MESA tutorial: Session 3

Late Evolution of Massive Stars

1 Population III stars

2. We're now going to consider the effect of the CNO cycle on the structure of a $5M_\odot$ star. Recall from class that stars above $> 2M_\odot$ undergo H burning via the CNO cycle, whereas lower mass stars undergo H burning via the pp chain.

   You've already computed a "standard" $5M_\odot$ model in Problem 1, so now lets explore a few modifications (make sure that you reset the stopping conditions to be the same as in Problem 1). First, compute a model in which the metallicity is $Z = 0.0$ (set `initial_z=0.0`). There will be no CNO elements in the star, so it must undergo pp chain H burning.

   Next, lets keep the metallicity at the default value ($Z = 0.02$) and simply turn off the CNO reaction networks in `MESA`, thereby forcing the star to undergo pp chain reactions. This experiment provides a more direct test of the effect of CNO cycle vs. pp chain burning because the opacities, mean molecular weight, etc. remain the same. To do this, copy over `\$MESA_DIR/data/net_data/nets/basic.net` to your work directory, name it `basic_no_cno.net`, comment out the four cno reactions (with `!` as the comment character), and point your inlist to the new file (using the `new_net_name` variable).

   (a) For these three models, plot `gradr_sub_grada` vs. m/M for the models at the stopping criterion (the last one printed to file). This quantity is > 0.0 in regions where the star is convectively unstable. What do you notice? Next, plot $\log T$ vs. $\log \rho$ profiles for these three models. Comment on what you observe. Why does CNO burning produce such a different core structure compared to pp burning?

   (b) Next, plot the evolution in $L - T_{\rm eff}$. Comment on what you see. Why are the differences more pronounced between the default model and the $Z = 0.0$ model, compared to the model in which CNO burning is turned off? Consider the other effects that the composition has besides the nuclear reaction rates.

2 Energy Production in Massive Stars

Let's explore the contributions of various nuclear reaction chains to the bolometric luminosities of massive stars.

- Run MESA models at $M = 15, 20, 30, 40, 60M_\odot$ through central carbon exhaustion. To achieve this, set:

```
xa_central_lower_limit_species(1) = 'c12'
xa_central_lower_limit(1) = 1d-5
```

1. Plot the evolutionary tracks of all five stars on a single HR diagram. Clip the first $\sim 10^3$ years of evolution for clarity.

   Color-code the tracks by the dominant source of nuclear burning. The three output quantities of interest are:

   - `log_LH`: H-burning luminosity
   - `log_LHe`: He-burning luminosity
   - `log_LZ`: Luminosity from burning heavier elements

2. Explore different ways of visualizing this data:

   (a) Create three panels, each color-coded by $\log(L_i/L_{\rm bol})$ where $i =$ H, He, Z.

   (b) Assign unique colors based on which burning source dominates the luminosity, and color the tracks accordingly.

   (c) Identify and mark regions where no single source dominates the total luminosity.

3. Interpret your results:

3 Stellar Winds

Mass-loss plays a critical role in the late evolution of massive stars. This problem focuses on the effects of including stellar winds in your MESA models.

- Use the same models as in Problem 1, but re-run them with the Dutch mass-loss scheme by setting:

```
    hot_wind_scheme = 'Dutch'
    cool_wind_RGB_scheme = 'Dutch'
    cool_wind_AGB_scheme = 'Dutch'
```

- Analyze the following:

  (a) Compare HR tracks with and without mass-loss (one panel per mass). Color-code the tracks with mass-loss using $\log \dot{M}$ (e.g., range from -6 to -4).

  Describe how the tracks differ as a function of stellar mass. Is there a threshold mass above which mass-loss effects qualitatively change the evolutionary path?

  (b) Investigate surface abundance changes due to mass-loss.

  - Plot surface abundances of He, C, and N versus time (all masses, one panel per element).
  - Color-code HR tracks by:

    (a) Surface helium abundance

    (b) Surface N/C ratio
  - Wolf–Rayet (WR) stars are generally defined by $X < 0.3$ (where X is surface H abundance). WR subclasses are defined based on surface C and N composition (WN vs WC). Indicate where WR stars appear in the HR diagram.

4 Evolution of massive stars with mass loss

In this exercise, we will evolve a massive star and investigate the effect of wind mass loss on the evolution of the star. As before, *create a new work folder* for each new model you evolve! (Otherwise the data from the previous models will be overwritten.)

1. Choose a mass between 20 $M_\odot$ and 100 $M_\odot$, and change the inlist. Similar to the previous exercise, run several models with a different wind strength. To do this, uncomment all the lines relating to 'wind mass loss' and vary the `Dutch_scaling_factor` between 0 and 1. Run 3 models again with scaling factors of e.g. 0.1, 0.5, and 1.0. During each run, take a close look at the `PGSTAR` plots. Analyse in detail both the motion of the star in the HR diagram and the changes in structure in the Kippenhahn diagram. Can you identify the different phases in the evolution of massive stars (e.g. RSG, LBV, WR, ...)?

2. Make a `Python` script to plot all 3 evolutionary tracks on an HR diagram. Can you explain the difference in the tracks? Discuss again with your neighbours to compare stars of different mass.

3. Plot the He abundance versus age for all 3 models, and compare how the lifetimes of the MS and of the He-burning phase change with increasing mass loss.

4. Next, make separate plots of the *surface abundances* of H, He, C and O vs age, one for each stellar model. Can you explain the changes you see, and their dependence on the mass-loss rate?

5. EXTRA: After analysing the effects of mass loss, choose one of the models you evolved and continue its evolution, by removing the stopping condition for the lower limit of the central helium abundance. Now follow the evolution and try to identify the different burning stages in the star and their effect on the abundances and the structure.