Stellar Structure and Evolution 2017
Computer Lab

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1 Introduction

The goal of this assignment is to study the evolution of a $2\,M_\odot$ star of solar composition from pre-main sequence to white dwarf. This study will be performed via a numerical simulation using the module MESA Star of the code MESA [1].

MESA is a suite of libraries for a wide range of applications in computational stellar astrophysics. It contains a 1D stellar evolution module, MESA Star, which combines many of the numerical and physical modules for simulations of a wide range of stellar evolution scenarios ranging from very low-mass stars to massive stars, including advanced evolutionary phases. MESA Star solves the fully coupled structure and composition equations simultaneously. More information on MESA and MESA Star can be found at http://mesa.sourceforge.net/.

2 Setting up MESA Star

In order to avoid the time-consuming installation of MESA on an individual basis, you will make use of a single source code directory. The location of the code is indicated by setting the environment variables `MESASDK_ROOT` and `MESA_DIR`. To set these variables, open the file `~/.cshrc`

```
gedit ~/.cshrc &
```

Then, add at the end the lines

```
setenv MESASDK_ROOT /disks/web1/users/nielsen/mesasdk
setenv MESA_DIR /disks/web1/users/nielsen/mesa-r7624
```

and save the file. Finally, update the environment variables.

```
source ~/.cshrc
```

You should now be able to use MESA. The `$MESA_DIR/star/work` folder contains an example to check that the Mesa Star module runs. Create a working directory and make a copy of this folder. The working directory must be located in one of the data disks on your office computer, such as `/net/computer_name/data1`, or on a public data disk in `/disks`. It should not be created in `/home/username`[2].

[1] MESA stands for Modules for Experiments in Stellar Astrophysics.

[2] I suggest you ssh into you home account: `ssh -X -Y NAME@COMPUTERNAME.strw.leidenuniv.nl`

```
mkdir /your_location/your_working_directory
cd /your_location/your_working_directory/
cp -rf $MESA_DIR/star/work .
```

Then, enter the `work` directory and compile the code.

```
cd work
source $MESASDK_ROOT/bin/mesasdk_init.csh
./mk
```

To recompile the code, you need to repeat the last two lines. Finally, run the code.

```
./rn
```

It should run for a few minutes while displaying various pieces of information on the evolution of the star. If this is the case, you can move on to the next section.

3 Running MESA Star

Now that Mesa Star is set up, you will run the simulation corresponding to the assignment which consists in studying the evolution of a $2\,M_\odot$ star of solar composition from pre-main sequence to white dwarf. The `$MESA_DIR/star/2M_prems_to_wd` folder contains the information required for the run. Make a copy of this directory into your working directory.

```
cd /your_location/your_working_directory/
cp -rf $MESA_DIR/star/2M_prems_to_wd .
```

Enter the `2M_prems_to_wd` directory, compile and run the code.

```
cd 2M_prems_to_wd
source $MESASDK_ROOT/bin/mesasdk_init.csh
./mk
./rn
```

It should run for a about an hour. In the meantime, you can start analysing the output files created during the simulation.

The output files that you need to complete the assignment are in the `LOGS` folder[3]. They consist of a collection of files `profile#.data`. Each of these files contains information on the star at a given time. They all have the following structure:

```
column numbers for the global properties of the star
column names for the global properties of the star
current values of the global properties of the star
blank line
column numbers for the zone properties of the star
column names for the zone properties of the star
current values of the zone properties of the star (1 line per zone)
```

The zones are ordered from the surface to the core, zone 1 corresponding to the surface and the last zone corresponding to the core. The global properties of interest for the

[3]The whole content of the `LOGS` folder is overwritten when a new simulation is launched. Therefore, the codes written for the analysis of the output files should not be put in this folder.

assignment are:

- `star_age` - age of the star in yr,
- `num_zones` - number of zones,
- `Teff` - effective temperature in K,
- `photosphere_L` - luminosity at the photosphere in $L_\odot$.

The zone properties of interest for the assignment are:

- `zone` - zone number,
- `logT` - $\log \mathrm{T}$ where T is the temperature in the zone in K,
- `logRho` - $\log \rho$ where ρ is the density in the zone in $\mathrm{g\,cm^{-3}}$,
- `logR` - $\log \mathrm{R}$ where R is the radius of the zone in $R_\odot$,
- `grada` - adiabatic gradient Δ_{ad},
- `gradr` - radiative gradient Δ_{rad}.

