the radius, which leads to an even larger increase in burning, and so on.

So for its evolution on the red giant branch, the solar radius will expand at increasingly faster rates [18]. This sentiment is further confirmed by Schröder & Smith (2008) [25] as well as Sackman et al.(1993) [24], whose calculations place the solar radius approaching 1AU well into the red giant branch.

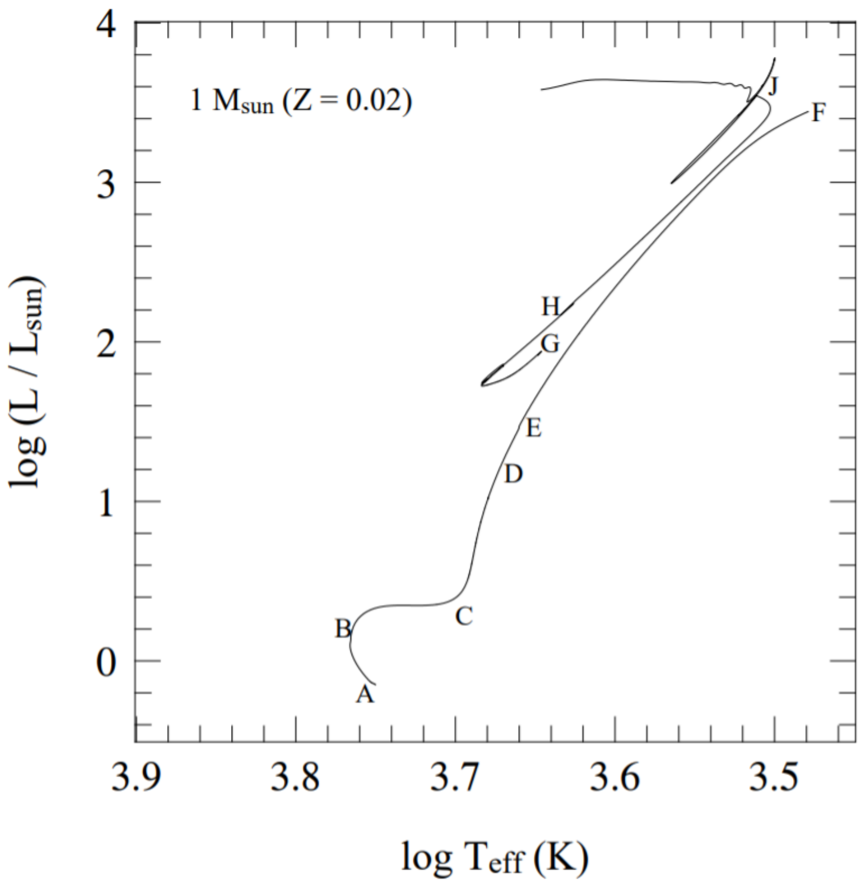


Figure 1: Evolution of a 1 $M_\odot$ star of initial composition X = 0.7, Z = 0.02. Point A is defined as the zero-age main sequence (ZAMS). At point B hydrogen in the core has been nearly depleted. By point C the helium core has become degenerate and the star is at the base of the red giant branch. Point D is the first dredge-up; The growing depth and subsequent retreat of the convective envelope creating a discontinuity in the composition layers just above the burning shell. At point E the shell encounters this discontinuity, causing a small dip in luminosity. Point F is the tip of the red giant branch, just before helium flash occurs. By point G the helium core is no longer degenerate, has settled into thermal equilibrium and has begun stable helium fusion. At point H helium has been exhausted in the core and the asymptotic giant branch begins [18].

It should also be noted that the solar radius will not continue to increase until the end of the Sun its life. Rather, the solar radius sharply decreases as helium is first ignited at the end of the red giant branch. After this helium flash is completed, once the Sun has settled into thermodynamic equilibrium and helium is being burned in the core, its radius will be an order of magnitude smaller than before ignition. For the radius to again increase to levels large enough to threaten the Earth, the Sun will need to exhaust the helium in its core as well, to enter the asymptotic giant branch, where it will evolve through helium burning in a shell above a degenerate carbon-oxygen core. Evolution along the asymptotic giant branch involves the same basic processes as were explained for the red giant branch [18]. Here, the important question is if the largest solar radius exceeds that which can occur on the red giant branch. This is an important consideration to make, as a scenario in which the Earth survives the Suns initial expansion, but stays bound, is one possible case for consideration. Could the Earth then be swallowed by the Sun as it evolves along the asymptotic giant branch? As stated by Schröder & Smith (2008), this is unlikely [25]. The reason lies in a process that the Sun experiences throughout its evolution along both the red and asymptotic giant branches: Stellar mass loss. MESA uses a mass loss rate during the red giant phase taken from Reimers Parameterization:

$$\dot{M} = -\eta \left(4 \times 10^{-13}\right) \frac{LR}{M} = -\eta \left(1.34 \times 10^{-5}\right) \frac{L^{3/2}}{MT_e^2} \tag{4}$$

where M, L and R are all in solar units and $\dot{M}$ is in unit $M_\odot \ yr^{-1}$, T_e is in unit Kelvin and η is the mass-loss parameter [5]. This mass loss causes both the expansion of the planetary orbits, as well as decreasing the maximum radius that can be achieved as the Sun evolves. With mass loss occurring along both giant branches, the later asymptotic branch is especially affected. Schröder & Smith (2008) found in their simulations, that the solar asymptotic giant branch radius would never reach that of the red giant branch. It should be noted however, that not all agree that the solar radius reaches its maximum on the red giant branch; Rybicki & Dennis (2000) concluded that the Sun would reach larger radii on the asymptotic giant branch [23]. So, with this uncertainty, we will have to be careful in our considerations of the Sun's evolution and watch the change in solar radius over time, so that we can assert at what point in the Sun's lifetime the simulation can be stopped.

In regard to the minimum time the Sun would have to evolve for it to become a danger to the Earth, the results of past simulations can be examined. It should also be stated, that the Sun's evolution only starts to affect the Earth in the latter half of the red giant branch; during the earlier parts of its life, the Sun does not exhibit strong mass loss nor expansion [18]. As such there is more utility in looking at the Sun from the final parts of the red giant branch onward. The solar radius is at a (local) maximum at the tip of the red giant branch, at an age between 12.17 Gyr and 12.233 Gyr [25][24]. The solar radius is also shown to sharply increase beginning around 12 Gyr [25][24]. This implies that the time span of interest to these simulations starts around 12 Gyr.

2.2 Possible orbits

As the Sun evolves on the red giant branch, a number of processes related to its evolution will affect the Earth and its orbit. Firstly, as explained in the above section, the Sun expands during its evolution along the red giant branch, then contracts after the tip of the branch and grows again after helium fusion has stabilised. The second effect was also addressed before: mass loss. A decreasing solar mass means decreasing orbital potential energy for the planets, which leads to larger and slower orbits. This effect would then be favourable to the Earth's survival. However, the third effect works against the chances of the Earth surviving: tidal interactions. As the Sun expands, its mass will be spread over a larger radius. Consequently, conservation of angular momentum predicts that the Sun's rotation will slow tremendously, with $T_f \approx \left(\frac{R_f}{R_i}\right)^2 T_i$. This will cause the Sun's rotational period to become much larger than orbital period of the Earth, even accounting for orbital expansion due to solar mass loss [25]. As a consequence of this difference in periodicity, a tidal bulge would be formed on the Sun's surface by the Earth, just as the Moon's pull creates bulges in the Earth's oceans. This tidal bulge would then create a stronger gravitational pull for the Earth, pulling it inwards.

Another scenario whose effects need to be considered, is that of the Earth coming into contact with the outer solar envelope, and experiencing friction as (part of) it moves though the solar medium. This presupposes that the Earth would not be torn apart the moment it touches the Sun's surface. Past simulations done on the Earth's existence within the solar envelope indicate that it wouldn't be torn apart, but that it couldn't reach a stable orbit and would spin into the core within 200 years [7]. However, this result did not take into account the possibility of the Earth going through a (highly) eccentric orbit, in which the Earth dips in and out of the envelope. This possibility can be seen in the fact that the Earth's orbital velocity is at a maximum at perihelion, and then via the vis-viva equation for the instantaneous orbital speed: $v = \sqrt{\mu(\frac{2}{r} - \frac{1}{a})}$, which would increase for highly eccentric orbits. As such the possibility will be considered of the Earth surviving inside the solar envelope and model the friction it experiences as a drag force on the planet.

With these conditions for the future Earth-Sun system, a number of scenarios are possible: the Earth escapes from its orbit, it spirals into the Sun or it remains gravitationally bound to the Sun.

