SSE lab course notes

Abel Schootemeijer, Andrea Ercolino (TA)

Sommersemester 2025

How to start a stellar evolution calculation with MESA

In this lab course, you learn how use MESA starting from scratch, assuming that MESA is already installed. You can remotely access a CIP-pool computer on which you can you run MESA (version 10000) via:
`https://guacamole-students.astro.uni-bonn.de/#/`
!IMPORTANT! Log out when ready so your colleagues can use the computer.

Things you need to do only once:

- Copy the following lines (the correct path to the MESA folder etc.) into your `~/.bashrc` file (which can be opened with e.g. `gedit ~/.bashrc`):
  ```
  export MESA_DIR=/vol/software/software/tools/MESA/MESA
  export OMP_NUM_THREADS=3
  export MESASDK_ROOT=/vol/software/software/tools/MESA/MESA/mesasdk
  source $MESASDK_ROOT/bin/mesasdk_init.sh
  ```
- The first time after that, you need to enter
  `source ~/.bashrc`
  (afterwards, this is done automatically when you open a terminal)
- Create a working directory for the SSE lab, e.g.
  `mkdir ~/Desktop/sse_lab`

Things to do for each new MESA calculation:

- Go to your SSE lab folder
  `cd ~/Desktop/sse_lab`
  and make a copy of the MESA work folder there.
  `cp -R $MESA_DIR/star/work 10Msol`
  (↑ if, for example, you want to run a $10\,M_\odot$ star)
- Go to directory you just copied with e.g. `cd 10Msol` and enter `./mk`
- Set the desired settings in `inlist_project` (or other inlists)
- Start with `./rn`

Instructions for your report

Writing the report

In your report, answer the questions in the exercises. These questions are indicated by '**Q1.1:**' etc. While answering the questions, try to be concise and to the point. No extra points are awarded for information that does not address the question.

Send your report to both aschoot@astro.uni-bonn.de and aercolino@astro.uni-bonn.de. In the email title, mention 'SSE lab report'. The deadline is on Saturday 21.06.2025 at 23:59.

We remind you that plagiarism (*"the practice of taking someone else's work or ideas and passing them off as one's own"*, as defined by the Oxford Dictionary) is absolutely not tolerated. This means that you are allowed to work together, but for the report you have to make your own plots and write your own text.

Accessing data on CIP-pool machines

The data from your MESA run will be stored on CIP-pool machines. Then, there are a few ways to work with your data:

- Click on the internet icon when using a CIP-pool machine and upload the `history.data` and `profile<nr>.data` to your Google Drive, Dropbox, or a similar service.
- When physically present in the CIP-pool room, use a USB-stick.
- Access and work with the data whilst logged in at a computer in the CIP-pool.

Of the above, we recommend the first option because i) it allows for more CIP-pool machines to be available ii) you do not require the CIP-pool room to be open (by default, it is closed).

Making plots

You may use this very basic python script as a starting point for plotting your data, but you can also use any other plotting software. When making plots, please include axis labels and units. To start the script, you can run it by entering e.g. `python plotter.py` in the terminal after you have saved the script.

```
import matplotlib.pyplot as plt
import numpy as np

path = "<path_to_LOGS_folder>"
d = np.genfromtxt("%s/history.data"%path, skip_header=5, names=True, dtype=None)
print( d.dtype.names )
plt.plot(d["star_age"], d["log_L"])
#logL_short = d["log_L"][3:]  # example:  array where first 3 entries are excluded
plt.show()
```

Running MESA on your own laptop

You are more than welcome to install MESA on your own laptop. You can find out how to do this on the MESA website: `https://docs.mesastar.org/en/release-r22.05.1/`. However, when you do so, please keep the following in mind:

- MESA runs on Linux or Mac.
- The lab is designed for MESA version 10000, so we would expect you to run the same version (you can find this at 'installation ... older MESA releases' on the MESA website).
- We are not able to help with possible issues that occur while installing MESA on your own laptop.

Basic Linux commands

`cd <dir>`	change directory to ⟨dir⟩
`cd ..`	go back one directory
`mkdir` ⟨dir⟩	make directory ⟨dir⟩
`rm <file>`	remove ⟨file⟩
`cp <file1> <file2>`	copy ⟨file1⟩ to ⟨file2⟩
`mv <file1> <file2>`	move ⟨file1⟩ to ⟨file2⟩
`ls`	list files in directory

Note: add `-R` ('recursive') if you want to copy or remove a directory, e.g.:
`cp -R $MESA_DIR/star/work 10Msol`

Notes on some columns in profile_column.list

- `grada` Adiabatic temperature gradient $\nabla_{\rm ad} = (d\ln T/d\ln P)_{\rm ad}$
- `gradr` Radiative temperature gradient $\nabla_{\rm rad} = (d\ln T/d\ln P)_{\rm rad} \propto \frac{\kappa l P}{mT^4}$
- `q` Relative mass coordinate. For stars of all masses, it has a value of 0 in the center and 1 at the surface.

