MESA Summer School 2022

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Lab 1: Convective Boundaries on the MS

In this lab, we will explore different convective mixing prescriptions and how they impact convective boundaries and other stellar parameters on the MS for both a high (10 $M_\odot$) and a low (1.5 $M_\odot$) mass star.

Getting Started

We will be modifying the default `work` directory to practice building projects off of the existing default controls. The `work` directory is designed to build a model from the pre-MS, but to save time, we have done this for you. For future reference, you will see the controls used to create a model from the pre-MS.

1. Make sure your environment variables are set and the `MESA SDK` is initialized :)
2. At your table, choose two people to run the 10 $M_\odot$ scenario, and two people to run the 1.5 $M_\odot$ scenario. Download and unzip the `conv_boundaries_2022.zip` file from the summer school website.
3. Create a workspace for this lab and copy the `$MESA_DIR/star/work` directory into it. Also move (or copy) all the respective `XM_caseX_to_ZAMS.mod` files and `inlist_pgstar_XM_lab1` file for your mass from the `conv_boundaries_2022` folder you downloaded above to this work space.
4. Open the `inlist_project` file and comment out `create_pre_main_sequence_model = .true.` Under `&star_job`, add the lines:

```
load_saved_model = .true.
load_model_filename = 'your_mass_case0_to_ZAMS.mod'
set_initial_age = .true.
initial_age = 0
set_initial_model_number = .true.
initial_model_number = 0
```

   Under `&controls`, comment out (or delete) `initial_mass` and `initial_z`.
   (Note: If you were creating a model from the pre-MS, you would need to set these parameters for your model! The loaded mod file has already done this for you with `initial_z = 0.02`.)

NOTE: Sometimes copying and pasting from the overleaf doc can yield spacing issues in the MESA inlist files. Be sure that if you copy and paste the lines in this document, that you fix any added spaces in the controls that may occur!

Case 0: sign algorithm and Schwarzchild

This case uses the sign algorithm and Schwarzchild criterion. The inlists set up here will be built on or modified in following cases. We will use this case (Case 0) as our reference case, since MESA largely defaults to it. (Note: the loaded mod file used case 0 controls in the pre-MS to the MS to maintain consistency.)

Part A: inlist_project

Here we will set up a few initial parameters your models will need to continue running with the compatible chemical network, opacities and interpolation schemes, solver specifications, mixing length coefficient of 1.8, MLT option specification, and controls that will save your files to directories specific to this case. The photo, profile, history, etc. intervals listed help to not overwhelm your workspace with files, but can be adjusted as you wish.
Keep in mind: If you are unsure what an inlist control is doing, you can open the respective `$MESA_DIR/star/defaults/X.defaults` file, find the control, and read the documentation :)

1. Open `inlist_project` and under `&star_job`, add:

```
show_log_description_at_start = .false. !can change to true if wanted
initial_zfracs = 6
```

   Re-name the filename you want the model to save to, to something you'll recognize for this case and make sure the model is being saved when it terminates! (Hint: change the control that does this from `.false.` to `.true.`)

2. Scroll to `&kap` and make sure `Zbase = 0.02`. Add the following:

```
 use_Type2_opacities = .true.
kap_file_prefix = 'a09'
 kap_lowT_prefix = 'lowT_fa05_a09p'
 kap_CO_prefix = 'a09_co'
```

3. Under `&controls`, comment out or remove the `stop_near_zams` stopping condition and the above luminosity limit (already done and saved to the loaded mod file). Change the lower `h1` limit to `1d-4`. Finally, add:

```
energy_eqn_option = 'dedt'
varcontrol_target = 1d-3
mixing_length_alpha = 1.8d0
MLT_option = 'TDC'
log_directory = 'LOGS_case0' ! or 'LOGS_case0', your preference
photo_directory = 'photos_case0'
photo_interval = 100
profile_interval = 100
history_interval = 1
terminal_interval = 10
write_header_frequency = 10
num_cells_for_smooth_gradL_composition_term = 10
threshold_for_smooth_gradL_composition_term = 0.02
num_cells_for_smooth_brunt_B = 10
threshold_for_smooth_brunt_B = 0.1
```

   Save and close `inlist_project`.

