MESA Summer School 2022: Session 1 Labs

Sunny Wong and Meridith Joyce

Abstract

This lab accompanies the first lecture of the 2022 MESA Summer School. Here, we introduce the MESA software and teach you how to navigate the code base. During this session, you will learn how to locate and change parameter settings, control output, and modify the source code via run\_star\_extras.

Google Drive link with repositories and solutions:

The following link hosts two folders: lecture1.zip, which contains a clean version of the working repository, and solutions.zip, which includes solutions to all pieces of this lab. Please consult this only if you get lost. While it is important that you do not fall behind, you will learn more if you issue the commands yourself.

https://drive.google.com/drive/folders/124eHggIEgsSvR\_vYl9uCUcXlbQyhpnJL?usp=sharing

1 Setting environment variables (microlab 0)

This section will cover:

• Environment variables

• What is .bashrc, and where is it?

To run MESA, you must set *environment variables* that point your system to the correct paths for dependent packages. These are $MESA\_DIR, $MESASDK\_ROOT, and $OMP\_NUM\_THREADS.

To avoid having to set your environment variables manually every time you run MESA, you can define these variables within the shell start-up file, which is executed whenever a user opens a new shell. The default for most Linux distributions is the bash environment, which is controlled by the .bashrc file. You can check which shell your system uses by running

echo $0

If this returns bash, then you will edit .bashrc. If this returns zsh (as on some Macs), you will edit .zshrc (substitute the appropriate file in subsequent instructions accordingly).

The .bashrc file is located at $HOME/.bashrc. Check that you can locate the .bashrc file by running ls -a $HOME

Here is an example from a machine that uses bash as its shell

# the location of your top - level MESA directory

export MESA\_DIR =/ home / mjoyce / MESA / mesa - r22 .05.1

# the location of the SDK

export MESASDK\_ROOT =/ home / mjoyce / MESA / mesasdk

source $MESASDK\_ROOT / bin / mesasdk\_init . sh

# the number of threads (= 2 x number of cores ) you choose to devote to MESA calculations export OMP\_NUM\_THREADS =8

Note that /home/mjoyce/MESA/ is a path on my (mjoyce’s) machine. Yours will be different. 1

2 Opening and modifying defaults files

This section will cover

• how to change control parameters

• the meanings of different inlist sections

• organizational structure of code base (e.g. noting that opacity defaults are located in a different place than controls.defaults and star\_job.defaults)

• controlling output (history vs profile)

• how to turn off/on pgstar

2.1 Compile and Run

Each time you want to start a MESA project, you should make a new copy of the star/work directory. cp -r $MESA\_DIR / star / work my\_new\_project

In this case, we have prepared and provided a work directory for you. Download, unpack, and enter this work directory.

unzip lecture1 . zip

cd lecture1

This directory evolves a 1*.*5 *M⊙* star from the main sequence to hydrogen exhaustion. To build your executeable (star or binary), which is the program that is built by the compiler and runs your simulation, issue the commands

./ clean

./ mk

Now you can run the code via

./ rn

Your run should stop at time step 271.

2.2 Minilab 1: Using inlists

Meanwhile, take a look at the inlists, which are Fortran namelists that contain value definitions for all of the parameters of your run. MESA/star currently has 5 inlist sections:

• star\_job - options for the program that evolves the star

• eos - options for the MESA eos module

• kap - options for the MESA opacities module, abbreviated kap

• controls - options for the MESA star module

• pgstar - options for on-screen plotting

The distinction between star\_job and controls can be a little subtle, and sometimes there are overlapping controls. In general, star\_job contains options that answer questions like:

• how should MESA obtain the initial model?

• are there any changes MESA should make to the initial model?

• which nuclear net and reactions should MESA use?

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whereas controls contains options that answer questions like:

• what conditions should cause MESA to stop evolving the model?

• which angular momentum transport processes should MESA consider?

• what numerical tolerances should MESA’s solvers use?

The eos and kap contain options for the equation of state and opacity modules, respectively, and answer questions like:

• which equation of state (EOS) components should be used and where (in terms of state variables) should they be blended?

