Homework 6

MESA Models for High- & Low-Mass Stars

In this assignment, you will work with output data from MESA to explore the interior evolution of a low- and high-mass star. We will provide you with a series of outputs from two separate simulations run with MESA. In the first, a $1\ M_{\odot}$ star is evolved from the pre-main sequence phase to the beginning of the planetary nebula phase. In the second run, a $25\ M_{\odot}$ star is evolved from the pre-main sequence phase to just before the core collapse supernova.

MESA evolves the models through a series of discrete time steps. In each .tar bundle you will find a `history.data` file, which contains information about global properties of the star at a fixed interval of steps. This file can be read as CSV. The "model_number" field is used to identify which time step number each row in the file corresponds to.

To actually see inside the star, you want to look at the `profile.XYZ.data` files, where the `XYZ` indicates you which "model_number" or time step the profile corresponds to. These too can be read as CSV files.

- **Note 1: T**here are only a few profiles provided, generated at special times during the evolution of the star.
- **Note 2:** In each profile the star is broken into a series of radial zones. The 'mass' and 'radius' columns tell you how much of the total star's mass and radius is enclosed interior to that zone (*not* the mass or radius *within* that zone).

`history.data` contains the following fields (note: log means $\log_{10}$):

model_number	Corresponding profile number for each row
star_age	Time since the start of the pre-main sequence (in years)
star_mass	Total mass of the star (in solar masses)
log_L	Log luminosity of the star (in solar luminosity)
log_Teff	Log effective temperature of the star (in K)
log_R	Log radius of the star (in solar radii)
center_h1	Central hydrogen mass fraction
center_he4	Central helium mass fraction

Note: the 25 solar mass history file also tracks masses of several core layers which form over time..

The `profile.XYZ.data` files contain the following fields:

radius	Enclosed radius at this zone (in solar radii)
mass	Enclosed mass at this zone (in solar masses)
logT	Log temperature in this zone (in K)
logRho	Log mass density in this zone (in g/cc)
logP	Log pressure in this zone (in dyn cm^-2)
logL	Log luminosity passing through this zone (in solar luminosity)
mu	Mean molecular weight in this zone
eps_nuc	Nuclear energy generation rate in this zone (in erg g^-1)
h1	Hydrogen mass fraction in this zone
he4	Helium mass fraction in this zone
gradr	Radiative temperature gradient in this zone
grada	Adiabatic temperature gradient in this zone

Part 1: Evolution of the 1 Solar Mass Model

(30pts - 5pts per Q)

For the first few questions, look at the evolution and internal structure of the 1 solar mass star. Five profiles are provided, which correspond to the following events in the star's evolution:

95 - Ignition of H burning in core (ZAMS)
147 - Present-day Sun
290 - Exhaustion of H in core
4903 - He core becomes non degenerate
5632 - Envelope of star ejected

Begin by constructing an H-R (log Teff, log L) diagram showing the evolution of the 1 solar mass star from the history file. Color the data points by time, so that you can tell apart the different post-main sequence phases. Highlight or identify the time steps that correspond to the 5 detailed profiles (via the “model_number” column).

Question 1: Identify and label the beginning and end of each phase of the star's evolution on your HR diagram.

Question 2: Starting at snapshot 290, the luminosity of the star increases while the surface temperature drops. What is happening in the core of the star at this point?

Question 3: From snapshot 290 onward, why is the luminosity of the star increasing?

Question 4: Eventually, the luminosity reaches a peak before the star contracts and heats up again. What is happening to the interior of the star at the peak?

Question 5: The envelope of the star is either contracting or expanding, depending on which phase of evolution we are in. Make a plot of the star's radius vs time. Identify each phase of evolution and determine whether the star is expanding or contracting during that phase. It might help if you also plot the evolution of the core hydrogen and helium fractions alongside the radius. Some of the changes in radius are not terribly obvious!