General tips

- You can open a text file with e.g. `gedit <text_file>` or `vim <text_file>`[1]
- Underscores, apostrophes, etc. might not be copied correctly from this pdf file (also depending on your pdf reader). If you get an error message, try to type your line instead of copying it.
- To look up definitions and units of variables, consult the profile_columns.list and history_columns.list files in the folder $MESA_DIR/star/defaults
- To find out which regions in the stellar models are convective, you can use either profiles or the variables `conv_mx1_top` and `conv_mx1_bot` in the history file.

[1] Exit vim by entering `:q` also, `:set nowrap` can help to read history/profile files

Exercise 1 — Model resolution and time scales

- Run a simulation of the evolution of a $1\,M_\odot$ star, starting at the the pre-main-sequence. To get started with the simulation, see 'How to start a run'.
- Change the initial mass to $1\,M_\odot$ in the `inlist_project` file.
- In &controls, also set:
  `stop_near_zams` to `.false.`
  `he_core_mass_limit` to `0.1`
  `history_interval` to `1`
  and comment out the `xa_central_lower_limit` controls with a `!`
  (You can refer to `MESA docs webpage` for extra information about these controls.)
- Start your simulation

Q1.1: Why is there only one history file but multiple profile files?

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.

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).

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

Q:1.5 *(For this question, you will need to calculate the following timescales from the information contained in the history file: dynamical timescale, thermal timescale, and nuclear timescale. You can find in the SSE lecture notes how these can be defined)*
During the evolution of the stellar model, on what timescales does the contraction/expansion take place? 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 mention in your answer how you defined them. Explain why the model follows certain timescales at different periods in the simulation.

Exercise 2 — High-mass stars and low-mass stars

- Draw a stellar mass between $8\,M_\odot$ and $45\,M_\odot$ that is random in log space. Round to the third digit after the decimal point (e.g., $21.918\,M_\odot$). To do so, in your terminal enter
  `(...)$ python`
  `» import numpy`
  `» print( 10**numpy.random.uniform(0.9,1.65) )`
  (you can use `quit()` to exit the python environment)

- As in Exercise 1, create a new work folder. Specify in `&controls` in `inlist_project`: the drawn mass; `profile_interval = 1000`; and, using the `stop_near_zams` and `xa_central_lower_limit` controls, make sure that you simulate until a central hydrogen abundance of $X_c = 0.01$

- We desire to add some variables to the profile files. While in your work folder, enter in the terminal:
  `(...)$ cp $MESA_DIR/star/defaults/profile_columns.list .`
  (do not forget to enter the dot as well – it means 'this folder')
  and in the file you copied, uncomment: `q, grada, gradr, opacity, luminosity`
  (some of these variables are explained at the beginning of this syllabus)

- Then start the run. When it is finished, take care that you remember which profile was the final one saved (you could rename it to make your life easier).

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. Enter the relative mass coordinates of the region that is convective at TAMS in your report and in the Google Sheets (← click to enter).
(!) Be sure to enter the values with decimal points and **not** commas, because that would wreck the csv (comma-separated values) file.

Q2.2: From the Google Sheets, show in an initial mass (x-axis) vs. q (y-axis) plot which parts of the stars simulated by you and your colleagues are convective at TAMS. Briefly explain i) the behavior as a function of mass, and, ii) discuss the main difference to the shaded region in fig. 8.8 of the SSE lecture notes and where this difference arises from.

- Change `inlist_project` such that MESA will run until a central helium (`he4`) mass fraction of 0.01 remains. Then restart your high-mass star run. If your final model number was e.g. 1076, this can be done by: `./re x076`

- With python, again draw a mass that is random in log space, this time between $0.6\,M_\odot$ ($\log(M\,/\,M_\odot) = -0.2$) and $2\,M_\odot$ ($\log(M\,/\,M_\odot) = 0.3$). Make a new work folder, and perform this simulation until the central ^{4}He mass fraction is 0.01, while not saving any saving profiles: add `write_profiles_flag = .false.` to `&controls` in `inlist_project`

Q2.3: Create an HR diagram that shows both stars that you simulated in this exercise. Show the points where they exhaust hydrogen in their cores. After H-exhaustion, is the change in $\log(L/L_\odot)$ the same in both stars? Why (not)?

