Exoplanets: Interiors & Atmospheres 2020
Lab Assignment 2: Modelling irradiated sub-Neptune mass planets

Auke Bruinsma (s1594443)

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1 Introduction

In the second practical assignment of the course Exoplanet: Interiors & Atmospheres (2020), we will simulate how irradiation from a star will effect the internal structure and evolution of a sub-Neptune mass planet. The simulation will be done using the MESA code (Paxton et al., 2013). In total, two planets will be simulated. One will receive 10 times the flux that the Earth receives from the Sun, and the second a 100 times the Earth flux. When the simulation is completed, 6 figures will be produced, containing the two simulated planets, and the planet from the previous lab assignment, with the same core mass and envelope mass fraction. This will make it easier for a qualitative comparison. The 6 figures will show the following data:

1. The evolution of the of the radius with time.
2. The evolution of the luminosity of with time.
3. The final mass vs. the final radius.
4. The final radiative gradient and the adiabatic gradient vs. the radius normalised to the total radius of the planet for the two extreme cases.
5. The temperature as a function of the radius normalised to the total radius of each planet.
6. The pressure as a function of the radius normalised to the total radius of each planet.

In section 2 the simulation process will be discussed and in section 3 the 6 figures will be shown and discussed. This report will end with section 4.

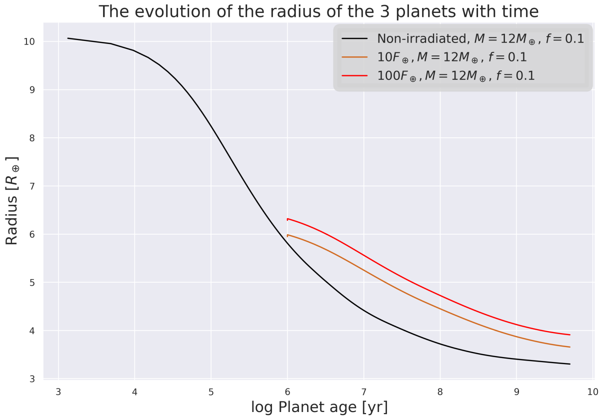
2 Methods

In this first practical assignment we simulated 10 planets, now we will only simulate two mini-gas planets. They both will receive a high amount of radiation from their host star. The simulation is divided in the following steps:

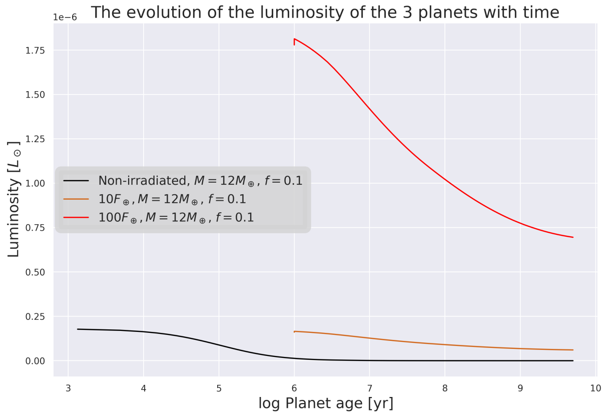
1. The starting point for this simulation is actually about halfway in the first assignment. The model created in step D where we had to set the initial entropy will be used as the beginning of the two planets' evolution. The planets will both have a core mass $M_{\text{core}} = 12M_{\oplus}$, and an envelope mass fraction $f_{\text{env}} = \frac{M_{\text{env}}}{M_p} = 0.1$. From here, the core luminosity will be relaxed, and the planet will be evolved for a period of 10^6 years.
2. Next, an external source of energy is added to the simulation, which means the planet will be under the influence of the irradiation of the star. Here there will be made use of two important parameters. The first one is the column depth, which determines how far light from the star penetrates into the planets atmosphere, which is set to 300 cm^2/g. The second parameter is the amount of flux that will be received from the star:

$$F_\star = \frac{L_\odot}{4\pi a^2} \tag{1}$$

The MESA software uses the two parameters to generate energy. The energy generation rate is computed in the following way: $\epsilon = F_\star/4\Sigma_\star$, where $F_\star$ is the flux of the star and $\Sigma_\star$ is the column depth (Paxton et al., 2013). This means that an outward flux of the planet is generated which is 4 times as small as the solar flux. This flux is present everywhere on the surface, which means there is no difference between day and night on the planet, regarding the temperature. This allows there to be an uniform temperature distribution on the planets' surface (Paxton et al., 2013).



((a)) The evolution of the radius of the 3 planets with time. On the horizontal axis the time is displayed in years, and on the vertical axis the radius is shown in Earth radii.



