MODELLING IRRADIATED SUB-NEPTUNE MASS PLANETS

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Introduction

The work for this lab was done using the MESA code [1]. In our previous work we have already installed and ran MESA in order to produce low mass gas planets, made mostly by H and He with a rocky core. In our current work we use a different approach to evolve one of the planets previously made, this time with irradiation from a central star. The work and methods that are present here, follow the work from [2]

In this report we will start by explaining how we simulated those planets, step by step. We will then look at the results and try to explain them based on previous knowledge about planetary composition and evolution.

Methods

In our previous work we created 10 planets with different core and envelope masses. This time we will start with the heaviest of the planets created by our previous work and we will evolve it under different conditions.

The planets in the previous work were created by starting with a single coreless planets of $M = 30M_{\oplus}$. We then create an earth-like core following the work of [3]. We created 5 different cases, but in our current work we are only interested in the $M_{core} = 12M_{\oplus}$ case. We then reduced the mass of the gaseous envelope using the equation $f_{env} = \frac{M_{env}}{M_p}$ for 2 different values of f_{env}, but this time we are only interested in the $f_{env} = 0.1$. We then inflated the planets by using an artificial luminosity of $L_{center} = 2 \cdot 10^{27} erg/sec$.

After this point we evolved our planets with no source of external heating. This time we will take our single case, the $M_{core} = 12M_{\oplus}$ and $f_{env} = 0.1$, and we will compare our original evolution with a different evolution that involves a source of heating.

In order to do that, we start with our non evolved planet and relax the core luminosity. By doing this we have created a planet that has not been fully evolved and has the correct core luminosity. In this step we have evolved our planet for a short time period $(1 \cdot 10^6 yr)$ with no irradiation.

In the next step we want to create 2 different scenarios and prepare our planets before our final evolution. We do that by slowly increasing the outside irradiation. We need to set up two parameters in our MESA code in order to indicate how much outside flux we will have and how deep will it penetrate our planets. For the last part we have the value of $300cm^2/g$ which [1] considers to be the appropriate value for planets like the ones we are examining. The amount of outside flux will create the 2 different cases we want to examine.

We know that the flux is given by the equation:

$$F = \frac{L}{4\pi a^2} \tag{1}$$

where L is the luminosity the star and a is the semi-major axis of the planet's orbit. For the case of the earth we have:

$$L_{\odot} = 3.8418 \cdot 10^{33} erg/s \text{ and } a_{\oplus} = 1AU = 1.49598 \cdot 10^{13} cm$$

With that we can calculate:

$$F_{\oplus} = 1.366 \cdot 10^6 erg/s \cdot cm^2$$

The 2 cases we will create in this step will have an outside flux of 10 and 100 times that of the earth. In Table 1 we sum up the characteristics of the planets. This step is used as a relaxation process before our final evolution, so it only evolves our planets for a few thousands years and prepares them for the final evolution in the next step.

Flux	Depth
$1.366 \cdot 10^7\ erg/s \cdot cm^2$	$300\ cm^2/g$
$1.366 \cdot 10^8\ erg/s \cdot cm^2$	$300\ cm^2/g$

Table 1: Information about the 2 different planets we created. In the first column is the flux that the planets are receiving from the outsided heat source. In the second column we see the depth that the irradiation penetrates our planet.

In this step we create 2 different planets with 2 different flux values. We can assume our planets are rotating a star with the luminosity of our own sun. By doing this we can calculate the semi-major axes that these planets will have and compare them to that of the earth and the gaseous planets of our solar system. We do that by using Equation 1:

$$\frac{a_{planet}}{a_{\oplus}} = \sqrt{\frac{\frac{L\odot}{4\pi F_{planet}}}{\frac{L\odot}{4\pi F_{\oplus}}}} = \sqrt{\frac{F_{\oplus}}{F_{planet}}} \tag{2}$$

In this equation $F_{planet} = 10F_{\oplus}$ and $100F_{\oplus}$ respectively. The results are shown at Table 2. We can see that the planets are rotating in very small orbits around the star as someone would predict from the values of the flux. As a comparison the closest gas giant in our solar system, Jupiter, is at $a_{jupiter} = 5.2044AU$

Flux	semi-major axis
$10F_{\oplus}$	$0.316\ AU$
$100F_{\oplus}$	$0.100\ AU$

Table 2: The sami major axes of our 2 planets if we assume they are rotating a star with the same luminosity as our sun. The axes are given in astronomical units

The last step is pretty straighforward. We set the correct luminosity for each of our planets as in our previous step indicated in Table 1 and we let it evolve for $5Gyr$ in order to produce our final planets. We now have 3 planets including the evolved case from our previous work and the 2 planets we created in our current work.

Results

The first thing we want to compare is how the planets evolved in the 3 different cases [4], [5]. We see in Figure 1 that our original planet with no irradiation has the smallest radius after $5Gyr$. This is something that should be expected. The outside radiation should prevent our planets from deflating as much as the one that doesn't have a heating source. The other 2 planets that have irradiation are as one would predict larger (in radius) than the original in every time step, with the case for $100 \cdot F_{\oplus}$ being higher than the $10 \cdot F_{\oplus}$ case.