• what composition should be assumed when calculating the opacity?

MESA’s many inlist options have their default values set in \*.defaults files. These files also provide documentation on the options, including possible values and references to the source material.

For a specific module, this file (or files) is located in <module>/defaults/. You can directly read these defaults files as plain text. Alternatively, they are rendered as part of the online documentation.

The individual module defaults appear under Module Documentation

• $MESA\_DIR/eos/defaults/eos.defaults

• $MESA\_DIR/kap/defaults/kap.defaults

while the star (and also binary and astero) defaults appear under Reference

• $MESA\_DIR/star/defaults/star\_job.defaults

• $MESA\_DIR/star/defaults/controls.defaults

• $MESA\_DIR/star/defaults/pgstar.defaults

They are roughly sorted into groups of related options. When you’re searching for an option, see if it seems to match any of the section headings and then look there first. If that fails, try searching for some key words.

Note that inlists can point to other inlists. This can be useful for keeping things organized. In the lecture1 directory, inlist points MESA to inlist\_project and inlist\_pgstar.

2.3 Controlling Output

By default, MESA stores output files in the LOGS/ directory. The two output file types are

• history.data, which contains *evolutionary information*. This stores the value of scalar quantities (e.g., mass, luminosity) at different timesteps, and

• profileX.data, which contains *structural information*. This gives you spatially varying quantities within the model at fixed time *t* (e.g. density, pressure, etc as a function of radius or *m/M⋆*).

You can adjust the frequency of these outputs in the inlists.

The contents of MESA’s output files are not directly controlled via inlists. The default output is set by the files

$MESA\_DIR / star / defaults / history\_columns . list

$MESA\_DIR / star / defaults / profile\_columns . list

In order to customize the output, you copy these files to your work directory.

cp $MESA\_DIR / star / defaults / history\_columns . list .

cp $MESA\_DIR / star / defaults / profile\_columns . list .

Then, open up history\_columns.list or profile\_columns.list in a text editor and comment/uncomment any lines to add/remove the columns of interest (’!’ is the comment character.)

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3 Minilab 2: compare two MESA output tracks

This section will cover

• renaming output files

• locating inlist parameter keys

• graphically comparing output between runs with different parameter assignments

Having run through a 1*.*5*M⊙* model with the default value of the mixing length parameter *α*MLT (take a look at controls.default to see what the default value is), now run another model with *α*MLT = 1*.*5. Make sure you do not overwrite the first output directory. Using your favorite plotting tool*⋆*, compare the two models on the HR diagram.

HINT 1: You can specify the directory in which MESA stores output files.

HINT 2: For each of the output directory and *α*MLT, is the option a star\_job or controls option?

*⋆*While we understand that each scientist has their preferred tools for data analysis, we are best equipped to help you with the MESA in-house plotting program pgplot or the Python tool py\_mesa\_reader, available on Github.

If you are having trouble with plotting, we provided a Fortran file hr.f that makes use of pgplot to generate a HR diagram. To use, first edit hr.f to provide it with the appropriate pathnames to your history files, then use the terminal command

make

to generate an executable hr, and finally run this executable

./ hr

Click here for solutions

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4 Maxilab 1: Modify stopping condition in run\_star\_extras This section will cover

• how to find, move, and compile the include file

• MESA flow-of-control

• data structures

• code organization

• how to write a custom stopping condition

Take a look at your run\_star\_extras.f90 file, located within the src directory. You can do this by opening the files in your text editor of choice or by using the terminal command:

cd ./ src

less -S ./ run\_star\_extras . f90

The stock version of run\_star\_extras.f90 is quite boring. It "includes" another file which holds the default set of routines.

include ' standard\_run\_star\_extras . inc '

which is located in the $MESA\_DIR/star/job/ directory.

The routines defined in the standard\_run\_star\_extras.inc file are the ones we will want to customize. Because we want these modifications to apply only to this working copy of MESA, and not to MESA as a whole, we want to replace this include statement with the contents of the included file.