((b)) The evolution of the luminosity of the 3 planets with time. On the horizontal axis the time is displayed in years, and on the vertical axis the luminosity of the planet is shown in solar luminosity.

Figure 1: The first two figures.

The first planet will receive 10 times more irradiation than the Earth, and the second planet 100 times more than the Earth. Given in the assignment instruction is $L_\odot = 3.8418 \cdot 10^{33}$ erg/s. Using equation 1 and the fact that the distance between the Earth and the Sun is 1 AU, we compute that the Earth receives $1.36607 \cdot 10^6$ erg s^{-1}cm^{-2}. This means the first planet will receive $1.36607 \cdot 10^7$ erg s^{-1}cm^{-2} and the second planet $1.36607 \cdot 10^8$ erg s^{-1}cm^{-2}. Assuming the two planets' host star has solar luminosity, they have a semi major axis $a = 0.316$ AU and $a = 0.1$ AU, respectively. Therefore, this lab assignment can also be seen as simulating the same planet twice, but at different distances from their host star.

3. After setting the right solar flux and column depth, it is time to evolve the planet for a period of 5 Gyr. This is done twice, because there are two planets.

3 Results

This section will contain all the 6 generated figures. There will be a subsection for each figure where it will be discussed. In all figures the three planets have the same colour. So, the non-irradiated planet, whose data comes from the previous simulations, is always shown in black, the middle irradiated planet is shown in brown, and the most irradiated planet is shown in red.

3.1 The evolution of the radius with time

The first thing that jumps in figure 1(a) out is that for the non-irradiated planet, there is more data present. This is simply because because for this planet the simulations were done in the previous lab assignment, which ran from earlier in time. From the period of 10^6 years until $5 \cdot 10^9$ years, the most irradiated planet has the largest radius, then the middle one, and the non-irradiated planet has the smallest radius. During their evolution, they decrease in size. The planets were all initialized with a radius of $3R_{\mathrm{Jup}}$, because planets have a large radius in the beginning of their formation process. The planets were also 'puffed up', to change the entropy. An artificial luminosity was added, so the planets inflated. After this, during their evolution, the planets shrink over time, because it wants to reach an equilibrium state, where the gravitational attraction equals the outward pressure forces.

3.2 The evolution of the luminosity with time

As expected in figure 1(b), the highest irradiated planet has the largest luminosity, the middle is in the middle, and the non-irradiated planet has the lowest luminosity. Because the $100F_\oplus$ planet is located at 1 AU from its host star, it receives a relatively high amount of irradiation. This heats up the planet and therefore it has the highest luminosity. The $100F_\oplus$ planet also has the largest absolute decrease in luminosity over time. This means that in the beginning of the planets' evolution, it reflected relatively more radiation from its host star than in the later stages of its evolution. It also means that over time, the planets atmostphere heats up. Eventually a moment will come when the amount of energy absorbed is the same as the amount of energy reflected. You can see this, because the graph becomes flatter near the end of the evolution. The non-irradiated planet has already reached this equilibrium state, which is zero solar luminosity because it is not irradiated.

3.3 The final mass vs. the final radius

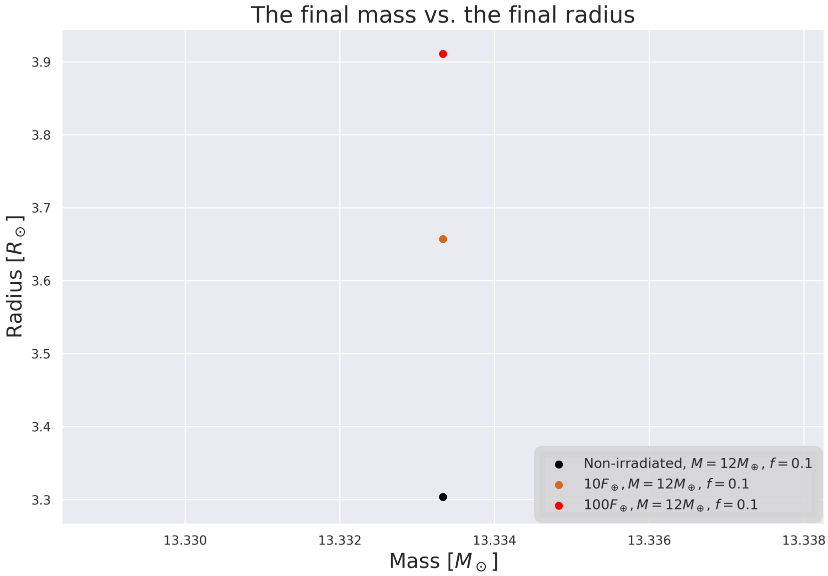


Figure 2: The final mass vs. the final radius. On the horizontal axis the mass is displayed in Earth masses, and on the vertical axis the radius is shown in Earth radii.

