Mini-Lab 2: Irradiating Sub-Neptune Size Planets in MESA

Leslie A. Rogers, TAs: Carl Fields, Jared Brooks

Most of the sub-Neptune size planets discovered to date that have had their radii and masses measured (by transits, radial velocity, and transit timing variations) are on close in orbits to their host stars ($P < 50$ days). This is due to the observational biases of the transit and radial velocity techniques. These close-in planets are more strongly irradiated by their host stars than the Earth is by the Sun. In this mini lab, we will explore the effect of irradiation on the evolution of sub-Neptune mass planets. (Recall that on Tuesday you explored the effect of irradiation on gas giant planets). You will use the same work folder `rogers_minilabs` as you did for mini lab 1.

As in mini lab 1, we've again highlighted action items in red.

a) Getting Started

We'll start from the models that you created in the "Set Entropy" step in mini-lab 1. We need to create a planet model that has an appropriately set core luminosity, but that hasn't evolved all the way to 5 Gyr. Make a new copy of your `inlist_1e_evolve` inlist that still reads in your `planet_1d_setS*` model, relaxes the core luminosity, but then only evolves the planet without irradiation for 10^6 years (before saving a `planet_2a_evolve*` model).

In case it's helpful we've provided a template inlist as `inlist_2a_evolve`.

b) Surface Heating

When working with hot Jupiters on Tuesday, you used the $F_\star$-$\Sigma_\star$ inlist options in MESA to irradiate your giant planets. Let's try to use this same option to irradiate our small planets. Let's simulate planets at 0.1AU around a sun twin (corresponding to planets that are 100 times more strongly irradiated than the Earth). This corresponds to $F_\star = L_\odot / \left(4\pi a^2\right) = 1.36 \times 10^8 \ \mathrm{erg\,s^{-1}\,cm^{-2}}$. Take the same $\Sigma_\star = 3.0 \times 10^2 \ \mathrm{cm^2\,g^{-1}}$ as on Tuesday.

Evolve the `planet_2a_evolve*` model that you saved in the previous step with surface heating for 5 Gyr. We've provided a template inlist `inlist_2b_setsurfheat`, but please try to create your own inlist for this exercise before looking at our template. If you use your `inlist_2a_evolve` as a starting point, don't forget to delete/comment out any lines where you're relaxing L_{core}, or resetting the initial age or model number.

Are you able to evolve your planet by setting the surface heating directly? If not, what error do you get? Input the final radius of your planet (at 5 Gyr), or the error that you obtained, in the Google spread sheet.

If you were assigned one of the higher values of M_{core}, you might find that MESA runs happily until `max_age`. However, MESA will definitely complain and error when we abruptly turn on irradiation for some of our lower planet masses (which can be a bit more finicky). You can repeat this step with the 3 $M_\oplus$ model provided, so that you can experience the errors for yourself.

c) Relax Irradiation

In order to model very low mass irradiated planets, we need to gradually dial up the incident irradiation. This is accomplished with `relax_initial_irradiation` in the `star_job` controls. Adjust your inlist to use `relax_initial_irradiation` in order to gradually irradiate your `planet_2a_evolve*` planet model. Then, save the model as `planet_2c_relaxsurfheat*` after the irradiated planet has evolved for a **short** time ($\leq$ 1000 years). Now, try again at evolving your planet with surface heating for 5 Gyr (i.e., run `inlist_2b_setsurfheat` again, but this time load the relaxed `planet_2c_relaxsurfheat*` model that you saved). Does this work better than before, when we turned the irradiation on abruptly?

If your model ran successfully, input the final radius of your planet (at 5 Gyr) in the Google spread sheet. How does the radius of your irradiated planet compare to the radius of your non-irradiated planet in mini lab 1? Everyone's reported radii will be used to crowd source a planet mass-radius diagram for irradiated planets.

You can take a look at inlists `inlist_2c_relaxsurfheat` and `inlist_2c_evosurfheat` if you need a hint for this exercise.

d) Grey Irradiated Atmosphere (Bonus)

MESA provides another irradiated atmosphere boundary condition applicable to planets called `grey_irradiated`. The `grey_irradiated` atmosphere option is based on an analytic temperature profile for an atmosphere that has both heat flux coming from below and irradiation from the outside, derived by Guillot (2010) by solving the equation of radiative transfer (under the "two-stream", semi-gray, plane-parallel assumptions).

$$T^4(\tau) = \frac{3T_{\rm int}^4}{4}\left\{\frac{2}{3}+\tau\right\} + \frac{3T_{\rm eq}^4}{4}\left\{\frac{2}{3}+\frac{2}{3\gamma}\left[1+\left(\frac{\gamma\tau}{2}-1\right)e^{-\gamma\tau}\right]+\frac{2\gamma}{3}\left(1-\frac{\tau^2}{2}\right)E_2(\gamma\tau)\right\} \qquad (1)$$

The first term is the standard Eddington approximation for an un-irradiated atmosphere, and the second term includes the effect of irradiation. $T_{\rm int} = (F_{\rm int}/\sigma_B)^{1/4}$ is the "effective temperature" of the flux entering the atmosphere from the interior of the planet, $F_{\rm int}$. $T_{\rm eq}$ is the equilibrium temperature of the planet and is related to the irradiation flux by $T_{\rm eq}^4 = F_\star/4\sigma_B$. Here, $\tau = \kappa_{th}P/g$ is the optical depth to outgoing thermal radiation, while $\gamma = \kappa_v/\kappa_{th}$ is the ratio between the visible opacity κ_v (to the incoming stellar photons) and the infra-red opacity κ_{th} (to the outgoing thermal photons). Lastly, E_2 is the 2nd exponential integral. This formula has been angle averaged over the surface of the planet, and hence represents a good temperature profile to use for studies of the evolution of the interior.

The `grey_irradiated` atmosphere option can be specified in `&controls`. MESA calls its Rosseland opacity routine to set κ_{th}, and sets $F_{\rm int}$ by the outgoing fluxes determined in the evolution calculation. The parameters κ_v and `atm_grey_irradiated_P_surf` (the pressure at the base of the atmosphere) need to be set in the inlist, along with various numerical tolerances.

Try evolving the same planet as in part c) with the `grey_irradiated` boundary condition (again assuming that the planet is 0.1AU from the sun). Start with the default values:

```
atm_grey_irradiated_kap_v = 4d-3
atm_grey_irradiated_P_surf = 1d6
```

Are you able to get it to work? The lower the planet mass and the higher the irradiation, the more challenging and finicky this will be. Groups who were assigned low values of $M_{\rm core}$ can try experimenting with a lower value of $T_{\rm eq}$ (say 300 K or 500 K) before trying to push up the irradiation. You may even want to experiment with one of your giant planet models from Tuesday to try to get this working.

Even with a giant planet, you will encounter issues if the starting model (with the $F_\star$-$\Sigma_\star$ boundary condition) is too different from the `grey_irradiated` boundary condition that you're trying to achieve. How can you adjust the parameters in the `relax_initial_irradiation` step to better approximate `grey_irradiated`? How should $\Sigma_\star$ relate to κ_v?

What does the star_job option relax_initial_tau_factor or set_initial_tau_factor do? Could one of these options be useful in the relax_initial_irradiation step to help you to more closely approximate your target grey_irradiated boundary condition?

References

Guillot, T. 2010, A&A, 520, A27