Assignment 2: MESA

ASTR3007/4007/6007 Stars

due on Sunday, April 19

This assignment is due on Sunday, 19th April, 11:59pm. It has to be submitted with cover sheet in time to the lecturer or marks will be deducted (penalty of 5% deduction per late day or part thereof will apply). Assignments must be presented in high quality type setting (e.g. LaTeX, Google Docs, Word). Illegible parts of a submission are considered a failure to communicate the solutions and will receive a mark of zero. Submission only as pdf file (no Word document etc) via wattle Note: all results must be rounded to four significant figures.

This assignment requires calculations performed by the MESA (Modules for Experiments in Stellar Astrophysics) stellar evolution program. You will generate your tracks using the web interface at `http://mesa-web.asu.edu/`. Please be aware that it can take a few hours for requests from their server to be fulfilled—**do not expect to receive your calculations immediately!** Please also be aware that as a `MESA` developer, I can check the number of individual requests made, so (1) I will be able to see whether or not you have tried to generate the data yourself and (2) I can retrieve the list of parameters submitted in every call. Learning how to use this tool is part of the assignment. Please do not share data.

This assignment involves data manipulation and plotting. You will need a text editor such as Sublime, gedit, nano, atom, etc. to view the data. You may search it by hand, using Excel, or using a programming language of your choice (my personal recommendation is Python, and it is the one I am best equipped to help you with). An interactive plotting tool and additional information on how to manipulate MESA data are available at
`https://github.com/mjoyceGR/ASTR3007_tools`

1. **(10 points)** Generate an evolutionary model of the Sun that terminates after the TP-AGB phase but before collapse into a white dwarf. Use a mixing length of $\alpha_{\rm MLT} = 2.0$ and a convective overshoot parameter $f_{ovs} = 0.1$. **You must make sensible, scientifically valid choices for the remaining parameters yourself.** Review Lecture 12 (stellar polytropes and MESA) for guidance on the appropriate values for unspecified parameters.

   (4 points) Submit a plot of the Luminosity-$T_{\rm eff}$ diagram for your track, in the style of Figure 1, noting the critical evolutionary stages.

   (a) **(1 point)** Which stopping condition did you select, and why?

   (b) **(1 point)** Which nuclear reaction network did you select, and why?

   (c) **(1 point)** Which metallicity did you select, and why?

   (d) **(3 points)** Generate an identical evolutionary track, except using $\alpha_{\rm MLT} = 1.0$. Describe the differences between this model and the one with $\alpha_{\rm MLT} = 2.0$ from above.

2. **(20 points)** Using MESA-web, generate evolutionary tracks for the following stars or combinations of stars. Use $\alpha_{\rm MLT} = 1.8$, $f_{ovs} = 0.1$, and `agb.net` unless otherwise specified.

   (a) **(5 points)** $1.0M_\odot$ star with $Z = 0.004$, $Z = 0.02$, and $Z = 0.04$ (3 tracks)

      i. **(1 point)** Plot these tracks on the same graph. See Figure 2 for an example.

      ii. **(2 points)** Either by inspecting the data manually or using the interactive plotting tool on Github, measure the duration of the main sequence (TAMS-ZAMS) for each model.