3 Method

The goal for this project is thus to see what happens to the Earth when the Sun evolves from a main sequence star to a red giant and beyond. For simplicity the planets Mercury and Venus will be ignored. They have a semi-major axis of respectively 0.38 and 0.72 AU and the Sun will evolve to a radius between 0.77 [24] and 1.19 AU [25]. Which is why the assumption is made that during the evolution of the Sun these two planets already spiraled into the Sun or got ejected out of the solar system.

The method of this project is to start with the stellar evolution of the Sun. After it has evolved to the moment where the Sun has entered the red giant phase, the hydrodynamics start. For this part the Sun will be divided into two parts: its core and a gas cloud around it. After making the hydrodynamics code for the gas cloud, the gravity particles can be added to the system. Now that the system is complete, it can be evolved for a certain amount of time to see what happens with the gravity particles. As mentioned in the introduction, AMUSE is used for this project [17][19][20][21]. With this framework the stellar evolution code can be combined with the gravity and hydrodynamics code.

The stellar evolution code and the gravity code has been made separately due to the run time of the code. For this, the assumption is made that during the evolution of the Sun to a red giant, it will not influence the orbit of the Earth. So the Sun will evolve for 12 Gyr and after that the Sun will be split up into a core and gas particles. Besides this condition, another conditions has been added to some of the runs. This extra condition is that it will evolve until it is at 90% of the orbital separation between the Earth and the Sun, i.e. 0.9 AU.

For the stellar evolution code, the MESA code is used [11][12][13][14][15]. The Sun will have a mass of 1 solar mass at the start of the evolution and all other parameters will be configured automatically as soon as the Sun becomes a MESA particle. These parameters will be the parameters the Sun had at the start of its main sequence lifetime. For the metallicity two values will be used. One value is the current metallicity which is equal to 0.0134 and the other value of 0.0142 corresponds to the proto-solar metallicity [1]. Besides the metallicity, the mass loss rate will also be varied. The default value in MESA for the mass loss rate is $\eta = 0.5$, where the Reimers scaling factor is used [22]. Another value of $\eta = 0.2$ will also be used, which is based on Schröder & Smith (2008) [25]. The evolution time will be, as mentioned before, equal to 12 Gyr. During the evolution, the luminosity and temperature of the particle has been saved to create a HR-diagram and check if these parameters of the Sun evolve according to the literature. In addition, the radius and the mass will also be checked.

After the evolution to a red giant, the Sun will be divided into a core and a gas cloud. The core will have a mass of 80% of the total mass of the Sun. The rest of the mass will be divided into gas particles with a mass of 25% of the smaller mass. Here the smaller mass is the mass of the Earth. In addition, the Earth will be added on a position of 1 AU from the Sun and with a velocity according to:

$$v_{orb} = \sqrt{GM/r} \tag{5}$$

where G is the gravitational constant, M is the mass of the Sun and r the distance to the Sun. Because the Sun has evolved to a red giant, the mass will be different too. Depending on which conditions will be used for the evolution of the Sun, the mass will be different and thus the orbital velocity as well. That's why it is important to calculate this orbital velocity and not put in the current orbital velocity of the Earth.

Now that the system is complete, the hydrodynamics and gravity code can be evolved. For the hydrodynamics code Fi is used [8][16][6]. This is a particle based code in the language C [19]. As gravity solver Huayno is used [9], which is a code made in the language C. A timestep of 0.1 year will be used for this solver. After making these two codes, the code will be bridged. The timestep for this bridge code will be half of the gravity timestep, which will be equal to 0.05 year. Before it adds the code to the bridge, the density at the position of the Earth will be checked to see if it is equal to 0 kg/m^3. If it is equal to zero it means that there are no gas particles which can cause dynamical friction in the system. If it is nonzero then the code will first handle the friction, which causes a change in the acceleration of the system. This is because when the Earth encounters the hydro envelop of the Sun, it will experience the force acting opposite to its orbital motion by the surrounding fluid. To take into account the friction caused by the hydro envelope to the Earth's orbital motion, the following function for the drag will be used:

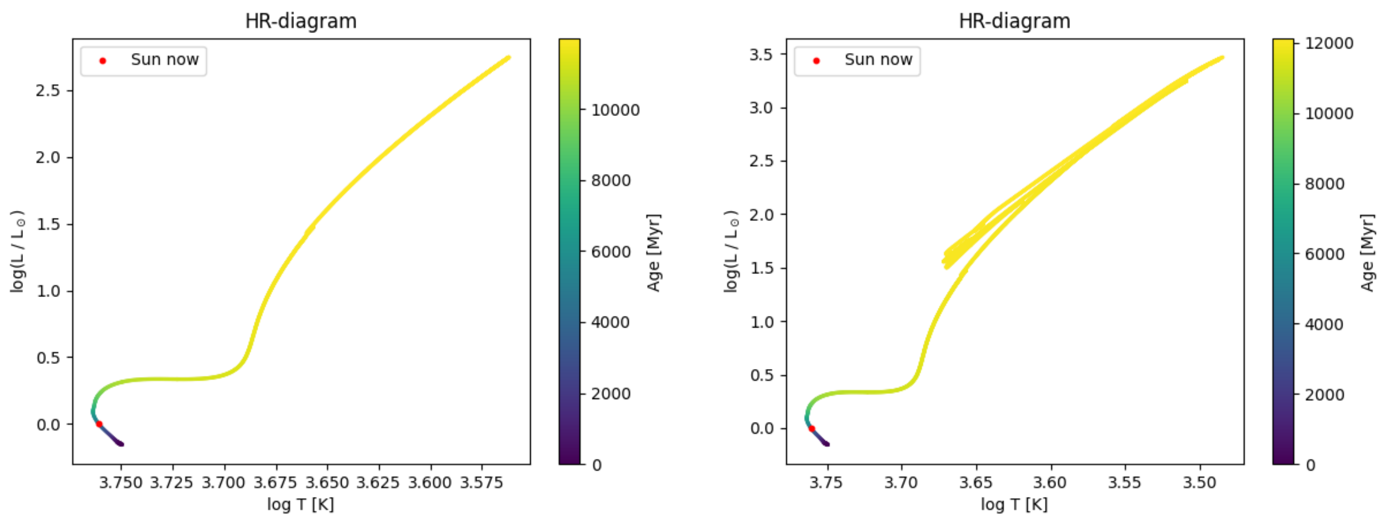
$$F_D = \frac{1}{2}\rho v^2 C_D A \tag{6}$$

where ρ is the density of the hydro envelope at the position of the Earth, v is the velocity of the Earth, A is the cross section area of the Earth and C_D is the drag coefficient for which the value 0.47 is used because the Earth is a spherical object. To achieve this in AMUSE, a `friction` class will be written, which returns the deceleration on the gravity particles by the drag. By adding the `friction` system through bridge, the friction will kick the gravity system. After that the bridge will be newly made with the two codes which had just been evolved. By adding the hydro particles with the new evolved parameters, the mass distribution will be reset at every start of a loop. With this the tidal force will be neglected. This means that the code doesn't have to be bridged in both ways which really decreases the run time, because now the code doesn't have to operate on the hydro timescale (which is much smaller than the gravity timestep). The code will then be evolved for different n times a certain time t_{end}. Where the values for n and t_{end} will be varied. It is important to take into account that when t_{end} will be too big, the friction will not be taken into account for a long time. This is because the density will only be checked at the start of the n loop, so after t_{end} is finished.

4 Result

4.1 HR-Diagram

Figure 2 shows the luminosity against temperature during the evolution of the Sun. The present stage of the Sun is labeled as a red dot in the plot. The Sun remains in the main sequence for around 10 Gyr, during which its luminosity and temperature steadily increase due to the hydrogen burning in the center of the core. As the Sun burns out all the hydrogen in the core into helium, it becomes more luminous and the temperature decreases due to its expansion. The Sun leaves the main sequence and moves to the giant phase. The core of the Sun becomes degenerate soon after leaving the main sequence which results in the unstable helium flash at the top of red giant branch. The oscillation of the luminosity and temperature after 12 Gyr in Figure 2b are due to helium flash.



(a) (b)