Because the planets we are simulating had the same initial core mass, which was $12M_\oplus$, they all have approximately the same final mass, see figure 2. The most irradiated planet has the largest radius, then the medium irradiated planet, and the non-irradiated planet has the smallest radius. The reason there is a difference in radii after evolution can be explained by the amount of flux the different planets receive. The planet that is closest to the host star, receives relatively the most amount of flux. Because of this the planets inflate. The extraordinary large amount of energy 'puffs up' the planet. Or, it shrinks less than a lower flux irradiated planet. The energy from the star goes into the interior of the planet, which will therefore not be able to decrease in size, w.r.t a lower flux irradiated planet.

3.4 The final radiative and adiabatic gradients vs. the radius.

So, when taking a look at figure 3, there is clear difference. The non-irradiated planet has a higher radiative gradient for almost anywhere in the interior of the planet; only near the surface the radiative gradient decreases rapidly and the adiabatic gradient is larger. For the $100F_\oplus$ planet, from about half of the planets interior until three quarters, the radiative gradient is larger. Higher up in the interior of the planet the adiabatic gradient is larger. A layer is stable against convection if $\nabla_{\rm rad} < \nabla_{\rm ad}$ (Pols, 2011). This means there is convection in the interior of the high irradiated planet until around three quarters of the planets interior. High up in the interior until the surface, the planet is stable against convection. For the non-irradiated planet, convection is the main energy transport mechanism in the interior. Because the planet located at 0.1 AU receives a relatively large amount of flux, the interior of the planet has a higher temperature, therefore conduction becomes more efficient, and convection is not needed to transport all the energy in the interior.

3.5 The temperature as a function of the radius

Figure 4(a) shows the temperature after evolution w.r.t the normalised radius. As expected the $100F_\oplus$ planet has the highest surface temperature, then the middle planet, and then the non-irradiated planet. This makes sense, because the non-irradiated planet receives nothing and the $100F_\oplus$ planet receives a large amount of radiation. In the interior, however, you can see that the medium irradiated planet has the highest temperature, for up to around 80% of the planets interior. This may be explained by the fact the highest irradiated planet transports energy more efficiently from the center to the surface. You can also see that for the two irradiated planets, there is a flat region near the surface. This is not present for the non-irradiated planet. This means that in the upper part of the two irradiated planets' atmospheres, there is a constant temperature. This has to do with the column depth parameter in the simulation. Because the star's radiation reached for a certain amount in the planets' interior, a uniform vertical temperature distribution is created, which means that there is an efficient energy transport mechanism present in the upper part of the atmospheres.

