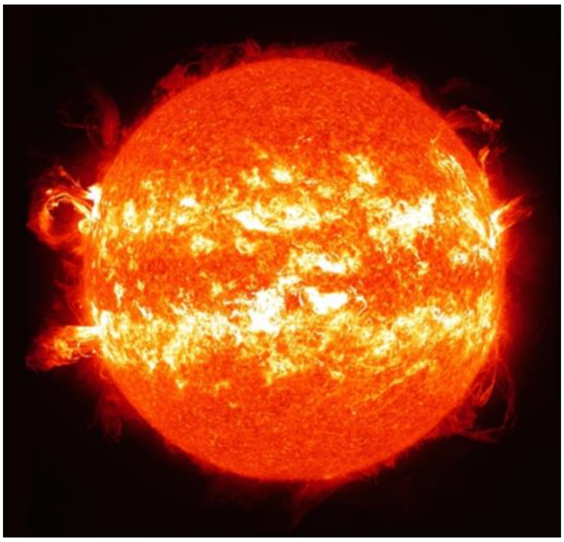
Computational Assignment 1

Becoming Stellar Drs.: Investigating the Life and Death of a Star



In this assignment you will act as stellar “forensic scientists”, reconstructing the evolutionary history of your assigned star using the MESA-Web interface:
http://user.astro.wisc.edu/~townsend/static.php?ref=mesa-web
You are expected to understand the physical meaning of the provided outputs and to analyse quantitatively the evolutionary phases of your stellar model.

Before starting, carefully read the explanation of the MESA-Web output: http://user.astro.wisc.edu/~townsend/static.php?ref=mesa-web-output#History_Output
Your report must contain figures, quantitative and qualitative results, and physical interpretation.

1. Understanding the MESA “Movie” Output

Study carefully the evolution movie and its panels.

(a) Interpretation of plots

For each panel:

- Explain what is shown on the x and y axes.
- State clearly whether the plot shows:
  - temporal evolution of usually global stellar properties, or
  - the internal structure at a specific timestep (snapshot).

- Identify which quantities are global and which are local (function of enclosed mass).

(a2) Understand the Kippennhan diagram (mid top of the movie)

- Does this depict temporal evolution or snapshot of the internal structure of the star?
- What does “model_number” refer to in the x-axis of the plot. Is it time?

(b) Final snapshot analysis

Discuss the final frame of the movie:

- What evolutionary stage has the star reached?
- Based on the HR diagram (HRD), identify:
  - When did the star contract?
  - When did it expand?
- Relate expansion/contraction phases to nuclear burning stages.

For the rest of the assignment, feel free to use parts of the movie (e.g. with screenshots) as pre-computed graphs. This cannot replace the plots that are requested below, but the movie can be used to add extra explanation of a phenomenon, justify a hypothesis or quantify on an requested parameter. Of course, in principle you can reproduce all (or at least most) of these plots from the trimmed_history.data and profiles.data

2. Main Sequence (MS) Phase

(a) Determination of ZAMS

- Identify the Zero Age Main Sequence (ZAMS), defined as the onset of stable hydrogen core burning.
Adopt the approximate criterion for ZAMS: **center_h1 ≤ 99% x center_h1$_{,\text{initial}}$**

Use trimmed_history.data to:

- Identify the time corresponding to ZAMS. Is this at the very beginning of your simulation? If not, explain qualitatively and briefly what was happening before (not from your model but from your theoretical knowledge). Is this consistent on the stellar track of the HRD until ZAMS?
- Report the:
  - Age at ZAMS
  - Luminosity
  - Effective temperature

Indicate the location of the star in the HRD at ZAMS.