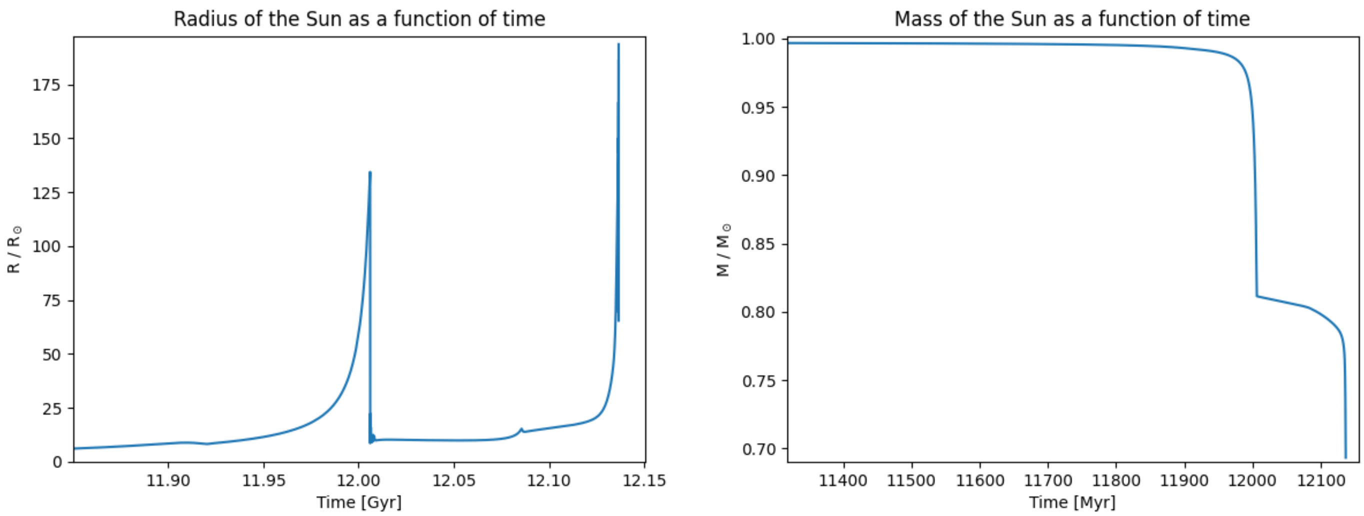
Figure 2: HR diagram of the Sun when the final evolving age is 12 Gyr (a) and when the Sun is evolved to a radius of 0.9 AU, which corresponds to an age of 12.137 Gyr (b).

4.2 Different metallicity and mass loss rate

The Sun has been evolved for different metallicities and mass loss rates. For the metallicity it is expected that the higher the metallicity, the more mass it looses by stellar winds[10]. This would indicate that something should change in the evolution compared to a lower metallicity. Also, because there will be less hydrogen in the core, you would expect the core to be exhausted faster, which will result in the Sun reaching the red giant phase faster. In addition a higher mass loss rate should also change the result. However, when changing the metallicity and mass loss rate, nothing changed for the evolution of the radius and mass of the Sun. These two parameters got the exact same result as in figure 3a and 3b, where a metallicity of $z = 0.0134$ and a mass loss rate of $\eta = 0.5$ was used.

4.3 Different evolutionary stages of the Sun and the orbit of the Earth

In Figure 4a the trajectory of the Earth is shown where the gravity system was added after the Sun has evolved to 12 Gyr. We can see that the Earth's orbit is gradually extending. After 11.35 yr, the eccentricity of the orbit of the Earth becomes larger than 1 (Figure 4c), which means the orbit of the



(a) (b)

Figure 3: Radius (a) and mass (b) of the Sun as a function of time. A metallicity of $z = 0.0134$ is used and a mass loss rate of $\eta = 0.5$. Note that the timescales of the two figures are different.

Earth has become a hyperbola, and the Earth is escaping the solar system. To explore how the mass loss rate influences the Earth's orbit, the Earth is also added after the Sun has reached the age of 12.05 Gyr. As shown in Figure 3b, the mass of the Sun has a sharp drop at around 12 Gyr, however, the mass decreases more steadily at around 12.05 Gyr. Figure 4b and Figure 4d indicate that the Earth remains in the solar system for around 29.45 years after it is added in the solar system, which is around 18 years longer than the case when the Sun is initially evolved to 12 Gyr. Because if the mass loss rate is faster, the escape velocity to escape the gravitational influence of the Sun on the Earth will also decrease faster, which makes it easier for the Earth to escape when the Sun is experiencing a higher mass loss rate.

Friction is another factor that influences the orbit of the Earth. The Sun is also initially evolved to have a radius of 0.9 AU, which is the same condition that the age of the Sun is 12.137 Gyr. In this condition, the Earth has a chance to encounter the envelope of the Sun. If the friction is not taken into account (Figure 5b), it would take the Earth around 14.3 yr to escape the solar system. If the friction of the hydro particles is added (Figure 5a), it would take the Earth around 64.89 yr to escape the solar system after the initial evolution, which is longer than the case with no friction. Another difference is that the orbit of the Earth becomes much more elliptical when friction is considered. Because when the Earth encounters the drag force, its velocity magnitude would decrease and the same for its angular momentum, which causes its orbit to shrink. However, the mass of the Sun keeps decreasing, so once the Earth leaves the envelope, its orbit would still expand.