4.1 Microtask: Replacing include statement

As we will do whenever we want to customize our run\_star\_extras.f90 file when starting from a fresh working directory, replace the include line, with the the contents of $MESA\_DIR/star/job/standard\_run\_star\_extras.inc.

Before we make any changes, we should check that the code compiles.

cd ../

./ mk

HINT 1: The command to insert the contents of a file in emacs is C-x i <filename>, in vim is :r <filename>, or you can just copy and paste.

HINT 2: If it doesn’t compile, double check that you cleanly inserted the file and removed the include line.

4.2 The star\_info structure and star\_data module

The star\_info data structure contains all the information about the star that is being evolved. By convention, the variable name s is used throughout run\_star\_extras.f90 to refer to this structure. In Fortran, the percent (%) operator is used to access the components of the structure. (So you can read s% x = 3 in the same way that you would read s.x = 3 in C or Python.)

The star\_info structure contains the stellar model itself (i.e., zoning information, thermodynamic profile, composition profile). The star\_data module contains the definition of the star\_info structure and more specifically, these components are listed in the file $MESA\_DIR/star\_data/public/star\_data.inc, which points to 3 other files:

include " star\_data\_step\_input . inc "

! input for taking a step

include " star\_data\_step\_work . inc "

! working storage for data derived from inputs while taking a step

include " star\_data\_procedures . inc "

! procedure pointers for hooks and such

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These "included" files are also located in $MESA\_DIR/star\_data/public/ . Most useful quantities about the stellar model are most likely in the step\_input or step\_work files; When in doubt, just search in that directory for your keyword, e.g.

cd $MESA\_DIR / star\_data / public

grep -i " Teff " \*

In addition, star\_info contains the values for the parameters that you set in your controls inlist (i.e., initial\_mass, xa\_central\_lower\_limit), although they are not contained in star\_data.inc and associated files.

4.3 User-specified inlist controls

There is one set of controls that will prove useful time and time again when using run\_star\_extras.f90, and these are x\_ctrl, x\_integer\_ctrl, and x\_logical\_ctrl. These are arrays (of length 100 by default) of double precision, integer, and boolean values, respectively. You can set the elements in your inlists

& controls

x\_ctrl (1) = 3.14

x\_ctrl (2) = 2.78

x\_integer\_ctrl (1) = 42

x\_logical\_ctrl (1) = . true .

/ ! end of controls inlist

and access them later on as part of the star structure (i.e., s% x\_ctrl(1), etc.). With these controls, you can specify parameters in your inlists instead of hard-coding them in run\_star\_extras.f90.

4.4 Physical constants (and const\_def.f90)

As we already saw, MESA defines its constants in MESA\_DIR/const/public/const\_def.f90. MESA uses cgs units unless otherwise specified. The most common non-cgs units are solar units. Since the run\_star\_extras module includes the line

use const\_def

you can access these definitions within run\_star\_extras. Using these built-in constants ensures that you are using exactly the same definitions as used throughout MESA.

4.5 Math functions

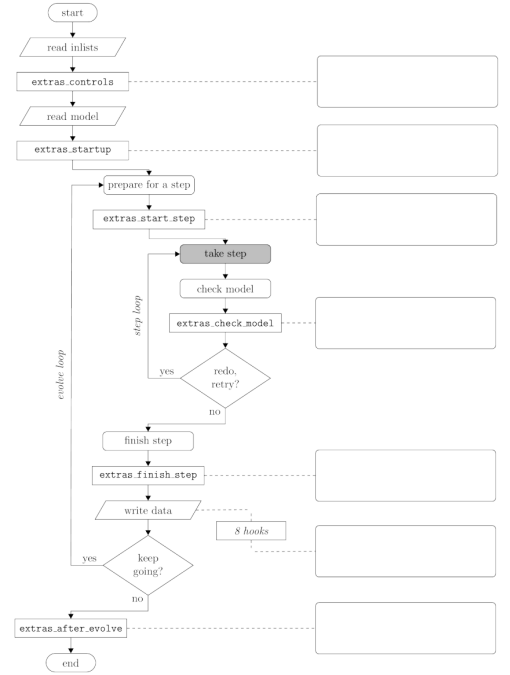
In run\_star\_extras.f90, you can readily access mathematical functions, such as safe\_log10 and sinh, found within $MESA\_DIR/math/public/math\_lib\_crmath.f90, thanks to the line

