MESA tutorial: Session 3
Late Evolution of Massive Stars

→ Download the MESA inlists needed for this tutorial from Brightspace.
`hw3_inlist_to_C_exhaust` will be used for problem 1, while `hw3_inlist_massive_stars` is for problem 2 (and 3).

Pro Tip

Some of the models you will run in this practicum may take a long time (5-10 min) to complete. There is no need to wait for *all* models to finish before starting on the analysis and plotting code!

1 Luminosity in the late evolution of Massive Stars

We have learned how stars spend their life balancing the energy they loose from their surface (aka Luminosity) with nuclear reactions from their core. Let's explore the contributions of various nuclear reaction chains to the photon luminosity, and compare this to neutrino losses during the life of massive stars.

- For this problem set, make a new copy of the `$MESA_DIR/star/work` directory and place `hw3_inlist_to_C_exhaust` and `history_columns.list` in your new working directory. In the `inlist` file, change `inlist_project` to point to `hw3_inlist_to_C_exhaust`. (for good measure you may want to remove `inlist_project`)
- Run MESA models at $M = 20, 30, 40 M_\odot$ through central C exhaustion. To achieve this add to the `&controls` section in `hw3_inlist`

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

  Note the setting `log_directory = 'M20_HW3'`: will redirect your output to a new directory with this name, so you don't have to copy the whole work directory each time you want to run a new model.

Pro Tip

You will be making a lot of HR diagrams in this practicum. Consider creating a reusable Python function to streamline the plotting process + save you time.

(a) Plot the evolutionary tracks of the three massive stars on a single HR diagram. Clip the pre-main sequence evolution from your plot for clarity. There are many ways you can do this, for example by finding the first time the central hydrogen abundance drops below 0.69

```python
# find index of MS
start = np.flatnonzero(np.asarray(hist.center_h1) < 0.69)[0]
# select range of interest
print(hist.star_age[start:])
```

Create three scatter plots, each colored by a different Luminosity: $\log(L_i/L_{\rm bol})$ where $i =$ H, He, Z. The output quantities of interest are: `log_LH`, `log_LHe`, and `log_LZ`.

(b) Create a fourth plot. This will again be an HR diagram, but instead of phothon luminosity on the y-axis, use the luminosity emitted in neutrinos, nuclear and thermal combined (`log_Lneu`)

(c) Interpret your results. It might be helpful to compare your results to Figure 2 from Farag et al. 2020

2 Evolution of massive stars with mass loss

We will next investigate the effect of wind mass loss on the evolution of massive stars. You need `hw3_inlist_massive_stars` for this exercise. This inlist results in more properly resolved stars (note the difference in HR diagram). Because of this it will take much too long to run the late evolution, which is why we will only run the stars until core He exhaustion.

- Choose a mass between 20 $M_\odot$ and 60 $M_\odot$, and change the inlist accordingly.
- Run the same mass model with 3 different mass-loss rates.
  To do this vary the `Dutch_scaling_factor` between 0 and 2, (for example 0.1, 0.5, and 1.5).
- As before, *change the* `log_directory = 'X'` for each new model you evolve! (Otherwise the data from the previous models will be overwritten.)

(a) Plot all 3 evolutionary tracks on an HR diagram, but now color-code the tracks with mass-loss using $\log \dot{M}$ (e.g., range from -6 to -4). Can you explain the difference in the tracks? Discuss with your neighbours to compare stars of different mass.

(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

(c) 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.

(d) 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?

(e) 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.

- 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.

3 Radius evolution of massive stars

Using your model for the star you picked with a mass between 15 and 100 $M_{\odot}$ from the previous exercise (with `Dutch_scaling_factor` set to 1.0.) compute the following:

(a) Make a plot of the radius of the star versus the age. What are the fast and slow phases of evolution? When does the star expand, and when does it contract? By how much does the star expand during its evolution?

(b) If the star is in a binary system, in which phase in its evolution is it most likely that the star fills its Roche lobe?
Note: Observations show that the distribution of the orbits of binary stars is roughly uniform in $\log(a)$. For example, the number of binary stars with separations in the range 10–100 $R_{\odot}$ is similar to that in the range 100–1000 $R_{\odot}$.

(c) Find the values of the radius of this star that delimit Case A, Case B and Case C of mass transfer. (See p. 225 in Chapter 15 of the lecture notes for a definition of these different cases.)