The reason we don't have data before $1 \cdot 10^6 yr$ for the two planets with irradiation, has to do with how we evolved them. As mentioned in Methods the first step involves an evolution with no irradiation for $1 \cdot 10^6 yr$. The final step which is the main evolution started from that time period, thus giving us data from that point onward. It's also the same for Figure 2.

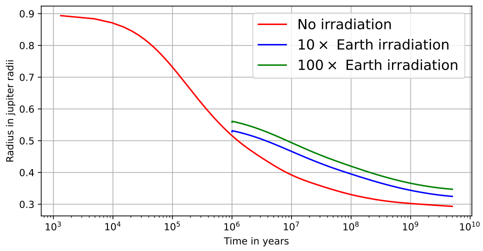

Figure 1: Time evolution of the planetary radii. We can clearly see that more irradiation from an external heat source translates into a bigger final radius. Data from early stages are not available for the two radiated cases.

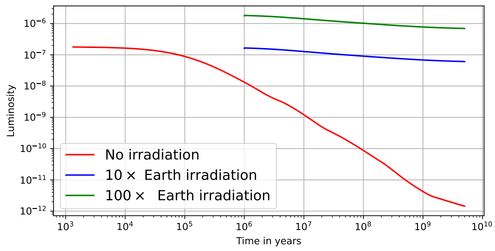

Figure 2: Time evolution of the planetary luminosities. The planets with an external heat source have a more steady evolution compared to the planet with no irradiation, that leads to a bigger final luminosity.

The evolution of the luminosity makes it even more clear how the external heat is affecting our planets' evolution. We can clearly see in Figure 2 that the red line representing the planet that doesn't have a heat source, rapidly goes to very small values after $1 \cdot 10^5 yr$. This is something that one would expect from the results of [6], [7]. On the other hand the 2 planets that do have a central star heating them up, manage to keep their luminosity at the same order of magnitude as they already had. Again we have the same order we would expect, with the planet with the bigger flux from the star being on top of the one with the smaller.

After comparing the time evolution of the planets we want to take a look at the final products. We put the evolved planets in a Mass vs Radius diagram in Figure 3 along with detected exoplanets that we got from [8]. In the right panel we can more clearly see that the planets have the same mass, as one would expect because of the way we set them up, and have slightly different radii. The more irradiated the planets are, the bigger is their final radius. This inflation can be perfectly explained by the external heat source, because it gives more energy to the gaseous envelopes and keeps them more inflated than they would be without it. This was already clear from Figure 1, if we look at were the lines end.

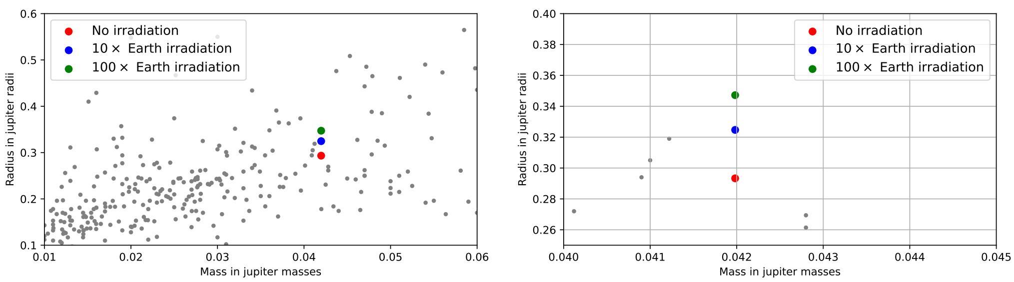

Figure 3: We can see our 3 planets in a Mass vs Radius diagram. In the left panel we see many different exoplanets that have been detected ([8]) and on the right panel we have a zoomed in version where details about the radius are more clear

In our previous work we mentioned how, by comparing the adiabatic and the radiative gradients of a planet in different regions, we can say how it transports its energy. In our current work we will compare the profiles of our 2 extreme cases. In the left panel of Figure 4 is the profile for our planet with no irradiation while on the right panel we have the planet that has $F_{planet} = 100F_{\oplus}$. The profiles have the normalized radius in the x-axis. To get that we divide the radius of each data point with the total radius of the planet. This helps us to better compare the results as the absolute value of the distance from the centre won't help us much in the case of inflated planets such as this.