SOMETHING TO CONSIDER:
As we edit `inlist_project` for each case, there are 2 options of some best practices I recommend:

1. You can do 'running updates' for each case such that the `inlist` file will always read in `inlist_project` for each case. (To see what I mean, open the `inlist` file to see the controls reading in `inlist_project`). Then copy the post-edited `inlist_project` file to another name (i.e. `inlist_project_caseX`) so you have each case's respective inlist controls saved and specified. This option eliminates the extra step to change the `inlist` 'extra' file name controls for each control section.

2. You can edit the `inlist` extra file names each time. This option can get tedious but helps you keep track of which case your code is currently set to run. Be sure you do update the `inlist` extra file names if you follow this option or your code won't run the case you think!

For this lab (and subsequent labs 2 and 3), we will go with option 1 and do running updates to help the work-flow go faster. Thus, copy `inlist_project` to `inlist_project_case0`. (To make a copy of `inlist_project` to `inlist_project_case0`, type:
`cp inlist_project inlist_project_case0`)

Part B: inlist_pgstar

Visualizing history and profile plots are useful to understand the impact that different convective boundary cases have. While one may use their own preferred plotting platform, we will be utilizing `MESA`'s `pgstar` capabilities (and plots generated from google sheets for crowd-sourcing). The `inlist_pgstar_XM_lab1` file from the `conv_boundaries_2022` folder has been pre-set up for a grid plot format with 5 panels, as shown in Figure 1.

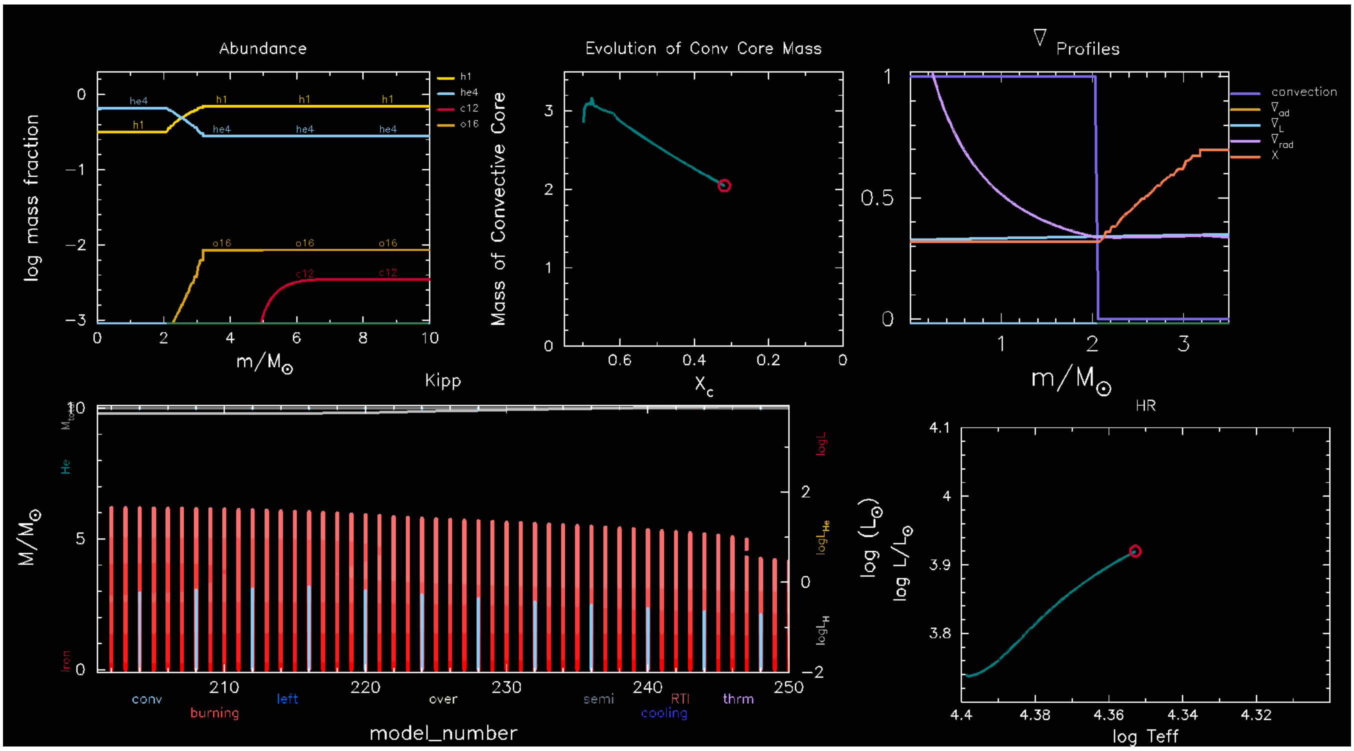

Figure 1: Case 0: Sign algorithm + Schwarzchild Criterion grid plot.