5 Discussion

As seen in Figure 3a, the solar radius from our simulations has a global maximum at the end of the asymptotic giant branch. This is in opposition to findings by Schröder & Smith (2008), who reported a smaller maximum on the asymptotic giant branch than on the red giant branch, but is in agreement with older results by Sackman et al. (1993) [25][24]. This discrepancy in results could have arisen due to a number of factors. Firstly, while Sackman et all (1993) used the same formula for mass loss as us,

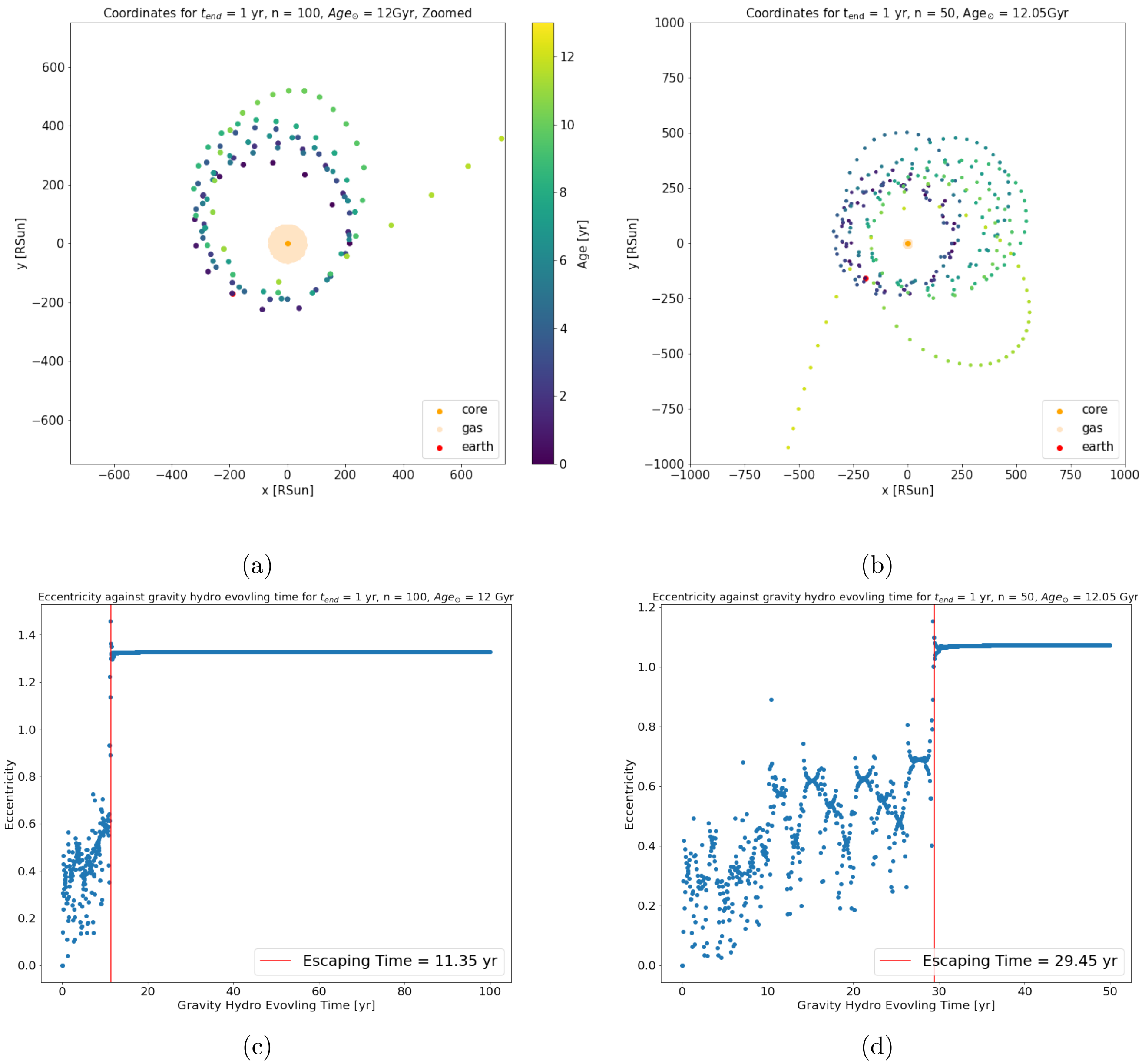
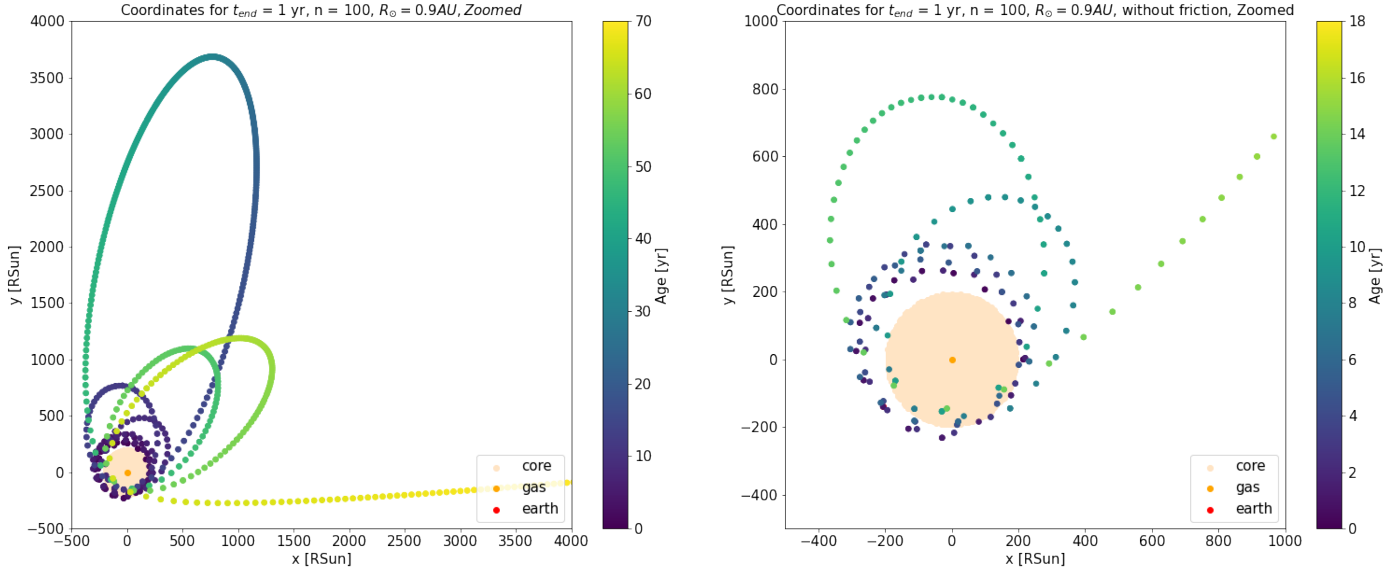