use math\_lib

4.6 Flow of control

MESA’s flow of control is described by Figure 1. Here you will note that subroutines in your updated run\_star\_extras.f90 file correspond to blocks in the flowchart: extras\_controls, extras\_startup, extras\_start\_step, extras\_check\_model, extras\_finish\_step and extras\_after\_evolve. When you wish to insert additional tasks into MESA’s exe cution, you will need to modify subroutines in the appropriate location. For example, an assignment made in side the extras\_start\_step subroutine will be executed *once per evolve loop*, whereas an assignment made inside extras\_check\_model will be made *once per solver iteration*. There can be many solver iterations per evolve loop, and one evolve loop corresponds to one time step.

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Figure 1: Flow of control for an evolutionary step in MESA.

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4.7 Task (example): Adding a stopping condition

Suppose we are trying to fit observations of a star, and we want to stop our calculation when the stellar model reaches a certain region of the HR diagram. Although stopping conditions such as Teff\_upper\_limit exist within controls.defaults, they do not bracket a region in the HR diagram. How can we do this?

First, look at how the routines in run\_star\_extras.f90 fit into a MESA run (Figure 1). To decide whether to stop, I want to check the effective temperature and luminosity of the stellar model after each evolutionary (e.g. time) step. Thus, I want the subroutine that is called after each time step, which is extras\_finish\_step.

Now, I need to figure out how to access information about the conditions at the stellar photosphere. I go to star\_data/public/ and start looking around. If I search for the word “photosphere,” I can find what I’m look ing for – photosphere\_L and Teff.

Looking through star\_data\_step\_work.inc shows that photosphere\_L is in units of Lsun, which is defined in $MESA\_DIR/const/public/const\_def.f90. Note the many other constants that are defined in const\_def.f90.

I want my stopping condition to be user-editable, so instead of hard-coding a value, I will specify x\_ctrl in my inlist, within the controls section,

! measured logTeff and uncertainty in logTeff

x\_ctrl (1) = 3.7 d0

x\_ctrl (2) = 0.01 d0

! measured logL and uncertainty in logL

x\_ctrl (3) = 0.85 d0

x\_ctrl (4) = 0.01 d0

and then access this value in my code. While we’re editing the inlist, comment out the H-depletion stopping condition, as this may conflict with our desired stopping condition. Also make sure to set *α*MLT back to its default value – otherwise our new stopping condition won’t work.

Now, edit the extras\_finish\_step function within run\_star\_extras.f90 so that the code understands the new x\_ctrl parameters we’ve introduced. We assign these in terms of star\_info, or s, attributes:

rl (1) - s % x\_ctrl (2)

logTeff\_hi = s % x\_ctrl (1) + s % x\_ctrl (2)

! upper and lower limits of logL

logL\_lo = s % x\_ctrl (3) - s % ! returns either keep\_going or terminate .

! note : cannot request retry ; extras\_check\_model can do that .

integer function extras\_finish\_step ( id )

integer , intent ( in ) :: id

integer :: ierr

type ( star\_info ) , pointer :: s

!

real ( dp ) :: logTeff\_lo , logTeff\_hi

real ( dp ) :: logL\_lo , logL\_hi

real ( dp ) :: logTeff , logL

!

ierr = 0

call star\_ptr ( id , s , ierr )

if ( ierr /= 0) return

extras\_finish\_step = keep\_going

! upper and lower limits of logTeff

logTeff\_lo = s % x\_ctx\_ctrl (4)

logL\_hi = s % x\_ctrl (3) + s % x\_ctrl (4)

! actual logTeff and logL of model

logTeff = safe\_log10 ( s % Teff )

logL = safe\_log10 ( s % photosphere\_L )

write (\* ,\*) 'logTeff and logL are ', logTeff , logL

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if (( logTeff <= logTeff\_hi ) . and . ( logTeff >= logTeff\_lo ) &

. and . ( logL <= logL\_hi ) . and . ( logL >= logL\_lo ) ) then

write (\* ,\*) 'The MESA model has reached the bracketed region '

extras\_finish\_step = terminate

end if

! to save a profile ,

! s % need\_to\_save\_profiles\_now = . true .