In order to run properly, you will need to add to the default `profile_columns.list` file, and the `history_columns.list` file. Copy these file to your work directory:

```
cp $MESA_DIR/star/defaults/profile_columns.list .
cp $MESA_DIR/star/defaults/history_columns.list .
```

We are interested in the Schwarzchild and Ledoux Criteria, which depend on the adiabatic temp gradient (∇_{ad}), the radiative gradient (∇_{rad}), and the gradient for the Ledoux criterion for convection (∇_L). These are termed as `grada, gradr, and gradL`, respectively, in `profile_columns.list`. Open `profile_columns.list` and change the file to include these terms (simply uncomment them). We also want to plot the `mixing_type` to determine where the convective boundary is,as well as `x` (Hydrogen mass fraction) so include (uncomment) those as well.
In `history_columns.list`, uncomment `mixing_regions` and `burning_regions`, and set the integer value to 20. This will allow you to visualize the mixing and convective regions in the kippenhaun diagram, as displayed in Figure 1.

Next, we need to make sure MESA reads the correct `pgstar` file to plot. There are two options:

Option 1: Open the `inlist` file and change the file name to your `inlist_pgstar_XM_lab1` file for `extra_pgstar_inlist1_name`, under the `&pgstar` section.

Option 2: Copy or move `inlist_pgstar_XM_lab1` to `inlist_pgstar` to over-write the original `inlist_pgstar` contents and avoid having to change the file name pointer.

Option 2 is probably preferred to maintain consistency for the subsequent labs.

Now that we've set up the `inlist_project` and `inlist_pgstar` files, we are ready to compile and run! (`./clean; ./mk; ./rn`). If all goes well, you should be able to see the grid plot evolving live with the run!

*Note: ∇_L (gradL) has been removed from the pgstar plot for easier readability so we can distinguish the more-important ∇_{ad} and ∇_{rad} terms.

Comparing and Analyzing Results

As we go through the lab, it will be useful to plot multiple cases in a single plot. This is difficult to implement in pgstar, but the information is all saved in the `history.data` and `profile.data` files for us to do externally. To disperse the work, we've assigned each table to be in charge of one case to upload these files to:

Table 1	Table 2	Table 3	Table 4	Table 5	Table 6	Table 7	Table 8
Case 0	Case 1	Case 2	Case 3	Case 0	Case 1	Case 2	Case 3

From your table, choose one person from each mass to upload their `LOGS_caseX/history.data` file and the **last** `LOGS_caseX/profile<last>.data` to the convective boundaries dropbox. **Please upload the files as:**

```
history_caseX_XM_TX.data
profile_caseX_XM_TX.data
```

Where X is the case number, mass size, and table number you were assigned. So for Case 0, Tables 1 and 5 need to upload their history files as `history_case0_1.5M_T1.data`,`history_case0_10M_T1.data`; `history_case0_1.5M_T5.data`, and `history_case0_10M_T5.data`.

While the results are being processed (may not be until end of the lab depending), you can start comparing the full evolutions of the cases you'll explore by compiling the png files into movies. Click here to learn how to do so easily!

BONUS TASK: Resolution study

Note: Should you do this exercise, you may want to either save your `LOGS, photos`, and `grid_png` directories, and the `save_model_filename` file to different names! (You'll be doing this as you explore other cases.) Otherwise you'll need to re-run at the default resolution to have the correct files for comparing to the subsequent cases at the same resolution.

The default mass and time resolution is rather terse, and doesn't refine the growth of the convective core as it should. Should you finish quickly, see what happens when you increase the mass and time resolution. There's a few ways to do this. To globally double the resolution, you could set (in the `&controls` section):

```
mesh_delta_coeff = 0.5
time_delta_coeff = 0.5
```

This says to decrease the spacing between cells by 50%, and decrease the time between each step by 50%, thus, doubling the resolution.

