

Stellar Structure Evolution with MESA

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Exercise 1

Q.1.1: Why is there only one history file but multiple profile files?

A: The history file contains the global properties of the star at each time step, while the profile files contain the detailed structure of the star at specific points in time. The history file is updated at each time step, but the profile files are only written at certain intervals. So there is one history file for the entire simulation, but multiple profile files corresponding to different time steps.

Q.1.2: Show with a plot whether or not the size of the time steps in the history file changes during the simulation, and discuss why.

A: The time steps in the history file do change during the simulation. This is because MESA uses an adaptive time-stepping algorithm to ensure that the simulation progresses at a rate that captures the important changes in the star's structure and evolution. The time steps are smaller during rapid changes (like during a shell flash) and larger during more stable phases. Cf. Figure 1 for a plot of the time steps recorded in the history file.

Q.1.3: Similarly, show with a plot whether or not the grid spacing in a profile file of your choice is constant, and discuss why. From this plot, also infer which zone is the most central zone (zone number 1 or the zone with the highest number).

A: The grid spacing in a profile file is not constant. MESA uses a non-uniform grid so it can better capture important changes inside the star, making the grid finer where the structure changes quickly and coarser where things are more uniform. In Figure 2, the top graph shows that zone number 1 is at the surface, while the highest zone number is at the center. The bottom graph shows that the spacing between zones (measured as $\log_{10}(\Delta R/R)$) is not the same everywhere, confirming that the grid is not evenly spaced. Here, ΔR is the difference in radius between adjacent zones, i.e. $\Delta R = R_{i+1} - R_i$.

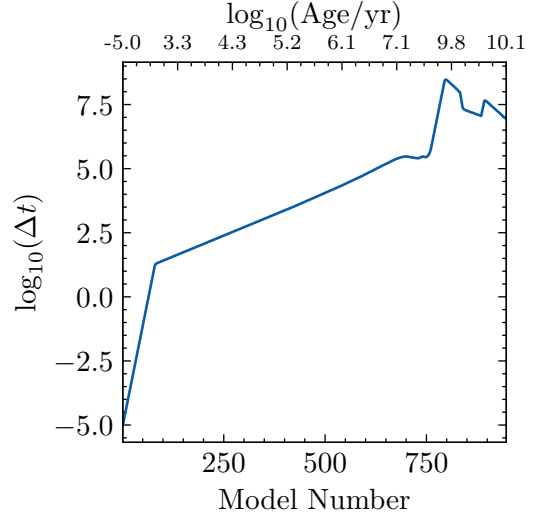


Figure 1: Time steps recorded in the history file. The x-axis shows the model number (bottom) and the logarithm of the stellar age (top). The y-axis shows the logarithm of the time step size.

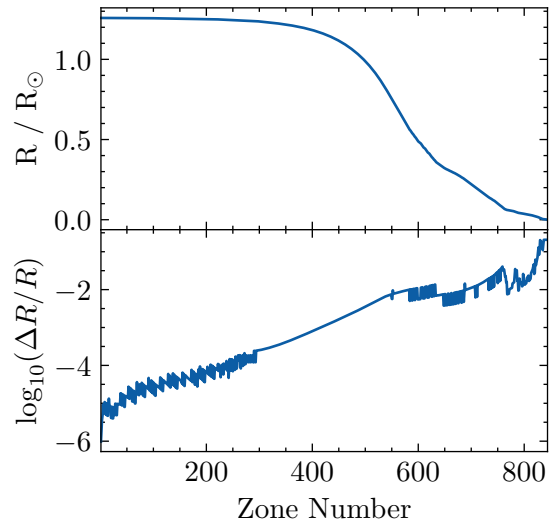


Figure 2: Grid spacing in a profile file. The x-axis shows the zone number. Top: The radius of each zone.

Q.1.4: Which burning stages did the simulation go through, and where did that burning take place? Graphically Illustrate your answer

A: Initially, during the pre-main sequence phase ($\lesssim 4 \times 10^7$ years), there is no nuclear burning. Once the star reaches the zero-age main sequence (ZAMS), defined as the point where the nuclear luminosity exceeds 99% of the total luminosity, hydrogen burning begins in the core. This is evident from the increase in the hydrogen-burning luminosity ($\log_{10} L_H$) in the history file. Due to the imposed limit `he_core_mass_limit=0.1`, the star does not reach the conditions necessary for helium burning; the triple-alpha luminosity ($\log_{10} L_{He}$) remains negligible throughout the simulation.