(b) Structure during MS

- Check the movie plots during MS, including the Kippenhahn diagram

(c) End of Main Sequence (TAMS)

Define the Terminal Age Main Sequence (TAMS) as: **center_h1 ≤ 0.01**

- Determine:
  - Age at TAMS
  - Central helium abundance (i.e. mass fraction) at TAMS. Is it as the initial? Is it 100%? Why is this value?
  - Luminosity and effective temperature at TAMS. Also Central temperature at TAMS. Is it enough to ignite helium?
- Compute:
  - Total MS lifetime (ZAMS → TAMS).
  - Total stellar lifetime
  - Fraction of lifetime spent on the MS (in %)
  - Briefly report on the importance of MS in the lifetime of a star.
- Calculate the approximate nuclear, thermal and dynamical timescale of your whole star using global quantities (M, R, L of the whole star) , i.e. the global, not layer by layer (refer to Onno Pols lecture notes, or to our computational slides). The MS evolution of our star in which timescale is it expected to occur? Is the model MS lifetime consistent with the timescales you calculate?

(d) HRD behaviour during the MS

- Plot an Hertzsprung-Russell diagram (HRD) including only the MS phase.
- Does the star remain fixed in the HRD during MS?
- Explain physically why luminosity and effective temperature change during hydrogen burning. (Refer to Onno Pols lecture notes)
- Has the star become a giant during MS?

3. Post–Main Sequence Evolution

(a) Immediate post-TAMS burning phase

From stellar evolution theory:

- What burning phase is expected immediately after TAMS?
- Does the star starts with helium core burning immediately after TAMS, or does hydrogen-shell burning dominate first? Does hydrogen-shell burning starts immediately after TAMS?

Use the central helium abundance decrease after TAMS to identify the onset of helium core burning (analogous to the ZAMS method, but now tracking a decrease in central He).
Determine:

- Age at start of helium core burning
- Time remaining until the end of the model
- Fraction of lifetime spent after helium ignition (in %)

(b) Chemical evolution

- What is the heaviest element significantly produced through burning in the model?
- Was carbon produced?
- Was iron produced?
- Explain qualitatively why the star did or did not reach advanced burning stages.

Compare with expectations for different initial stellar masses. Would colleagues with different initial masses obtain similar results?

(c) Radius evolution

- Plot Radius vs time for the full evolution.
  - Can you identify the reason of the biggest "jumps/kinks" radius? What is the physical reasoning behind them?
- Report the maximum radius reached.
- Identify in which evolutionary phase it occurs. Was it during the MS?

4. Wind mass loss (Using trimmed_history.data)

- What is the final mass of your star?
- Plot wind mass loss rate vs time (linear time axis).
  - Can you identify the reason of the biggest "jumps/kinks" in mass loss rate? What is the physical reasoning behind them?
- Determine the maximum mass loss rate reached. Estimate, very roughly and at order-of-magnitude level: If this maximum mass loss rate had been constant over the entire lifetime, what would the final mass be? Comment on why this assumption is physically unrealistic.

Then:

- Plot mass loss vs "remaining time until end": **t_max – t** and use a logarithmic axis if helpful.

5. Radiative vs Convective Regions from a Stellar Profile

Choose one profile (profile*.data) near or slightly after ZAMS, but clearly during the MS and before TAMS.

- **Schwarzschild criterion:** Plot ∇rad and ∇ad vs mass coordinate and identify where ∇rad > ∇ad . Which regions are convective? Confirm with the Kippenhahn diagram from the movie. Approximately how much fractional mass of your star is convective near ZAMS?
  - **Bonus question: Adiabatic gradient:** Compare the profile value of ∇ad with the ideal gas approximation ~0.4. $\nabla_{\rm ad} \simeq \frac{\gamma - 1}{\gamma} \approx 0.4 \quad (\gamma = 5/3)$ Briefly explain possible deviations.
- **Physical interpretation:** During the MS, which part of your star, core or envelope, is convective? Explain qualitatively the main physical reason for convection and how this differs between low- and high-mass stars.

- **Convective overshooting:** From the chemical abundance profile slightly after ZAMS (e.g. the top left panel in the movie), estimate approximately the extent in mass coordinate of the overshooting region.

What is Expected in Your Report

Your submission must include:

- **Figures and plots:** All requested plots should have clear axis labels, correct units, and a concise caption explaining what is shown.
- **Recommended tool:** You may use the MESA-Web helper script to load and handle the output files efficiently:http://user.astro.wisc.edu/~townsend/resource/tools/mesa-web/mesa_web.py
- **Interpretation:** For each result, provide a brief physical explanation. We want to test our physical understanding of what is going inside our stars!