Note: You will probably find that all of the post-main sequence evolution gets very squished together towards the right side of your plots. To remedy this, try making your x-axis log(t_end - t), where 't_end' is the timestamp of the final model and invert the x-axis. This should make it so that the early evolution of the star gets squished together on the left side of the plots, while the relatively fast post-main sequence evolution gets stretched out.

Question 6: From the main sequence onward, the star goes through a progressive series of phases where nuclear burning is either happening in the core, or in a shell around the core. Can you tell where the nuclear burning is happening, just by looking at how the radius of the star is changing? Why does the star contract in one case, and expand in the other?

Part 2: Comparing the 1 & 25 Solar Mass Models

(40pts - 5pts per Q)

Next you will make comparisons between the internal structures of the low- and high-mass stars. For the high mass model, a series of profile snapshots are provided at the following times:

352 - Ignition of H burning in core, ZAMS
474 - A little while after exhaustion of H in core
1116 - Just before iron core collapse

For the high mass star, the evolutionary phases go by pretty quick, and there aren't a whole lot of data points that get recorded to the history file.

Stars don't convert their entire supply of hydrogen into helium during the main sequence. Instead, only the hydrogen that is "within reach" of the core gets used as fuel.

After the end of the main sequence (snapshots 290 and 474 for the 1 and 25 solar mass star, respectively), plot the hydrogen mass fraction profile inside of both stars. To make it easy to compare, make your x-axis show 'fraction of enclosed mass'.

Question 7: Just by looking at the profiles, which star has used up a larger fraction of its total hydrogen supply?

Question 8: For the 25 solar mass model, you should see the composition change much more sharply as you move out from the core. Why is the composition gradient so much steeper for the high-mass star?

Question 9: Calculate the total mass in hydrogen that was burned during the main sequence for both stars. You will have to integrate the hydrogen mass fraction over the mass of the star to figure this out (numpy.trapz is an easy way to do numerical integration). Which star converted a larger fraction of its mass into helium? Don't forget that both stars already had some amount of hydrogen when they formed!

Convection is an instability that occurs inside of stars when energy can't be carried away fast enough by radiation. The “Schwarzchild criterion” for convection to occur is set by the relative size of the radiative and adiabatic temperature gradients to each other:

$$\nabla_{ad} < \nabla_{rad}$$

These quantities can be rather complicated to calculate. Fortunately MESA provides these to you as 'grada' and 'gradr'.

Question 10: For the 1 and 25 solar mass main sequence profiles, plot the radiative and adiabatic temperature gradients as a function of stellar radius. Note: the structure of the ZAMS 1 solar mass model is still settling down from the pre-main sequence. The present day snapshot is a better representation of the internal structure for a low-mass star. You may have to zoom the y-range in to see both.

Question 11: Based on the “Schwarzchild criterion”, where do you expect convection to occur in each of the two stars? If you were to analyze a spectrum from each star, would they both show signs of surface granulation?

Question 12: Explain why convection is occurring in very different places in each of the two stars. You should find that the adiabatic temperature gradient is quite similar between the two models. What makes the radiative temperature gradient so different in each case?

Stars are the cosmic 'engines' that fuse hydrogen and helium into heavy elements, which are returned to the ISM when the star dies. However, not all stars contribute to this process equally. Take a look at the final snapshot (1116) for the 25 solar mass star. Shortly after this time, the star will undergo a core collapse supernova, which is something that a 1D code like MESA is not well-suited to model.

Question 13: How much mass in 'metals' did this star produce over the course of its life? (Don't forget that some of those metals were already present when the star formed). Now do the same calculation for the 1 solar mass star (use snapshot 5632).

Question 14: Which type of star (low- or high-mass) do you think is responsible for producing most of the metals in the universe? Will they both ‘eject' metals back into the ISM?

Turn in your write-up, including the labeled plots, as a PDF. Remember to include an attribution for any group work! Also turn in your code or Jupyter Notebook used to solve the assignment. Note: we’d like to be able to run your code to check that it actually works, so be sure (if using Jupyter notebooks) to check that it runs “top down”!

Use the Dropbox upload link. **DUE: March 17, 11PM PST**