You could also try `mesh_delta_coeff = 0.2` and `time_delta_coeff = 1.0`, so see how important the mass resolution is by itself. Feel free to try other values, just keep in mind that increasing resolution increases run-time ;)

Case 1: Sign + Ledoux Criterion

Let's see what happens when we use the Ledoux Criterion. Open `$MESA_DIR/star/defaults/controls.defaults`, and search for "`Ledoux`". Read the documentation notes about using the Ledoux criterion. Next, open your `inlist_project` file and in the `&controls` section, add `use_Ledoux_criterion = .true.`

Before we re-run the model, remember we want to compare this result to the prior Schwarchild case (case 0). That said, be sure to change the directories your profiles, history, and png files are being saved to! Otherwise, you will overwrite the files from the previous case! You can name them anything you want, but as an example, edit your `inlist_project` by doing something like this:

```
&star_job
...
load_model_filename = 'your_mass_case1_to_ZAMS.mod'
save_model_filename = 'your_mass_endMS_case1.mod'
...
&controls
...
```

```
log_directory = 'LOGS_case1'
photo_directory = 'photos_case1'
...
```

You'll also want to edit your `inlist_pgstar_XM_lab1` file to save to the appropriate png directory. Scroll to the end of the file, and edit "`Grid1_file_Dir = grid_png_case0`" to something like "`grid_png_case1`".
As a **checklist** to refer to for the following cases, make sure to edit:

1. `load_model_filename (inlist_project`, under `&star_job`)
2. `save_model_filename (inlist_project`, under `&star_job`)
3. `log_directory` (`inlist_project` under `&controls`)
4. `photo_directory` (`inlist_project` under `&controls`
5. in `inlist_pgstar`, edit the `Grid1_file_dir` folder name

Once all your filenames and directories are corrected for this case, go ahead and run with the Ledoux criterion!
Remember: Copy the edited `inlist_project` to `inlist_project_case1` so you have a saved copy of this case's specifics and so you can refer to it later!

TIP: If using `vim`, simply type: `:%s/caseX/caseXnew/g` in `inlist_project` for items 1-4. This replaces every instance of the old 'caseX' with the new 'caseXnew', assuming each case's inlist was named by case number.

Case 1 Question Set:

As your model runs, watch the panel that depicts the growth of the convective core and think about the following questions:

1. What is happening (is the convective core growing, receding, staying the same)?
2. How does this compare to the Schwarzchild case?
3. What explains why this is happening?
   (**Hint**: look at the panel with the gradient profiles. What do you notice at the convective boundary?)

Click here for answers if you have the 1.5M model.
Click here for answers if you have the 10M model.

***Reminder:** Tables 2 and 6 need to upload their last profile and history file to the convective boundaries dropbox ;)

If your run finishes quickly, make a movie of the Case 1 evolution!

Case 2: Predictive Mixing + Schwarzchild

We now want to test using predictive mixing with both the Schwarzchild and Ledoux criteria. Before adding the code for this, let's read a little bit of information about these controls. Go to the MESA controls documentation and search for "predictive." Spend a couple of minutes reading about these controls. For best practice, find examples of when these controls are used. One example is found in the inlists of the MESA IV (4) paper. (*It's always good to go back to the MESA papers and read about topics being studied!*) Click here to learn how to navigate to the inlists from the MESA papers (can come back to this later too!).
Another example comes from the `test_suite` cases. For example, `test_suite` case 16_M_predictive_mix uses predictive mixing the MS and the case hb_2M uses predictive mixing on the CHeB.
In there, we find:

```
    predictive_mix(1) = .true.
    predictive_zone_type(1) = 'any'
    predictive_zone_loc(1) = 'core'
    predictive_bdy_loc(1) = 'top'
```

We will adopt these values, so add them to the `&controls` section in `inlist_project`!

Also, since we want to look at the Schwarzchild case, comment out `use_Ledoux_criterion = .true.` (or set it to false).

Again, edit the files and directories to save for this case (refer to the **checklist** above to remember what needs to be edited! Make sure to load in the correct file for case 2!)
Save and close `inlist_project` and `inlsit_pgstar`. Then run case 2!