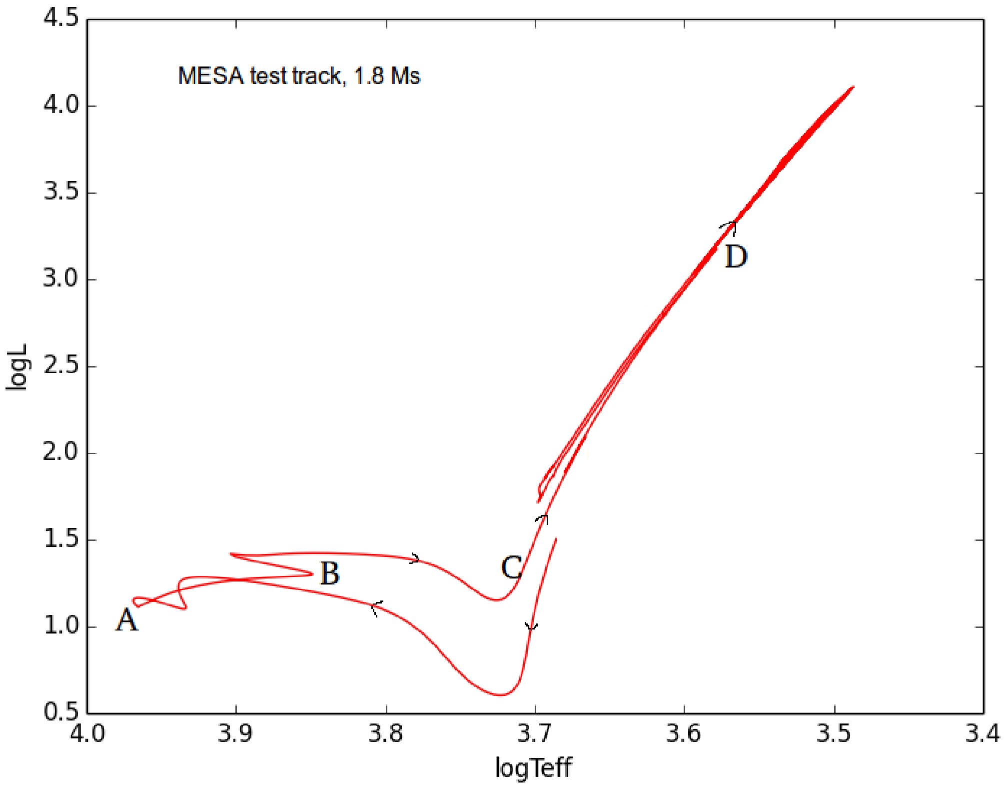

Figure 1: Evolutionary tracks can be generated from "history.data" files.

iii. **(2 points)** Using your understanding the mean molecular weight μ and the role it plays in the stellar structure equations, explain how and why the duration of the main sequence changes when Z is modified. Note that $\mu \propto Z$.

(b) **(10 points)** Stars with masses $0.5M_{\odot}$, $1.0M_{\odot}$, $1.4M_{\odot}$, $2.0M_{\odot}$, $6.0M_{\odot}$, $6.5M_{\odot}$, $8.0M_{\odot}$, $10.0M_{\odot}$, and $15.0M_{\odot}$, all with $Z = 0.02$ (9 tracks). Select appropriate stopping conditions such that all of these stars evolve until they have gone through their last nuclear burning stages. End ages are acceptable stopping conditions, but note that this will vary by mass.

i. **(1 point)** Plot these tracks on the same graph.

ii. **(2 points)** State the stopping condition you used for each model and measure the duration of the main sequence for each track.

iii. **(3 points)** Identify which, if any, of these models undergo (1) thermal pulses; (2) the CNO cycle; (3) Carbon burning; (4) Oxygen burning. **Hint:** the `history.data` file contains columns such as `mass_He_core`, which provides the mass of Helium in the core over time in units of solar masses.

iv. **(4 points)** Is there greater difference in the evolutionary trajectories of a
(1) $1.0M_{\odot}$ star vs $1.4M_{\odot}$ star,
(2) $1.4M_{\odot}$ star vs $2.0M_{\odot}$ star,
(3) $6.0M_{\odot}$ star vs $6.5M_{\odot}$ star, or
(4) $10.0M_{\odot}$ star vs $15.0M_{\odot}$ star?
Explain.
"Differences" can include qualitative differences between the tracks, timescales of certain evolutionary phases, the occurrence or not of certain evolutionary phases, etc.