Figure 3 shows the evolution of hydrogen and helium burning luminosities as the star ages. After reaching the ZAMS, hydrogen burning becomes dominant, while helium burning remains negligible throughout the simulation. To illustrate where hydrogen burning occurs, two additional plots are provided: the x-axis shows stellar age, the y-axis shows the mass coordinate, and the colorbar indicates the abundances of hydrogen and helium, respectively.

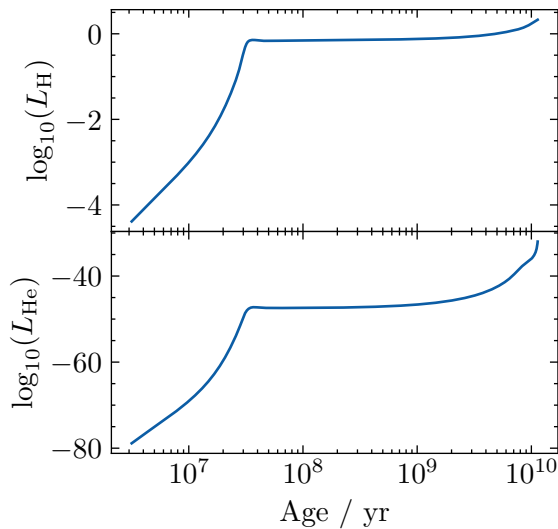


Figure 3: Hydrogen and helium burning luminosities as a function of stellar age.

Q.1.5:

Q.1.5: During the evolution of the stellar model, on what timescales does contraction or expansion occur? You can estimate the contraction/expansion timescale as $|R/\dot{R}|$. Show this in a plot with `model_number` on the x-axis. Furthermore, show the evolution of the three timescales mentioned above in this plot, and explain in your answer how you de-

Figure 4: Hydrogen abundance as a function of mass coordinate and stellar age. The colorbar indicates the hydrogen mass fraction. Hydrogen burning occurs in the core, where the abundance decreases over time.

Figure 5: Helium abundance as a function of mass coordinate and stellar age. The colorbar indicates the helium mass fraction. Helium accumulates in the core as hydrogen is fused.

fined them. Discuss why the model follows certain timescales during different phases of the simulation.

A: The contraction or expansion timescale can be estimated as $\left| R/\dot{R} \right|$, where R is the radius of the star and \dot{R} is the time derivative of the radius. This can be calculated from the history file, where the radius and its change over time are recorded. The evolution of the contraction/expansion timescale can be plotted against the model number, showing how the star's size changes over time. We calculate the timescales of stellar evolution as follows:

$$\begin{aligned}\tau_{\text{dyn}} &\simeq 0.02 \left(\frac{R}{R_{\odot}} \right)^{3/2} \left(\frac{M_{\odot}}{M} \right)^{1/2} \text{ days}, \\ \tau_{\text{KH}} &\simeq 1.5 \times 10^7 \left(\frac{M}{M_{\odot}} \right)^2 \frac{R_{\odot}}{R} \frac{L_{\odot}}{L} \text{ years}, \\ \tau_{\text{nuc}} &\simeq 1.5 \times 10^6 \left(\frac{R}{R_{\odot}} \right)^2 \left(\frac{M}{M_{\odot}} \right)^{-1} \text{ years}.\end{aligned}$$

During the pre-main sequence phase $\lesssim 10^7$ years, the star contracts under the influence of gravity, leading to a decrease in radius. As the star contracts, the dynamical timescale (the time it takes for the star to achieve HE¹) also drops, because the star is becoming more compact and can respond more quickly to changes in its internal structure ($\tau_{\text{dyn}} \propto R^{3/2}$). Furthermore, the Kelvin-Helmholtz timescale (the time it takes for the star to achieve TE²) also decreases since . Since during this phase nuclear fusion is not yet active, one can clearly see that the evolution of the star occurs at the thermal timescale ($\tau_{\text{KH}} \simeq 10^7 \text{ yr}$).

1 Exercise 2

Q2.1: : In terms of relative mass coordinate (q), what parts of your star are convective at the terminal-age main sequence (TAMS)? Use information about temperature gradients in a profile to show this in a plot.

A:

¹hydrostatic equilibrium

²thermal equilibrium