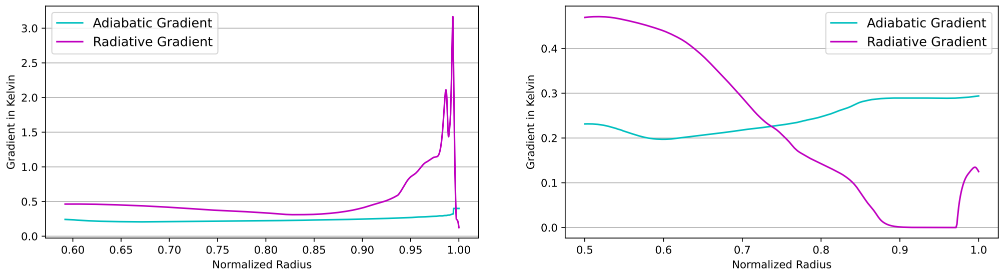

Figure 4: The radiative and adiabatic gradient as a function of the normalized radius for the two extreme cases: no irradiation (left panel) and 100× Earth irradiation (right panel). We see that the profiles have many differences that indicate different heat transportation mechanisms in different parts of the planets.

The planet with no irradiation has both gradients almost equal at the smaller distances from the core, with the radiative gradient being a little bit more dominant than the adiabatic. As we go more into the outer regions of the envelope we see that the radiative gradient has much greater values than the adiabatic. This leads to the conclucion that the main way of heat transfer [9], especially in the outer regions is convection. With the radiative gradient rapidly dwindling in the very edges of the planet, we have the adiabatic gradient becoming bigger than the radiative for a small part of the planet. We should expect that the radiation is the main way that heat transfers in that region.

This is not the case for the planet that has evolved with an external heat source. We see that the radiative gradient is bigger than the adiabatic in the beginning of the envelope, but it then switches with the adiabatic gradient being the dominant one in the outer regions. This means that the way heat transfers in that envelope is convection for the first part and radiation for the outer part of the planet.

This difference can be explained if we consider the external heat source that is absent in the first case and really dominant in the second. The radiation from the central star will have a great impact in the outer regions of the envelope and its significance will fade as we go into deeper layers. This will affect the way energy transfers in such ways as described above.

In Figure 5 we have the temperature profiles of all 3 planets. We see that the temperatures in the outermost region of the envelopes follows the order we would expect, the no irradiation case goes to 0 and the more irradiation we have, the hotter it gets [10], [11]. We can also see that the shapes are very similar for the two cases that an external heat source is present and very different in the absence of it.

In the inside of the envelope, the temperatures vary and for different values of the normalized radius we have different planets become the hottest or the coldest of the 3. This, probably, has to do with the way that heat transfers in the inside of the planets. As we saw in our discussion about the energy transfer, the planet with no irradiation had a completely different profile than the one with maximum flux from the central star. This combined with the radius inflation that affects the normalization can factor in and create this picture, where the planet with no external heat source is for a small part (between 0.8 and 0.95) the hottest of the 3.

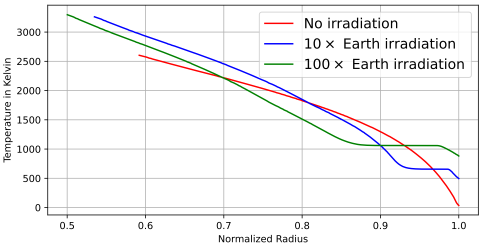

Figure 5: Temperature as a function of the normalized radius for the 3 planets. The temperature of the planet with no irradiation is 0 for in the edges of the envelope, while the other planets are hotter.

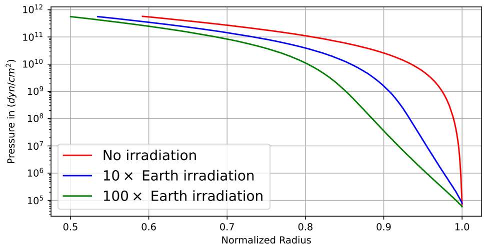

Figure 6: Pressure as a function of the normalized radius for the 3 planets. The more irradiated planets have lower pressure for the same value of the normalized radius.

The final thing we want to compare between the 3 planets are their pressure profiles. Again we plot them for the different values of the normalized radius. In Figure 6 we can see the results. The red line for the planet with no central star has the higher pressure. The two planets that have an external heat source follow the same logic, with the more irradiated one having a smaller pressure for each value of the normalized radius. This seems to be normal if we consider the inflation of the irradiated planets. As seen in Figure 1 and Figure 3 the total radius of the planets with an external heat source are appropriately inflated [12] resulting in smaller pressures for the same values of the normalized radius. More information on the way irradiation affects the pressure and temperature profiles can be found in [13].

Conclusion

We have used the MESA code in order to produce 3 planets that have the same composition but receive different flux from a central star. From the analysis of the data from the simulations we were able to gain a useful insight on how these planets evolved. We also gained information on the ways they transport heat in their inside and how the temperature and pressure varies in different regions of their gaseous envelopes.

In this work we extracted some conclusions on how irradiation affects the internal structure and evolution of low mass gas planets. We saw that irradiated planets have an inflated radius proportionate to the flux they receive from the central star. The luminosity that they have is preserved (same order of magnitude) during their evolution. The profiles of the radiative and adiabatic gradient are completely different from the planets with no irradiation which leads to different heat transfer mechanisms. The temperatures in the outer parts of the envelopes are greater, when they receive more energy from the central star. Lastly they tend to have smaller pressure for points with the same distance from the core proportional to the total radius.

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