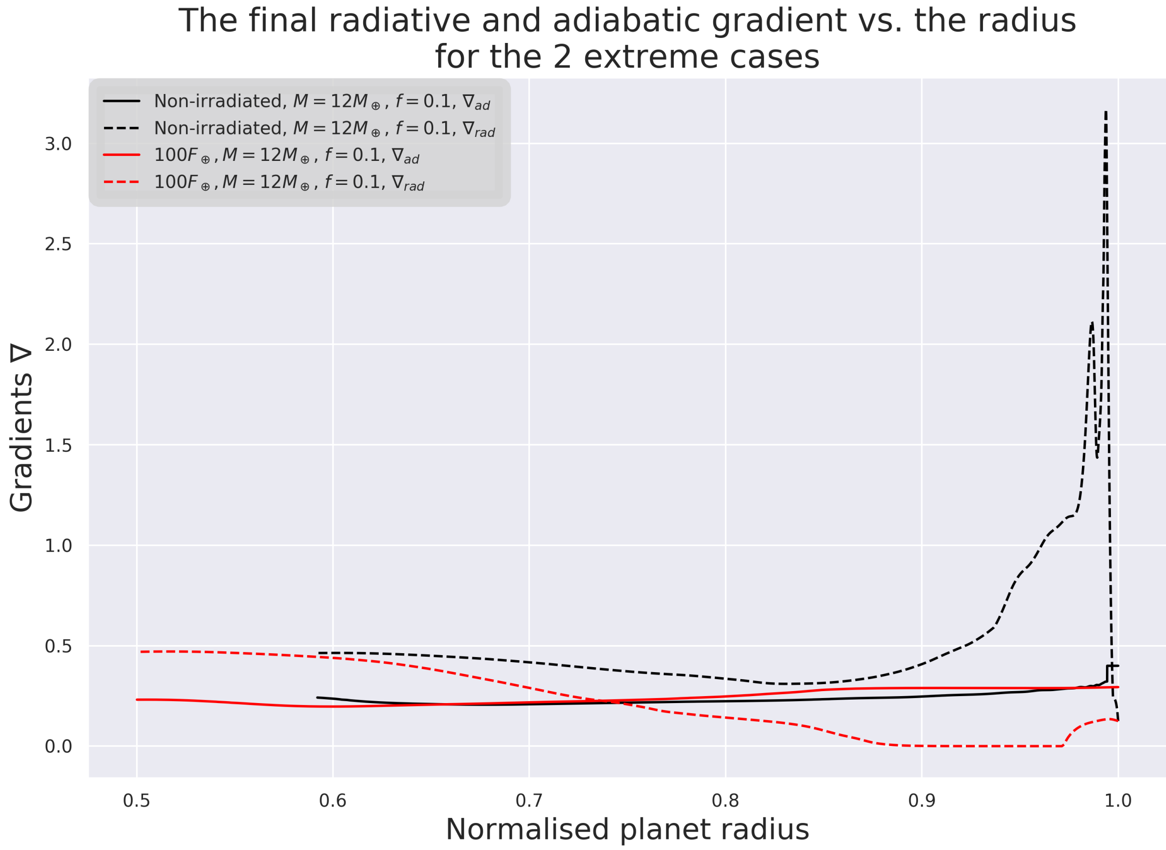


Figure 3: The final radiative and adiabatic gradients vs. the radius for the 2 extreme cases. On the horizontal axis the normalised planet radius is displayed. This means at the surface of the planet, the radius equals one. On the vertical axis, the radiative and adiabatic gradients are shown.

3.6 The pressure as a function of the radius

In the last figure, 4(b), you can see the pressure after evolution vs. the normalised radius. They all evolve in a similar way, but the non-irradiated planet has the largest pressure for a certain radius. This is related to the final mass vs radius figure, 2. Because the irradiated planets are puffed up, and there is relatively a large amount of energy present in the interior of the planets, there also is a lower pressure w.r.t the non-irradiated planet. So a larger irradiation means a lower interior pressure.

4 Conclusion

We conclude that we have succesfully simulated the two irradiated planets. From the figures we conclude that the irradiated planets are inflated w.r.t the non-irradiated planet. This happens because of the large amount of energy they receive from their host star.

References

Bill Paxton, Matteo Cantiello, Phil Arras, Lars Bildsten, Edward F. Brown, Aaron Dotter, Christopher Mankovich, M. H. Montgomery, Dennis Stello, F. X. Timmes, and Richard Townsend. Modules for experiments in stellar astrophysics (mesa): Giant planets, oscillations, rotation, and massive stars. 2013. doi: 10.1088/0067-0049/208/1/4.

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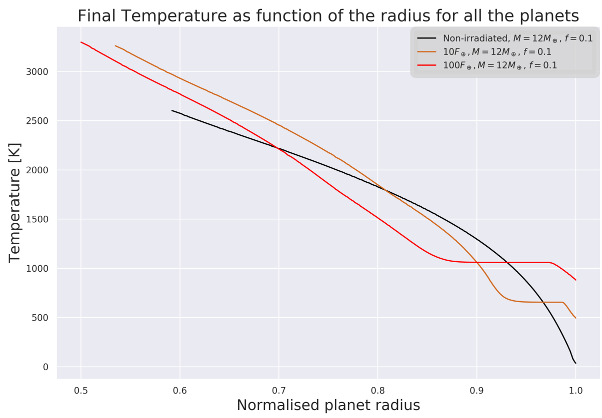
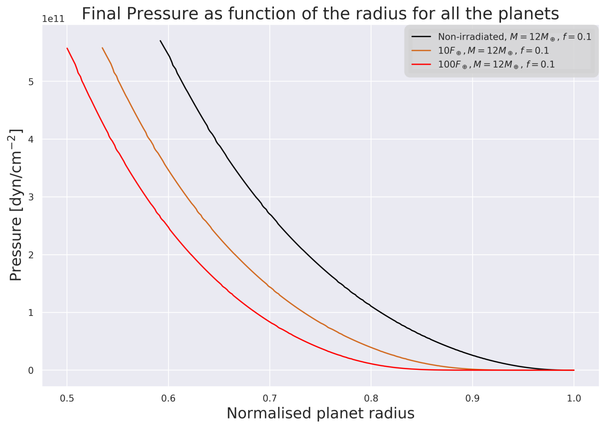


((a)) The final temperature as a function of the radius for all the planets. On the horizontal axis the normalised planet radius is displayed, and on the vertical axis the temperature is shown in Kelvin.



((b)) The final pressure as function of the radius for all the planets. On the horizontal axis the normalised planet radius is displayed, and on the vertical axis the pressure is shown in dyn/cm^{-2}.

Figure 4: The last two figures.