Remember: Make a copy of `inlist_project` to `inlist_project_case2`!

Case 2 Questions:

As your model runs, and looking at the gradient profiles panel plot,

1. Does $\nabla_{rad} = \nabla_{ad}$ on the convective side of the boundary?
2. Is this result different than the Sign + Schwarchild Case 0?

Click here for answers.

***Reminder:** Tables 3 and 6 need to upload their last profile and history file to the convective boundaries dropbox ;)

If your run finishes quickly, make a movie of the Case 2 evolution!

Case 3: Predictive Mixing + Ledoux

For case 3, simply edit your `inlist_project` by including (uncommenting) `use_Ledoux_criterion = .true.` Change the mod fileneames and directory names to match this case as done in previous cases (**see checklist**).
Save and close your `inlist_project, inlist_pgstar_XM-lab1` files. Run the code.

Remember: Make a copy of `inlist_project` to `inlist_project_case3`!

Case 3 Question:

1. How do the results compare to the sign+Ledoux (Case 1) and pred + Schwarzchild (Case 2)?

Click here for answer.

***Reminder:** Tables 4 and 8 need to upload their last profile and history file to the convective boundaries dropbox ;)

If your run finishes quickly, make a movie of the Case 3 evolution!

BONUS TASK: Resolution study again

The growth of the convective core is rugged with the default resolution. Should you have extra time, try adjusting the `mesh_delta_coeff` and `time_delta_coeff` values for an improved result. Suggested values are `mesh_delta_coeff = 0.5` or`mesh_delta_coeff = 0.2`, keeping `time_delta_coeff=1` for both. The former is estimated to take about 5 min of run time while the later may take around 12 min.
Remember: if you are able to do this exercise, save the directory files to appropriate places so you don't over-write the results using the default mass and time resolution! (i.e. follow the checklist and save a copy of the edited `inlist_project`.)

BONUS Excercise: Study the pgstar inlist

Open the `pgstar` inlist to familiarize yourself with how the panels and grid plot were set up! Click here for a detailed explanation of the file.

Solutions

The full solutions directories for both masses are located in the `conv_boundaries_2022/lab1_XM_solutions` folders, if you'd like to compare files or if you got stuck on one part of the lab. The solutions do not include the bonus exercises however.

Answers to Case 1 Questions

1.5 M model:

1. Growth of Convective core does not grow!
2. Very different than Schwarzchild case...
3. Profiles show a discontinuity at convective boundary so the sign algorithm cannot correctly place the boundary.

Click here to return to the Case 1 Question set.

10 M model:

1. Convective core is receding.
2. Same as the result from case 0.
3. The abundance profile is continuous and the sign algorithm works well when there are no discontinuities at the boundary. (So we get the same result as before!)

Click here to return to the Case 1 Question set.

Answers to Case 2 Questions

1. Yes, you should have seen that $\nabla_{rad} = \nabla_{ad}$.
2. The result is the same as Case 0 for both masses!

Click here to return to the Case 2 Question set.

Answer to Case 3

1. Now the core behaves the same way when using Ledoux than when using Schwarzchild – good!

Click here to return to Case 3.

Navigating to inlist examples

You can navigate to the inlists by going to the MESA marketplace web site and clicking the “Inlists" tab near the top of the page. Then search for “convective boundaries". You should see two instances from the MESA instrument papers IV and V. Click “Get" for the Mesa IV paper. You can then download and view the inlists that were used in the MESA instrument paper!

Click here to return to Case 2.

Making movies

You can use the built-in `images_to_movie` executable in MESA to quickly make movies. Simply type in your terminal:

```
images_to_movie '<grid_png_directory>/*.png' <movie_name>.mp4
```

where you only need to specify the png directory to point to and the name for your movie.

A more custom-made movie can be done by utilizing flags, and pointing to ffmpg in the `$MESASDK` folder. For instance, to slow the frame-rate, you could do something like:

```
$MESASDK_ROOT/bin/ffmpeg -framerate 24 -pattern_type glob -i '<grid_dir>/*png' -vf
"scale=trunc(iw/2)*2:trunc(ih/2)*2" -c:v libx264 -pix_fmt yuv420p -y <name>.mp4
```

All in one line haha. you can adjust the framerate from 24 to something smaller for a slower movie, or something larger for a faster movie.

