MESA Summer School 2022

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Lab 3: Convective Boundaries during Core Helium burning (CHeB)

We will now analyze different convection scenarios during the Core Helium Burning (CHeB) phase. For this lab, we have pre-evolved a 4 Msun Star from the pre-MS to the ZACHeB (zero-age CHeB) for you. You will load in this mod file for this for all cases explored.

Getting Started

We will again practice building upon the `work` directory included in MESA as we did in lab 1. We will edit the default `inlist_project` file so that is it appropriate for a 4 $M_{\odot}$ model evolving during the CHeB phase for the cases we'll explore.

Create a workspace for lab 3 and copy the contents of the `$MESA_DIR/star/work` directory into it. For example:

```
mkdir lab3_cheb_4M
cd lab3_cheb_4M
cp -r $MESA_DIR/star/work/* .
```

We will start all runs from the same mod file, which was previously produced for you. From the unzipped `conv_boundaries_2022` folder, copy (or move) the `zacheb.mod` to your lab 3 work directory.

Open `inlist_project` and delete the `create_pre_main_sequence_model = .true.` line in the `&star_job` section. You can also delete the 'save a model' lines if you'd like. Now add the following:

```
    show_log_description_at_start = .false.
    load_saved_model=.true.
    load_model_filename= 'zacheb.mod'
    set_initial_age = .true.
    initial_age = 0
    set_initial_model_number = .true.
    initial_model_number = 0
    initial_zfracs = 6
    write_profile_when_terminate = .true.
    filename_for_profile_when_terminate = 'profile_4M_TACHeB.data'
    change_net = .true.
    new_net_name = 'basic.net'
```

The above controls will be used for all the following cases. We set the initial ages to 0 because we want to start tracking time from the start of the CHeB.

Next, in `&kap`, add:

```
    kap_file_prefix = 'a09'
    kap_lowT_prefix = 'lowT_fa05_a09p'
    kap_CO_prefix = 'a09_co'
```

In the `&controls` section, delete or comment out the `initial_mass`, and delete the following lines:

```
! stop when the star nears ZAMS (Lnuc/L > 0.99)
Lnuc_div_L_zams_limit = 0.99d0
stop_near_zams = .true.
! stop when the center mass fraction of h1 drops below this limit
xa_central_lower_limit_species(1) = 'h1'
xa_central_lower_limit(1) = 1d-3
```

We'll use the same smoothing controls and mixing length controls as we did in labs 1 and 2. We also want to stop at the terminal age of the CHeB. Add the following to `&controls`:

```
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
varcontrol_target = 1d-3

mixing_length_alpha = 1.8d0
MLT_option = 'TDC'

x_ctrl(1) = 0
x_ctrl(2) = 0
x_ctrl(3) = 0
stop_at_phase_TACHeB = .true.
recalc_mix_info_after_evolve = .true.
```

The last control updates the calculation of the mixing info after a step in the evolution. The `x_ctrl()` controls will be used as flags later when we edit `run_star_extras`.

Remember: You can always refer to the controls documentation (`controls.defaults` or the webpage) for brief descriptions on what each control does!

A little run_star_extras editing...

To compare the different cases, it will be useful to look at profile plots at the same points along the CHeB phase. Using Figure 43 from the MESA 5 paper as a reference, we'll save profiles when central Helium drops to $Y_c = 0.9, 0.6$, and 0.3.

First, let's get all the needed code for this file. Open the provided `src/run_star_extras.f90` file and note the line `include 'standard_run_star_extras.inc'`. We want to customize the routines defined in the included file. Since we want the 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.
Delete the aforementioned include line and insert the contents of `$MESA_DIR/include/standard_run_star_extras.inc`. (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.)

Now, navigate to the `extras_finish_step` routine. Insert the following lines below the commented out lines of code:

```
if ((s% center_he4 < 0.90) .and. (s% x_ctrl(1) == 0)) then
    s% need_to_save_profiles_now = .true.
    s% x_ctrl(1) = 1
    write(*,*) 'SAVED PROFILE FOR Yc = 0.9'
    call star_write_profile_info(id, s% x_character_ctrl(1),ierr)
end if
if ((s% center_he4 < 0.6) .and. (s% x_ctrl(2) == 0)) then
    s% need_to_save_profiles_now = .true.
    s% x_ctrl(2) = 1
    write(*,*) 'SAVED PROFILE FOR Yc = 0.6'
    call star_write_profile_info(id, s% x_character_ctrl(2),ierr)
```

```
    end if
    if ((s% center_he4 < 0.3) .and. (s% x_ctrl(3) == 0)) then
        s% need_to_save_profiles_now = .true.
        s% x_ctrl(3) = 1
        write(*,*) 'SAVED PROFILE FOR Yc = 0.3'
        call star_write_profile_info(id, s% x_character_ctrl(3),ierr)
    end if
```