! to update the star log ,

! s % need\_to\_update\_history\_now = . true .

! see extras\_check\_model for information about custom termination codes ! by default , indicate where ( in the code ) MESA terminated

if ( extras\_finish\_step == terminate ) s % termination\_code = t\_extras\_finish\_step end function extras\_finish\_step

Now, recompile your working directory

./ mk

You will need to do this step each and every time you edit run\_star\_extras.f90! You will not need to do this when you edit only inlist files.

We can now start the model again from the beginning

./ rn

This run should halt around step 401.

Note that, though not necessary for this exercise, we could limit the time step via controls such as delta\_lgTeff\_limit and delta\_lgL\_limit, such that MESA doesn’t take steps that are too big for the bracketed region.

4.7.1 Compilation errors

Sometimes the compilation will fail with for example the following message:

Symbol 'logteff\_lo ' at (1) has no IMPLICIT type

In this case it is because I forget to declare the data type of the variable logTeff\_lo, i.e. the following line near the top of the function is missing:

real ( dp ) :: logTeff\_lo

Other common compilation errors are those indicating that MESA cannot locate makefile\_header or some other component of the code. 99% of the time, these occur because an environment variable has not been properly specified, or there is an error with file paths. To check, you can compare the output of the pwd command to the output of echo $MESA\_DIR.

5 Maxilab 2: Changing input physics

This section will cover:

• overriding MESA’s built-in routines

• replacing a static variable with an adaptive variable

MESA provides hooks to override or modify many of its built-in routines. These routines mostly affect things that occur within “take step” box of the flowchart (Figure 1), referred to as “other” routines. There are two main steps needed to take advantage of this functionality: (1) writing your own “other” routine; and (2) instructing MESA to use your routine instead of its own.

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First, navigate to $MESA\_DIR/star/other, where you will see a set of files named with the pattern other\_\*.f90. In general, find the one corresponding to the physics (or numerics) that you want to alter. Open one up and read through it. Many of the files contain comments and examples.

Note that we do not want to directly edit these files. Instead we want to copy the template routine into our copy of run\_star\_extras.f90 and then modify it there. The template routines are usually named either null\_other\_\* or default\_other\_\*.

In this example, we will focus on other\_alpha\_mlt.f90. Open up this file. Copy the subroutine default\_other\_alpha\_mlt and paste it into your run\_star\_extras.f90. It should be at the same “level” as the other subroutines in that file (that is, contained within the run\_star\_extras module.).

subroutine default\_other\_alpha\_mlt ( id , ierr )

integer , intent ( in ) :: id

integer , intent ( out ) :: ierr

type ( star\_info ) , pointer :: s

integer :: k

ierr = 0

call star\_ptr ( id , s , ierr )

if ( ierr /= 0) return

s % alpha\_mlt (:) = s % mixing\_length\_alpha

end subroutine default\_other\_alpha\_mlt

Note that this routine already does something; default\_other\_alpha\_mlt sets the mixing length parameter within the star uniformly to the mixing\_length\_alpha set in the controls section of the inlist. Rename the subroutine to lecture1\_other\_alpha\_mlt, and replace the line

s % alpha\_mlt (:) = s % mixing\_length\_alpha

with

do k = 1 , s % nz

s % alpha\_mlt ( k ) = s % mixing\_length\_alpha

end do

In Fortran, you can write expressions that operate on the whole array at once, e.g.

s% alpha\_mlt(:) = s% mixing\_length\_alpha.

However, it is often simplest to explicitly set the value of alpha\_mlt (or some other array) one value at a time, by using a loop.