Figure 4: Trajectories of the Earth before escaping, when the Sun is initially evolved to 12 Gyr (a) and 12.05 Gyr (b). Eccentricities of the orbit of the Earth as a function of time, when the Sun is initially evolved to 12 Gyr (c) and 12.05 Gyr (d)

Schröder used a slightly different equation based on the Reimers parameterization:

$$\dot{M} = \eta \, \frac{L_* R_*}{M_*} \left(\frac{T_e}{4000K} \right)^{3.5} \left(1 + \frac{g_\odot}{4300 g_*} \right) \tag{7}$$

Here $g_\odot$ is the solar surface gravitational acceleration, and all other parameters are defined the same as in Equation 4, except η. Here η has been redefined to include the separate constant in Equation 4. Schröder & Smith (2008) lists their value as $\eta = 8 \cdot 10^{-14}$ $M_\odot$ y^{-1}. Calculating this back to the Reimers formulation returns $\eta = 0.2$, not accounting for the new temperature dependent factor. For comparison, Sackman et al (1993) used both $\eta = 0.6$, 0.4 and 1.4 for their simulations, though 0.6 was their preferred value based on their own initial calculations [24]. For the radius over time, only graphs based on the 0.6 and 0.4 values are shown. The latter of these shows a slightly larger radius than the former on



(a) (b)

Figure 5: Trajectories of the Earth before escaping, when the Sun is initially evolved to have a radius of 0.9 au (12.137 Gyr). The frictions caused by the hydro particles of the envelope of the Sun are taken into account for (a), while in (b), those frictions are ignored.

