Maxi Lab: Evaporation of Sub-Neptune Mass Planets in MESA

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Strongly-irradiated planets will loose mass over time to atmospheric escape. Mass loss can be especially important for sub-Neptune mass planets; if a Jupiter looses 1% by mass H/He over its lifetime you might not notice, but if a sub-Neptune planet (which may only have $\sim 1\%$ by mass H/He to start out with) looses a similar amount it would represent a large qualitative different in the planet's bulk composition, transit radius, and mean density.

In this lab, you will use MESA to simulate the simultaneous thermal and mass-loss evolution of low-mass planets. Ultimately, we will use our crowd-sourced results to explore how mass loss could sculpt the observed properties of small close-in exoplanets.

Planet Mass Loss Physics Intro

Extreme ultraviolet and X-ray radiation (EUV; $200 < \lambda < 911$ Angstroms) from a planet's host star heat the outer reaches of a planet's H/He envelope. For close-orbiting planets, this energy imparted to the atmosphere can drive a hydrodynamic wind, causing some of the planet's H/He to escape.

A common assumption when modeling mass loss from planets is to assume that the mass loss is energy limited. In this case, it is assumed that a fixed fraction $\epsilon_{\rm EUV}$ of the incident energy in EUV photons absorbed by the planet contributes to unbinding the outer layers of the planet. $\epsilon_{\rm EUV}$ (dimensionless) is called the mass loss efficiency factor, often assumed to be 0.1 (Jackson et al., 2012; Lopez et al., 2012). Neglecting any tidal effects, the energy-limited mass loss rate is given by:

$$\frac{{\rm d}M_{\rm p}}{{\rm d}t} = -\frac{\epsilon_{\rm EUV}\pi F_{\rm EUV} R_{\rm EUV}^3}{G M_p}, \tag{1}$$

$F_{\rm EUV}$ is the extreme ultraviolet energy flux from the host star impinging on the planet atmosphere. R_p and M_p are planet radius at optical depth $\tau_{\rm visible} = 1$ (in the visible) and the total mass of the planet respectively. G is the gravitational constant. Finally, $R_{\rm EUV}$ is distance from the center of the planet to the point where the atmosphere is optically thick to EUV photons. Let's replace $R_{\rm EUV} = rR_{\rm p}$ to introduce another nuisance parameter $r = R_{\rm EUV}/R_{\rm p}$.

For sun twins, Ribas et al. (2005) found observationally that the EUV luminosity (at a distance of 1AU from the star) varies in time roughly as,

$$F_{\rm EUV} = 29.7 t^{-1.23}\ {\rm erg\,s^{-1}\,cm^{-2}}, \tag{2}$$

where t is the stellar age in Gyr. Recall that the stellar flux will be diluted by a factor of $(a/AU)^{-2}$ by the time that it reaches the planet.

a) Getting Started

Create a fresh, clean, new work folder for this maxilab.

Copy your `planet_2c_relaxsurfheat*` model from mini lab 2 into the maxilab work folder. Alternatively, we also provide some starting models that you may use, if needed. It may also be useful to copy over the inlist from part c of mini lab 2 that you used to evolve an irradiated planet with the $F_\star$-$\Sigma_\star$ surface heating (or the inlist template named `inlist_2c_evosurfheat`) to use as a starting point for your inlist for this maxi lab.

b) Turn On Other Mass Loss

We will be using the `other_adjust_mdot` hook to implement our own mass loss prescription. Copy the template `other_mdot` routine found within one of the files in `$MESA_DIR/star/other` into your `run_star_extras`, and give it a more informative name (e.g., `energy_limited_mdot`). Edit the controls section of your inlist, along with the `extras_controls` routine in `run_star_extras.f` to point at the `other_mdot` routine that you'll eventually want to be executed.

Recompile MESA and run to make sure everything's set up properly. Since our `other_mdot` routine is still just the empty template, this should reproduce the evolution of your irradiated planet that you ran in part c) of mini-lab 2.

c) Code Up Energy Limited Escape

Modify your `other_mdot` routine in `run_star_extras` to implement energy limited escape. Use `x_ctrls` specify the values of 3 input parameters in the inlist: $\epsilon_{\rm EUV}$ (dimensionless), r (dimensionless), and a (the orbital separation of your planet in AU). Let's take $\epsilon_{\rm EUV} = 0.1$, $r = 1.1$, and $a = 0.1$ AU for our default values.

d) Set up output history options

We will want to have the planet mass loss rate $\dot{M}_{\rm p}$, as well as its current envelope mass fraction $f_{\rm env}$, and mean planet density included as columns in the history output file. Adjust your `history_columns.list` or `run_star_extras` (or both) to achieve this.