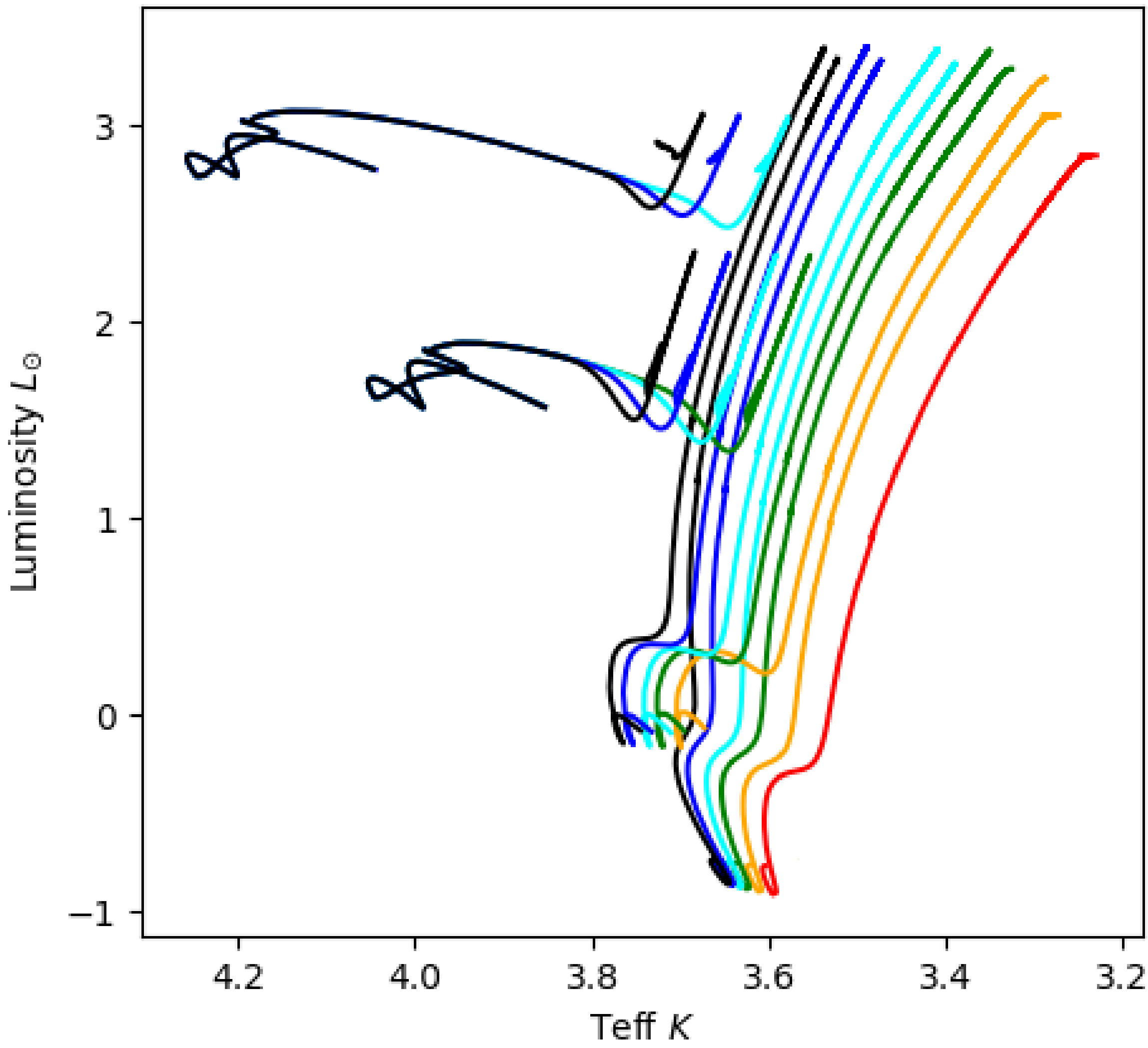

Figure 2: Multiple tracks with different parameters on the same plot. **NOTE:** Astronomical convention is reverse the effective temperature axis.

(c) **(5 points)** For a star with mass $25M_{\odot}$ and $Z = 0.02$, generate one evolutionary track using `basic.net` and one using `mesa_49.net` (2 tracks). Use the stopping condition `iron core collapse`.

i. **(1 points)** Plot these tracks on the same graph and describe any differences you see between the tracks.

ii. **(2 points)** Which nuclear burning chains should be active in a $25M_{\odot}$ star, and for what proportion of its life?
Hint: we discussed the reaction chains and timescales of a $20M_{\odot}$ star in class.

iii. **(2 points)** Based on your understanding of nuclear burning in massive stars, which stages of the model's evolution should be most impacted by using the nuclear reaction network with heavier elements, `mesa_49.net`? Do you see evidence of this in your models?

3. **(10 points)** I have computed MESA `profile` data for a solar model at the ZAMS, TP-AGB, and RGB (specifically, a luminosity-inversion feature known as the "red giant branch bump," or RGBB). The `.profile` files are text files similar to `history.data` and can be manipulated using a text editor in the same way. The files are located at
`https://github.com/mjoyceGR/ASTR3007_tools/tree/master/profile_files`

Using these structural data, answer the following questions:

(a) **(2 points)** For the ZAMS model, plot the density versus mass coordinate $m/M_\odot$ and density versus radial coordinate $r/R_\odot$. These are both called "density profiles." You may use either convention when answering subsequent questions.

(b) **(3 points)** Plot the density profiles as a function of the same coordinate for all three phases and discuss their differences. In particular, what happens to the outer 30% of the star as it evolves through later evolutionary stages?

(c) **(5 points)** Select some non-zero internal radial value very close to the core (ex. $r_{\text{specific}} = r_s = 0.005R_\odot$). Report the following for each model, using r_s as your coordinate for the core:

   i. surface temperature T_{eff} and core temperature $T(r_s)$

   ii. surface pressure and central pressure, $P(r_s)$

   iii. the volume of the associated sphere, $V = \frac{4}{3}\pi r_s^3$

   Assuming the temperature and radius you recorded, $T(r_s)$ and r_s, recompute the pressure under the assumption of an ideal gas law. How close is this value to $P(r_s)$ estimated directly from the models in part (ii)? What does this tell you about the validity of the ideal gas law as an approximation during the ZAMS, RGBB, and TP-AGB?