the asymptotic giant branch, though as stated both place the global maximum radius on the asymptotic giant branch. It is interesting that a smaller mass loss parameter leads to a larger radius on the asymptotic giant branch, as although this might seem to be the expected result, it does not explain how Schröder & Smith (2008) obtained such a reduced radius on the asymptotic giant branch, using an even smaller mass loss parameter. To examine the effects of the mass loss parameter, we attempted to use multiple different values in our simulations. The default value in MESA is 0.5. However, while changing this value seemed to be possible, the results of simulations implementing any change in the mass loss parameter were the same as those using the default value. We do not know if this functionality is currently fully implemented and working in MESA, but as Figure 3b shows, mass loss is occurring. We can therefore only conclude that MESA is currently only able to use its default value for the mass loss parameter, $\eta = 0.5$. Finally, it should be noted that Schröder & Smith (2008) does specify that their total mass loss exceeded that of Sackman et al (1993) by the time the tip of the red giant branch was reached. This leaves more uncertainty on what could have affected their total mass loss to such an extent as to compensate for a lower mass loss parameter. If we are to assume that their description of mass loss is more accurate, as it was specifically created to reduce the large uncertainties that the Reimers relation suffered from, then this would suggest even more favourable outcomes for the Earth. After all, even with a larger solar radius on the asymptotic giant branch, our simulations still result in the Earth's survival (i.e. the Earth not getting torn apart). Were the radius to be smaller at these points in time, it would simply reinforce our previous result.

As for the mass over time in Figure 3b, this seems to agree again with Sackman et all (1993), but not quite with Schröder & Smith. As with the radius, this can be attributed to different rates of mass loss.

The first plan for this project was to add the Moon as well. However when running the code with gas particles of the envelope of the Sun with a mass of 25% the mass of the Moon and also a timestep of about 10% the orbital period of the Moon, the code killed the process. That is why for this project only the Earth has been added in this research. For future research it may be interesting to see what the Moon does as well when the Sun has evolved to a red giant.

Another thing which was mentioned in the method was to investigate different values for t_{end} and n to see how that would influence the result. However when the simulations where carried out, the realization came that a big t_{end} meant that the friction would not be taken into account for that whole time. That is why it was decided to leave that part out of the research and only use a value of 1 year for t_{end}.

As already explained in the method, the Earth particle has been added after doing the stellar evolution of the Sun to a red giant. It would be good to check if the assumption that the Earth will not be affected in this period is a good one to make, or that the results because of this assumption will be different.

6 Conclusion

In this project the framework AMUSE is used to explore the fate of the Earth after the Sun moves into its red giant phase. A code is used which simulated the stellar evolution of the Sun, the hydrodynamics of the core and gas particles of the Sun and the gravitational forces when putting the Earth in this system. One aspect of the motivation for this study may be obvious, i.e. the important role that the Sun plays for our (or actually the Earth's) survival. In addition, it can also help in understanding planetary systems with a host star which is already in the red giant phase.

First the stellar evolution is compared with the literature to see if this resembles. According to the HR-diagram and the radius and mass evolution, the stellar evolution of our simulation was very comparable with the literature. Changing the metallicity and mass loss rate of the Sun did not change anything to the result, which is something that was not expected at first. In addition to the stellar evolution, different conditions were used to stop the stellar evolution. An evolving time of 12 Gyr was used and also an evolving time of 12.05 Gyr was applied. Where the first time was during a big drop in the Sun's mass and the other time was during a time where the Sun's mass was more steady. From the eccentricity evolution plots it followed that a longer evolution time resulted in the Earth staying bound for a longer time compared to the shorter evolution time. This can be due to the different mass loss rates at those stages. A higher mass loss, causes a more unstable system, which lets the Earth get unbound earlier, compared to a more stable mass loss. Besides changing the evolving age, another condition is applied where the radius of the Sun should be evolved until 0.9 AU, to see how the friction influences the orbit of the Earth. The result is that the Earth escapes the solar system at a later time when friction is taken into account. This is because of a decrease in the Earth's velocity due to a negative acceleration coming from the friction, which also causes the Earth's orbit to be less circular.

Thus the conclusion of this study is that the Earth will escape the solar system when the Sun moves into the red giant phase. However, the Earth will survive, i.e. it will not be torn apart. Depending on the friction mechanism, the ejection can be postponed to a later time or happen quickly after the increase in the radius and the decrease in the mass of the Sun during its stellar evolution.

For future research it would be interesting to see what happens if the Earth will be put in immediately from the start, instead of after the stellar evolution of the Sun for 12 Gyr or more. In addition, it would be interesting to investigate the fate of the Moon as well.

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