What the above code is doing is saving profiles when the central helium drops below our criterion points, and specifies the file names the code will write to so you can find them easily. The write statements help as you watch the terminal output know when the evolution reaches these points, and verifies the code reaches these `if` statement conditions. The `x_ctrl()`s are flag variables. They are initialized to 0 in `inlist_project`. The 0 value means the condition has not been met yet. When the condition is met, the flag is updated to 1 so that the second part of the `if` statement is false the next step. This eliminates profiles being saved at EVERY step after Y_c drops below the criterion points. This helps minimize the profile output so we don't clog your computer space ;)

The user-specified profile names are set by the `x_character_ctrl()`s that you add in `inlist_project`. Include the following in `inlist_project` (in `&controls`):

```
    x_character_ctrl(1) = 'profile_Yc_0.9_caseX.data'
    x_character_ctrl(2) = 'profile_Yc_0.6_caseX.data'
    x_character_ctrl(3) = 'profile_Yc_0.3_caseX.data'
```

Where 'X' is the case number you will update in each case explored. You may name them whatever you like, as long as you can distinguish between the Y_c values and cases for each profile.

NOTE:. **The profiles will be saved in your work directory, NOT your LOGS directory!** (I attempted to direct them to the LOGS directory but was having trouble for some reason... if you want to try fixing this, do so in your free time lol)

Now save and close the file. Make sure the copied and pasted lines will compile correctly with `./clean` then `./mk`. If all goes well, just a few more steps before testing cases!

inlist_pgstar

We want to plot the same pgstar panels as before, and need to make sure our profiles save all the data we want to plot by hand later. We've done the heavy lifting in the first lab, so copy over the `profile_columns.list`, `history_columns.list` from your lab 1 directory, and `inlist_pgstar_1.5M` from the `conv_boundaries_2022` folder. Re-name `inlist_pgstar_1.5M` to `inlist_pgstar`.

Open `profile_columns.list` and make sure `gradr, grada`, `gradL`, and `y_mass_fraction_He` are included (not commented out). (They should be included from lab 1 but always good to check!). We may want to plot some composition profiles so search for `h1, he4, c12`, and `o16` and include (uncomment) those abundances. Save and close `profile_columns.list`.

Open `history_columns.list` and make sure `mass_conv_core` is included, and that `mixing_regions 20` is still there.

Help: If you weren't able to successfully edit the `profile_columns.list` or `history_columns.list` files in lab 1, you may copy them over from the `conv_boundaries_2022/help` folder :) You'll still need to include `h1, he4, c12`, and `o16` parts.

Open `inlist_pgstar`. This was set up for a 1.5 $M_\odot$ star, so let's edit the axes for a 4 $M_\odot$ star. This was also set up for the MS (tracking H depletion). We want to track He depletion on the CHeB. Scroll to the `'! mass of convective core...'` section, where the `History_Track1` panel is set up. Change `History_Track_xname` to `center_he4`. Change `History_Track1_xmax` to 0.99 and `History_Track1_ymax` to 0.5.

Now scroll to the next section, that sets up the gradient profiles with the `Summary_Profile` panel. Change `Summary_Profile_xmax` to 1.5. You can set it to a smaller value to hone in on the core, but 1.5 allows you to see the full splitting of convection. 1.4 or 1.2 would probably be fine. Set `Summary_Profile_name(4) = 'y'` and

`Summary_Profile_legend(4) = 'Y'` so we can look at the Helium profile.

Scroll to the following Abundance section and update `Abundance_xmax = 4.0` in order to see the entire profiles of the star.

Save and close `inlist_pgstar`.

Uploading Instructions for Comparing Cases

We again want to compare multiple cases in a single figure for easy comparison. This time, we have set up `run_star_extras` to spit out profiles at precise moments in the evolution for each case (Each case will have saved profiles at $Y_c = 0.9, 0.6,$ and 0.3.). So our comparisons will be even more precise when analyzing the gradient profiles!