Q2.4: Draw the tracks of your evolutionary models computed in this exercise in a $\log T_c$ – $\log \rho_c$ diagram, and identify the key differences between the two. Draw the dashed lines of fig. 3.4 in the SSE lecture notes in your plot, and explain how you drew them.

Exercise 3 — Convective overshooting

- With the `numpy.random.uniform()` function, draw a random overshooting value between 0.1 and 0.3.
- Make a new work folder. With `inlist_project`, take care of the following: initial mass of $15\,M_\odot$; a profile is saved every 100 models; you simulate until a central ^{4}He mass fraction of 0.01 remains; you use the default criterion for convection. See the MESA docs webpage for information about overwriting the MESA default settings.

Q3.1: Does MESA use the Schwarzschild or Ledoux criterion for convection by default?

- Add these two lines to `&controls` in `inlist_project`:
  `step_overshoot_f_above_burn_h_core = <drawn_value>`
  `overshoot_f0_above_burn_h_core = 0.01`
  (this will make sure that convective overshooting is included in the simulation during the main sequence) and start the simulation.

Q3.2: How many millions of years (Myr) do H and He core burning last? Also enter your answer in the Google Sheets

Q3.3: Collect the data from the Google Sheets and show graphically how overshooting affects the core hydrogen and the core helium burning lifetimes. Explain why.

- Now make a new work folder where you do the same simulation as before, but you use the other criterion for convection.

Q3.4 For the first profile before hydrogen is exhausted in the core (which happens when, say, $X_c < 10^{-6}$) and for the first profile after that, plot the H and He abundances as a function of mass coordinate. Do this for both the Ledoux and the Schwarzschild simulation. For which simulation did the abundance profile change more dramatically, and why?

Exercise 4 — Nuclear networks

- Make a copy of $MESA_DIR/star/work again and for this simulation adopt the same mass as for the low-mass star model you computed in Exercise 2. Make sure it will run until a few per cent of hydrogen in the center have been burnt. Also make sure you save information about `grada` and `gradr`. Reminder: you can rerun the simulation later with a different profile interval if this helps you answer a question better.
- Change the nuclear network in the `&controls` part of `inlist_project`:
  `default_net_name = "pp_extras.net"`

Q4.1: What extra isotopes are included in this network? Look for clues in the folder `$MESA_DIR/data/net_data/nets`

- copy a file that sets the initial abundances to the folder you just made:
  `cp /vol/software/software/tools/MESA/SSE_LAB/extras/xa_extended.data .`
  In this file, 0.001% of the stellar mass – that used to be ^{24}Mg – has been converted to ^{2}H. Then in the `&star_job` section of the `inlist_project` file, add the lines:
  `file_for_uniform_xa = "xa_extended.data"`
  `set_uniform_xa_from_file = .true.`
  (this tells MESA to adopt the initial abundances specified in the file you copied here)
- Now we will use MESA's `pgplot` to plot chemical abundance profiles. Enter in `inlist_pgstar`:
  `Abundance_win_flag = .true.`
  `Abundance_which_isos_to_show(7) = "h2"`
  `Abundance_file_interval = 5`
  `Abundance_file_flag = .true.`
  (this way an abundance plot gets saved in the `png` folder every five models)
- Start the run.

Q4.2: Compare the pre-MS (i.e., before ^{4}He is synthesized from hydrogen) radius evolution of this simulation with that of the low-mass star in Exercise 2. Is there any difference? If so, provide a plot that shows the different behavior, and explain what caused it.

Q4.3: ^{2}H undergoes nuclear burning around 10^6 K. Once ^{2}H burning starts, graphically show if the ^{2}H abundance decreases everywhere in the star at roughly the same time, or only locally. Explain why this happens.

Q4.4: Use python to draw an integrer k from the list [2,3,5,7] using the line:
`numpy.random.choice([2,3,5,7])`
What value did you draw for k?
Now assume we live in a different universe, where ^{2}H burns at $k \cdot 10^6$ K instead of 10^6 K. In that case, would you expect ^{2}H to be absent in every layer of the star once it is exhausted in the center of the star? Use a plot to motivate your answer.

Grading

Q1 counts for 30 points in total; Q2 and 3 for 25 points in total; Q4 for 20 points in total.

Q1.1	2
Q1.2	4
Q1.3	6
Q1.4	4
Q1.5	14
Q2.1	4
Q2.2	8
Q2.3	6
Q2.4	7
Q3.1	1
Q3.2	4
Q3.3	10
Q3.4	10
Q4.1	2
Q4.2	6
Q4.3	6
Q4.4	6
Total:	**100**