Click to go back to comparing results section
Click to go back to end of case 1
Click to go back to end of case 2
Click to go back to end of case 3

Detailed explanation of pgstar file

1. **Abundance Panel** (Top left of Figure 1). This plot is useful to track the current state of the model's evolution along the MS. Here we see the extent of core H burning, and watch the evolving exchange as hydrogen depletes and helium grows. We include carbon and oxygen in mix to see their small contribution from the initial metallicity. This panel is set up with the following lines in the `pgstar` file:

```
! Abundance profile plot
Abundance_num_isos_to_show = 4
Abundance_which_isos_to_show(1)  = 'h1'
Abundance_which_isos_to_show(2)  = 'he4'
Abundance_which_isos_to_show(3)  = 'c12'
Abundance_which_isos_to_show(4)  = 'o16'
Abundance_title = 'Abundance'

! number and size of isotope labels along curves
num_abundance_line_labels = 4
Abundance_line_txt_scale_factor = 0.8

! xaxis name and orientation
Abundance_xaxis_name = 'mass'
Abundance_xaxis_reversed = .false.

! xaxis limits
Abundance_xmin = 0.0
Abundance_xmax = 10.0 ! PUT YOUR MASS HERE (10.0 or 1.5)

! yaxis limits
Abundance_log_mass_frac_min = -3.0
Abundance_log_mass_frac_max =  0.3 (go slightly more than one for cleaner plot)

! file output: feel free to change any of these parameters to your liking
```

```
    Abundance_file_flag = .false. ! change to true if you want separate file output
    Abundance_file_dir = 'abund_png'
    Abundance_file_prefix = 'abund_'
    Abundance_file_interval = 5     ! output when mod(model_number,file_interval)==0
```

NOTE: you can see where these controls came from by opening `$MESA_DIR/star/defaults/pgstar.defaults` and reading under the section 'Abundance window'.

2. **Evolution of Conv Core**. This plot is useful to track each time step's convective core mass as a function of central hydrogen abundance - the history of the convective core extent. This plot utilizes the customize-able 'History_Track' pgstar controls. Under your 'Abundance profile plot' code block, the lines for this panel are:

```
!------------------------------------------------------------------------------------------
  ! mass of convective core vs. X_c (central H abundance)
  ! This is a History Track that you specify, so it'll be History_track1
  ! set parameters and labels for the mass of convective core
    History_Track1_title = 'Evolution of Conv Core Mass'
    History_Track1_xname = 'center_h1'
    History_Track1_yname = 'mass_conv_core'
    History_Track1_xaxis_label = 'X\dc\u'
    History_Track1_yaxis_label = 'Mass of Convective Core'
! set up limits of the plot
    History_Track1_reverse_xaxis = .true.
    History_Track1_reverse_yaxis = .false.
    History_Track1_log_xaxis = .false.
    History_Track1_log_yaxis = .false.
    History_Track1_xmin = 0.0 !-101d0
    History_Track1_xmax = 0.75 !-101d0
    History_Track1_ymin = 0 !-101d0
    History_Track1_ymax = 3.5 !-101d0
! file output: adjust to your liking.
    History_Track1_file_flag = .false.
    History_Track1_file_dir = 'conv_core_png'
    History_Track1_file_prefix = 'conv_core_'
    History_Track1_file_interval = 5
```

The first 5 lines of controls name the plot and label the axes. The '`X\dc\u`' is a pgplot format key that subscripts 'c' onto X. The limits of the plot can be played with, but are suitable for the 10 $M_\odot$ model in this example. Note that '`xmax`' won't ever be above ~ 0.75, so that is why it is the max here. For file output, you can adjust those parameters to your liking and flag to `.true.` if you want these plots stored separately in another directory.