You may also find it convenient to output the planet mass and radius in the history file in Earth-based units.

e) Evolve Planet and report results

Evolve your planet for 5 Gyr. Does the calculation make it all the way to `max_age`? How does your planet's final radius compare to its size without mass loss?

Note your planet's final envelope mass fraction $f_{\rm env}$, mean density, $\rho_{\rm ave}$ (in $\rm g\,cm^{-3}$), and planet radius (in $R_\oplus$) at 5 Gyr in the Google spreadsheet. If your planet has completely lost its envelope before making it all the way to 5 Gyr, you should report the radius of the remnant core.

We will crowd source these results to look at the radius distribution of your final planets.

f) Explore different levels of incident flux

So far, all the mass-loosing planets that we've simulated have been at 0.1 AU. Let's explore how the distribution of planet radii and densities depends on orbital separation.

Let's now also consider $a = 0.032$, 0.32, and 1 AU (repeat step e for each of these orbital separations). **Don't Forget** to adjust the irradiation flux along with the orbital separation in your `x_ctrls` inlist. Note, you may also have to repeat the "relax irradiation" step from mini-lab 2.

Once you're done, again add your resulting $f_{\rm env}$, $\rho_{\rm ave}$, and planet radius at 5 Gyr in the spreadsheet.

g) Bonus: Set $r = R_{\rm EUV}/R_{\rm p}$ Internally

So far we have artificially set r and kept it fixed. In reality, as the planet contracts and its surface gravity changes over time, the pressure as well as the radius at $\tau_{\rm EUV} = 1$ will vary. As a bonus problem, you can adjust your `other_mdot` routine to more physically set r and to account for its variation in time.

We may first approximate the difference between $\tau_{\mathrm{visible}} = 1$ and $\tau_{\mathrm{EUV}} = 1$ (the photo-ionization base) with

$$R_{\mathrm{EUV}} \approx R_p + H \ln\left(\frac{P_{\mathrm{photo}}}{P_{\mathrm{EUV}}}\right) \tag{3}$$

where $H = (k_{\mathrm{B}} T_{\mathrm{photo}})/(2 m_H g)$ is the atmospheric pressure scale height at the photosphere (the factor of 2 in the scale height equation denotes the molecular form of hydrogen in this regime). P_{photo} and T_{photo} are the pressure and temperature at the visible photosphere.

Following Murray-Clay et al. (2009), we estimate the pressure at $\tau_{\mathrm{EUV}} = 1$ from the photo-ionization cross-section of hydrogen, $\sigma_{\nu_0} = 6{\times}10^{-18}\,(h\nu_0/13.6\text{ eV})^{-3}\text{ cm}^2$ as $P_{\mathrm{EUV}} \approx (m_H G M_p)\,/\,\left(\sigma_{\nu_0} R_p^2\right)$, adopting a typical EUV energy of $h\nu_0 = 20$ eV instead of integrating over the host star's spectrum.

Create a new copy of your `run_star_extras` (just so that you have a saved working version if anything breaks). Then adjust your `other_mdot` routine to set r internally using the equations above instead of reading it in from the inlist.

References

Jackson, A. P., Davis, T. A., & Wheatley, P. J. 2012, MNRAS, 422, 2024

Lopez, E. D., Fortney, J. J., & Miller, N. 2012, ApJ, 761, 59

Murray-Clay, R. A., Chiang, E. I., & Murray, N. 2009, ApJ, 693, 23

Ribas, I., Guinan, E. F., Güdel, M., & Audard, M. 2005, ApJ, 622, 680

Hints

- If you need a refresher on using "other" hooks, you can see the instructions on the MESA website `http://mesa.sourceforge.net/run_star_extras.html#toc-3`
- If you need a refresher on adding extra columns to the history file, you can see the instructions on the MESA website `http://mesa.sourceforge.net/run_star_extras.html#toc-1-2`
- Be very careful of units. Use `star_data.inc` and the default `history_columns.list` to verify units.
- It may also be helpful to look at `const_def.f90` to see the constants that are defined within MESA along with their names.
- Please avoid looking at it, but we do provide a sample `run_star_extras.f` solution, along with an inlist.