While we’re looking code with a loop, it is a good time to mention that in MESA, the outermost zone is at k=1 and the innermost zone is at k=s% nz. Arrays may also have a size in excess of nz, but only elements 1 through nz are meaningful.

5.1 Task: changing the mixing length parameter

Use the other\_alpha\_mlt routine to change the mixing length parameter from a fixed, static value adopted at every layer of the model to the depth-dependent function:

*α*MLT =

*α*2 *− α*1 2

tanh

*Mr − M*0 ∆*M*

+

*α*2 + *α*1 2

(1)

where *Mr* is the enclosed mass, *M*0 = 1 *M⊙*, ∆*M* = 0*.*1 *M⊙*, *α*1 = 1*.*5, and *α*2 = 2.

The lower left panel in the pgstar plots displays the value of s% alpha\_mlt, so you should be able to easily check if it looks OK. *α*MLT should asymptotically approach 1.5 in the core and reach 2 at the surface.

You can receive valuable MESA bonus points if your routine allows for user-specified values of ∆*M* and *M*0, *α*1 and *α*2.

HINT 1: After you locate within star\_data the variable name for the enclosed mass, check its units. You may need to do a unit conversion (or not).

HINT 2: Read the top of other\_alpha\_mlt.f90. It contains instructions on how to activate other\_alpha\_mlt. Click here for solutions

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6 BONUS maxilab exercise: adding an extra profile column

Using what we have learned about modifying run\_star\_extras, add an additional profile\_columns output named alpha\_mlt.

HINT 1: identify the subroutine that controls profile output

HINT 2: note that you will have to change the number of extra profile columns—which is zero by default—as well as collecting the alpha\_mlt quantity. This will involve touching two subroutines: how\_many\_extra\_profile\_columns and data\_for\_extra\_profile\_columns.

For time step X of your choice, plot alpha\_mlt as a function of mass from the associated profileX.data. Click here for solutions

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7 Solutions

7.1 Minilab 2 Solutions

You can either simply rename the first directory to avoid over-writing it:

mv LOGS LOGS\_default

and/or add the following line in controls when running with the updated *α*MLT: log\_directory = 'LOGS\_1 .5 '

The tracks should look similar to Figure 2.

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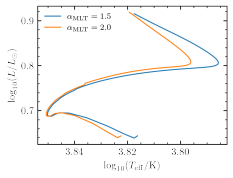


Figure 2: The difference between two 1*.*5*M⊙* stellar tracks with different values for *α*MLT. 12

7.2 Maxilab 2 Solutions

The following is our new other\_alpha\_mlt subroutine

subroutine lecture1\_other\_alpha\_mlt ( id , ierr )

integer , intent ( in ) :: id

integer , intent ( out ) :: ierr

type ( star\_info ) , pointer :: s

integer :: k

real ( dp ) :: delta\_M , M0

real ( dp ) :: c1 , c2 , a1 , a2

ierr = 0

call star\_ptr ( id , s , ierr )

if ( ierr /= 0) return

a1 = 1.5 d0

a2 = 2 d0

c1 = 0.5 d0 \*( a2 - a1 )

c2 = 0.5 d0 \*( a2 + a1 )

delta\_M = 0.1 d0

M0 = 1.0 d0

do k = 1 , s % nz

s % alpha\_mlt ( k ) = c1 \* tanh (( s % m ( k )/ Msun - M0 )/ delta\_M ) + c2 end do

end subroutine lecture1\_other\_alpha\_mlt

You will also need to add the line

s % other\_alpha\_mlt = > lecture1\_other\_alpha\_mlt

in the extras\_controls subroutine of your run\_star\_extras.f90, and set use\_other\_alpha\_mlt = . true .

in the controls section of your inlist.

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7.3 Bonus Solutions

Add the following lines to the data\_for\_extra\_profile\_columns subroutine:

names (1) = 'alpha\_mlt '

do k = 1 , nz

vals (k ,1) = s % alpha\_mlt ( k )

end do

Change the number of extra profile columns by setting

how\_many\_extra\_profile\_columns = 1

in how\_many\_extra\_profile\_columns.

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