3. **Summary_Profile**. This is probably the most informative plot in regards to the convective boundary study, and most revealing when comparing other cases. Here, we plot, $\nabla_{\rm ad}, \nabla_{\rm rad}$, and X as a function of mass. (The x-axis is truncated to capture the inner half of the star, but the profile curves extend to the full mass of the star.) We also plot the `'mixing_type'` in order to see the convective boundary (value of 1.0 is convection; when it drops to 0, that's the edge of the boundary). This is another customized plot that is not one of the pgstar default panels.
Best practices: Always make sure the profiles you want to plot are set in your `profile_columns.list` and that if you want a kippenhauhn diagram, set the mixing regions in `history_columns.list`!
Remember we needed `grada, gradr,` and `X` un-commented in `profile_columns.list` file to see this in the plot.

```
!------------------------------------------------------------------------------------------
    ! set up for evolution of convective boundaries
    ! grad_rad, grad_ad, grad_L, X, vs mass
    Summary_Profile_win_width = 5
    Summary_Profile_win_flag = .false.
    Summary_Profile_num_lines = 4
    !Summary_Profile_scaled_value(:)=.false.
    Summary_Profile_title='\(0583)\d Profiles'

    Summary_Profile_name(1) = 'mixing_type'
```

```
    Summary_Profile_legend(1) = 'convection'
    !Summary_Profile_txt_scale = 1.0
    Summary_Profile_scaled_value(1) = .false. !.true.

    Summary_Profile_name(2) = 'grada'
    Summary_Profile_legend(2) = '\(0583)\dad'
    Summary_Profile_txt_scale = 1.0
    Summary_Profile_scaled_value(2) = .false. !.true.

    Summary_Profile_name(3) = 'gradr'
    Summary_Profile_legend(3) = '\(0583)\drad'
    Summary_Profile_xmax=0.2
    Summary_Profile_scaled_value(3) = .false. !.true.

    Summary_Profile_name(4) = 'x' !'center_h1'
    Summary_Profile_legend(4) = 'X'
    Summary_Profile_scaled_value(4) = .false.

    Summary_Profile_file_flag = .false.
    Summary_Profile_file_dir = 'grad_profiles_caseX'
    Summary_Profile_file_prefix = 'grad_profiles_'
    Summary_Profile_file_interval = 5
```

Here we set the window width, and specify that we want 4 profile lines, then specify which profiles we want (grada, gradr, and X). The '`\(0583)\d`' is another formatting key for the '∇' symbol in pgplot. (For other useful pgplot symbol codes, check here!)

4. **Kippenhan Diagram**. This plot shows the mixing (ie. convective, burning, radiative) regions in the star. It also annotates relevant luminosities and abundances. The code for this panel is:

```
!-----------------------------------------------------------------------------------------------
! Kippenhahn diagram history plot
    Kipp_win_flag = .false.
! y axis limits
    Kipp_mass_max = 10.0
    Kipp_mass_min = 0
    Kipp_show_mass_boundaries = .true.

! x axis limits
    Kipp_xmax = -101     ! maximum step number.  negative means use default.
    Kipp_xmin = 0        ! minimum step number.  negative means use default.
    Kipp_max_width = -1  ! only used if > 0.  causes xmin to move with xmax.

    Kipp_show_mixing = .true.
    Kipp_show_burn = .true.
    Kipp_show_luminosities = .true.

! file output
    Kipp_file_flag = .false.
    Kipp_file_dir = 'kipp_png'
    Kipp_file_prefix = 'kipp_'
    Kipp_file_interval = 5      ! output when mod(model_number,file_interval)==0
    Kipp_file_width = 14         ! (inches) negative means use same value as for window
    Kipp_file_aspect_ratio = -1 ! negative means use same value as for window
```

5. **HR**. This is the easy one because it's already in your `inlist_pgstar` file! Since we wanted to zoom in on the MS part for particular masses, we changed the limits from the default values. (For the $10M_\odot$ model, we set `HR_logT_min = 4.25`,`HR_logT_max = 4.45`, `HR_logL_min = 3.6`, `HR_logL_max = 4.2`, and changed the flag to `.false.` to not show the HR diagram live in a separate pgstar plot.)