To make things simple, we would like each table to be in charge of 2 cases:

Table 1	Table 2	Table 3	Table 4	Table 5	Table 6	Table 7	Table 8
Case 1	Case 2	Case 3a	Case 3b	Case 1	Case 2	Case 3a	Case 3b
Case 4	Case 5a	Case 5b	Case 6	Case 4	Case 5a	Case 5b	Case 6

Each student will upload one profile per case assigned to the convective boundaries dropbox. Students with the fastest computers (those who finish the cases first) should upload the profiles for $Y_c = 0.3$. That student is also in charge of uploading the `history.data` files for each case. Students with the slowest computers should upload the profiles for $Y_c = 0.9$. As your cases reach the Y_c value you are in charge of, please use the following naming convention so we don't over-write data:

```
profile_Yc_X_caseX_TX.data
history_caseX_TX_lab3.data
```

The `X` values are the Y_c value, the case number, and table number respectively.
For example: I have the fastest computer at table 5. So I'd re-name/copy the saved `profile_Yc_0.3_case1.data` file to `profile_Yc_0.3_case1_T5.data` and re-name/copy `LOGS_cheb_case1/history.data` to `LOGS_cheb_case1/history_case1_T5_lab3.data`. Then upload those files to the dropbox.

Ok, let's start up the first case!

Case 1: Predictive+Ledoux

Let's look at predictive mixing and the ledoux criterion on the CHeB for the $4M_\odot$ model. We can get an idea of the needed predictive mixing controls for the CHeB from existing examples. One can view the inlists from the MESA IV paper, or one can look at a test suite case. We'll follow the controls from the inlists used in the MESA IV paper. Click here to learn how to access the MESA IV paper inlists (can come back to later while models run).

Open `inlist_project` and add the following in the `&controls` section:

```
! Case 1: pred + ledoux cheb

use_ledoux_criterion = .true.

time_delta_coeff = 2

predictive_mix(1) = .true.
predictive_zone_type(1) = 'burn_H'
predictive_zone_loc(1) = 'any'
predictive_bdy_loc(1) = 'any'
predictive_avoid_reversal(1) = 'h1'

predictive_mix(2) = .true.
predictive_zone_type(2) = 'burn_He'
predictive_zone_loc(2) = 'any'
predictive_bdy_loc(2) = 'any'
predictive_avoid_reversal(2) = 'he4'
```

```
    predictive_superad_thresh(2) = 0.005

    predictive_mix(3) = .true.
    predictive_zone_type(3) = 'nonburn'
    predictive_zone_loc(3) = 'any'
    predictive_bdy_loc(3) = 'any'

    log_directory = 'LOGS_cheb_case1'
    photo_directory = 'photos_cheb_case1'
    photo_interval = 200
    profile_interval = 500
    history_interval = 1
    terminal_interval = 10
    write_header_frequency = 10
```

NOTE: The `time_delta_coeff=2` doubles the Δt values between each step, decreasing the time resolution of the model. Doing this allows for faster run-time, but it may be costly if one is going for accuracy! It's always a good idea to do convergence studies to get optimal time and mass resolution :). For this lab, we tested this case with decreased mass and time resolution and found that we can get away with decreasing time resolution to this value. Should you finish your cases quickly, feel free to do the same tests in the **BONUS** section!

We'll need a slightly modified **Checklist** to update all the items for differentiating between different cases and profiles:

Checklist:

1. `filename_for_profile_when_terminate` (`inlist_project`, under `&star_job`)
2. `log_directory` (`inlist_project` under `&controls`)
3. `photo_directory` (`inlist_project` under `&controls`
4. `x_character_ctrl()`s names (i.e. caseX → caseX+1)
5. in `inlist_pgstar`, edit the `Grid1_file_dir` folder (i.e. change to "caseX" at the end of "grid_png" for your case number).
6. after editing `inlist_project`, make a copy of `inlist_project` to `inlist_caseX` for reference

PLEASE REFER TO THIS FOR EACH CASE!

TIP for vim users: As mentioned in a prior lab, the checklist can be extremely easy to update with a little knowledge. Assuming you only need to update the case number for each item, simply open `inlist_project` and type

```
:s%/caseX/caseX+1/g
```

This automatically updates every instance of `caseX` with `caseX+1`. That completes steps 1-4 in a single step :)

Once all the updates are done, run Case 1 on the CHeB! Remember these runs will take longer than the prior labs. **For Tables 1 and 5, as your models reach your assigned Y_c value, upload your profile file to the drobox! When the files are uploaded, the TA will plot the results and we will discuss them!**

When your run finally finishes, be sure you've done item 6 in the checklist! (i.e. copy to `inlist_project` to `inlist_project_case1`.)