The instructions provided to Mesa Star to run the simulation are contained in the file `inlist_2M_prems_to_wd`. This file contains numerous parameters which can be varied. However you should only modify those concerning the output files. These parameters, located under the line `&controls`, are the following:

- `profile_interval` - frequency in terms of timesteps at which `profile#.data` files are written. Mesa Star computes the structure of the star at each timestep and these timesteps can be very short. Therefore, creating a `profile#.data` file at each timestep is unnecessary and consumes a lot of disk space. The frequency in terms of timesteps at which `profile#.data` files are written is set by the parameter `profile_interval`. It is set to 50 by default which means that a `profile#.data` file is written every 50 timesteps. You need to adjust this value depending on how many points you want in your plots and what is sensible in terms of disk space. Note that the timesteps vary during the simulation. Therefore, even though the `profile#.data` files are written at even intervals in terms of timesteps, they are not necessarily written at even intervals in time. Furthermore, during important events of the evolution, `profile#.data` files can be written more frequently than specified by `profile_interval`.
- `max_num_profile_models` - maximum number of `profile#.data` files that can be written. It is set by default to 150. This value should be increased if more than 150 `profile#.data` files are created during the simulation. Otherwise, when `profile150.data` is reached, the previous files will be overwritten starting from `profile1.data`.

4 The Assignment

The assignment for this computer lab is composed of running the above simulation, making four plots using the output files and writing an essay. The plots and the essay can be produced with any program you want.

You need to create four plots to analyse the evolution of a $2\,M_\odot$ star of solar composition from pre-main sequence to white dwarf. The plots and the instructions to produce them are the following:

1. **Evolution of the core in the $\log \mathrm{T_c} - \log \rho_\mathrm{c}$ plane**

   (a) Using the output files created during the simulation, plot the evolution of the core in the $\log \mathrm{T_c} - \log \rho_\mathrm{c}$ plane where T_c and ρ_c are the temperature and density of the core respectively. Use $\log \mathrm{T_c}$ as the horizontal axis and $\log \rho_\mathrm{c}$ as the vertical axis.

   (b) Label the evolutionary stages.

   (c) Indicate the age of the star either by explicitly labeling some points or by including a color bar.

   (d) Indicate the regions of the $\log \mathrm{T_c} - \log \rho_\mathrm{c}$ plane corresponding to the four different equations of states. Derive the equations delimiting these different zones.

   (e) Add the theoretical evolutionary track of a $2\,M_\odot$ star in the $\log \mathrm{T_c} - \log \rho_\mathrm{c}$ plane.

   (f) Mark the current position of the solar core.

2. **Hertzsprung-Russell diagram**

   (a) Using the output files created during the simulation, plot the evolution of the star in the Hertzsprung-Russell diagram, that is in the $\log \mathrm{T_{eff}} - \log \mathrm{L}$ plane where T_eff is the effective temperature and L the luminosity of the star.

   (b) Label the evolutionary stages.

   (c) Indicate the age of the star either by explicitly labeling some points or by including a color bar.

3. **Convection in the pre-main sequence phase**

   (a) Plot the adiabatic and radiative gradients Δ_ad and Δ_rad as a function of radius when the star is in the pre-main sequence phase. You only need to make use of a single `profile#.data` file. However, this file has to correspond to the pre-main sequence phase.

   (b) Label the regions where convection occurs.

4. **Convection in the main sequence phase**

(a) Plot the adiabatic and radiative gradients $\Delta_{\rm ad}$ and $\Delta_{\rm rad}$ as a function of radius when the star is in the main sequence phase. You only need to make use of a single `profile#.data` file. However, this file has to correspond to the main sequence phase.

(b) Label the regions where convection occurs.

Finally, you need to write an essay about the evolution of the star. The essay must be written according to the following structure:

1. **Introduction**
2. **Methods**

   This section must only contain one paragraph. A precise description of the code is not required.
3. **Results**

   In this section, you must present the four plots and describe them without interpretation.
4. **Discussion**

   This section is the most important. It must contain one subsection for each evolutionary stage of the star. In each subsection, you must explain physically and in detail the evolution of the star based on the four plots.
5. **Conclusion**

The lectures and the reading materials must be enough for you to complete this assignment successfully. However, you can use other sources if you want. If you do, cite these sources in an appropriate manner. The essay should not exceed 5 pages of A4 size, including figures. The figures should not be larger than half of an A4 and the 5 pages are to be counted in Times New Roman font of size 12. Please do indicate your student number(s) on the assignment.

5 Important Information

The **deadline** to hand in the essay is **April 17, 2017 at 10:00 AM**. Send your essay by email in PDF format to nielsen@strw.leidenuniv.nl, quiroganunez@strw.leidenuniv.nl and emr@strw.leidenuniv.nl.

The essay will be graded. The grades will be given on April 21, 2017. A pass is required in order for the written exam to be graded. If not passed at the first go, the report can be improved until **May 8, 2017 at 10:00 AM**. Improved reports will graded again, and the grade will be given on May 12, 2017.

The essay can be written in pairs. This is preferred but doing it on your own is also allowed.