6. **Compiling it all into one grid plot**. Finally, we set up the grid for all 5 of the above plots with the code below:

```
!-------------------------------------------------------------------------------------------
! grid1 plot of all 5 panels
   Grid1_win_width = 14
   Grid1_win_aspect_ratio = 0.55
   Grid1_win_flag = .true.
   Grid1_xleft = 0.03
   Grid1_xright = 0.95
   Grid1_ybot = 0.05
   Grid1_ytop = 0.97
   Grid1_num_plots = 5
   Grid1_num_cols = 3
   Grid1_num_rows = 2
   Grid1_title='Case0_sign_schwarz'
! panel 1: abundances
   Grid1_plot_name(1) = 'Abundance'
   Grid1_plot_row(1)=1
   Grid1_plot_col(1)=1
   Grid1_plot_colspan(1) = 1
   Grid1_plot_rowspan(1) = 1
   Grid1_plot_pad_left(1) = 0.04     ! fraction of full window width for padding on left
   Grid1_plot_pad_right(1) = 0.02    ! fraction of full window width for padding on right
   Grid1_plot_pad_top(1) = 0.06      ! fraction of full window height for padding at top
   Grid1_plot_pad_bot(1) = 0.06      ! fraction of full window height for padding at bottom
   Grid1_txt_scale_factor(1) = 0.7 ! multiply txt_scale for subplot by this
! panel 2: Evolution of Conv core (History_Track1 pgplot name)
   Grid1_plot_name(2) = 'History_Track1'
   Grid1_plot_row(2)=1
   Grid1_plot_col(2)=2
   Grid1_plot_colspan(2) = 1
   Grid1_plot_rowspan(2) = 1
   Grid1_plot_pad_left(2) = 0.08     ! fraction of full window width for padding on left
   Grid1_plot_pad_right(2) = 0.02    ! fraction of full window width for padding on right
   Grid1_plot_pad_top(2) = 0.06      ! fraction of full window height for padding at top
   Grid1_plot_pad_bot(2) = 0.03      ! fraction of full window height for padding at bottom
   Grid1_txt_scale_factor(2) = 0.7 ! multiply txt_scale for subplot by this
! panel 3: profile plot of grada, gradL, gradr, X (Summary_Profile pgplot name)
   Grid1_plot_name(3) = 'Summary_Profile'
   Grid1_plot_row(3)=1
   Grid1_plot_col(3)=3
   Grid1_plot_colspan(3) = 1
   Grid1_plot_rowspan(3) = 1
   Grid1_plot_pad_left(3) = 0.03     ! fraction of full window width for padding on left
   Grid1_plot_pad_right(3) = 0.04    ! fraction of full window width for padding on right
   Grid1_plot_pad_top(3) = 0.06      ! fraction of full window height for padding at top
   Grid1_plot_pad_bot(3) = 0.06      ! fraction of full window height for padding at bottom
   Grid1_txt_scale_factor(3) = 0.7 ! multiply txt_scale for subplot by this
! panel 4: kippenhaun diagram
   Grid1_plot_name(4) = 'Kipp'
   Grid1_plot_row(4)=2
   Grid1_plot_col(4)=1
   Grid1_plot_colspan(4) = 2
   Grid1_plot_rowspan(4) = 1
   Grid1_txt_scale_factor(4) = 0.75
   Grid1_plot_pad_left(4) = 0.04     ! fraction of full window width for padding on left
   Grid1_plot_pad_right(4) = 0.06    ! fraction of full window width for padding on right
   Grid1_plot_pad_top(4) = 0.05      ! fraction of full window height for padding at top
   Grid1_plot_pad_bot(4) = 0.05      ! fraction of full window height for padding at bottom
!panel 5: HR
   Grid1_plot_name(5) = 'HR'
   Grid1_plot_row(5)=2
   Grid1_plot_col(5)=3
   Grid1_plot_colspan(5) = 1
   Grid1_plot_rowspan(5) = 1
   Grid1_plot_pad_left(5) = 0.068     ! fraction of full window width for padding on left
   Grid1_plot_pad_right(5) = -0.035    ! fraction of full window width for padding on right
```

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  Grid1_plot_pad_top(5) = 0.08      ! fraction of full window height for padding at top
  Grid1_plot_pad_bot(5) = 0.01      ! fraction of full window height for padding at bottom
  Grid1_txt_scale_factor(5) = 0.65 ! multiply txt_scale for subplot by this
! file output
  Grid1_file_flag = .true.
  Grid1_file_dir = 'grid_png'
  Grid1_file_prefix = 'grid_'
  Grid1_file_interval = 5
  Grid1_file_width = 24
  Grid1_file_aspect_ratio = -1
```

Click to go back to bonus exercise