Case 2: Predictive + Schwarzchild

Open `inlist_project` and change `use_ledoux_criterion` to `.false.` Follow the checklist to update the files saved for this case. Run the code.
How do the results compare to when we use the Ledoux criterion? What is the age at TACHeB? Is the age the same as with Predictive + Ledoux? (Case 1)

For comparing evolutions, you can make movies of each and watch the growth of the convective core panels and compare :). Feel free to do this on any/all cases, should you have time.

Be sure to make a copy of the edited `inlist_project` to `inlist_project_case2` ;)
For Tables 2 and 6, as your models reach your assigned Y_c value, upload your profile file to the drobox! When the files are uploaded, the TA will plot the results and we will discuss them!

Case 3a: Predictive + ledoux + control edits

How important are the predictive mixing controls we specifed in `inlist_project`? Comment out `predictive_avoid_reversal(2) = 'he4'` and `predictive_superad_thresh(2) = 0.005` in `inlist_project`. Also switch `use_ledoux_criterion = .true.` Follow the checklist to update the files saved for this case (case 3a). Run the code.
What happens?

For Tables 3 and 7, as your models reach your assigned Y_c value, upload your profile file to the drobox! When the files are uploaded, the TA will plot the results and we will discuss them!

Case 3b: Predictive + ledoux + control edits part 2

What if we increase the `super_ad_thresh`? Try setting `predictive_superad_thresh(2) = 0.05`, and include (uncomment) `predictive_avoid_reversal(2) = 'he4'`. Follow the checklist to update the files saved for this case (case 3b). Run the code.
What happens in this case?

For Tables 4 and 8, as your models reach your assigned Y_c value, upload your profile file to the drobox! When the files are uploaded, the TA will plot the results and we will discuss them!

Case 4: Sign + Schwarzchild

In this case, we'll want to comment out all the predictive mixing controls and set `use_ledoux_criterion` to `.false.`. Follow the checklist to update the files saved for this case (case 4). Run the code.
Carefully pay attention to the gradient profile plots when the core stops growing. Does $\nabla_{rad} = \nabla_{ad}$ on the convective side of the boundary? Also, what is the age at TACHeB? How does it compare to prior cases?
While your model is running, begin thinking about how overshoot could impact this case by looking at the overshoot controls in `controls.defaults`. The following case includes overshooting on the cheb (with sign+schw criteria). What controls do you think would be suitable?

For Tables 1 and 5, as your models reach your assigned Y_c value, upload your profile file to the drobox! When the files are uploaded, the TA will plot the results and we will discuss them!

Case 5a: Sign + Schwarzchild + 'reasonable' overshooting

If short on time, split your table so half do 5a and the other half do 5b!

(We will compensate for missing file uploads if need be.)

Does overshooting help the growth of the convective core, and allow for $\nabla_{rad} = \nabla_{ad}$? Further, what value is 'good'? We will try a small but conventional value first. Try including the following to your `inlist_project` controls:

```
overshoot_scheme(1) = 'exponential'
overshoot_zone_type(1) = 'any'
overshoot_zone_loc(1) = 'core'
overshoot_bdy_loc(1) = 'top'
overshoot_f(1) = 0.01d0
overshoot_f0(1) = 0.001d0
```

Follow the checklist to update the files saved for this case (case 5a). Run the code.
Pay attention to the nature of the growth of the convective core, and the extent of the convective core. How does it compare to the predictive mixing cases (Cases 1, 2, 3a)?

For Tables 2 and 6, as your models reach your assigned Y_c value, upload your profile file to the drobox! When the files are uploaded, the TA will plot the results and we will discuss them!

Case 5b: Sign + Schwarzchild + larger overshooting

Now try changing `overshoot_f(1)` to a larger value (i.e. 0.03). Follow the checklist to update the files saved for this case (case 5b). Run the code.

What do you notice about this case compared to the previous case with a lower overshoot value?

What do you think will happen if we include both overshooting and predictive mixing?

For Tables 3 and 7, as your models reach your assigned Y_c value, upload your profile file to the drobox! When the files are uploaded, the TA will plot the results and we will discuss them!

Case 6: Pred+Schw+overshoot

Uncomment the predictive mixing controls in your `inlist_project`. Change `overshoot_f(1)` back to 0.01. Make sure you set `predictive_superad_thresh(2) = 0.005` (back to original value). Follow the checklist to update the files saved for this case (case 6). Run the code.

What do you notice about the convective core mass size?

For Tables 4 and 8, as your models reach your assigned Y_c value, upload your profile file to the drobox! When the files are uploaded, the TA will plot the results and we will discuss them!

Wrap up

From the global results, what can we conclude about the mixing and convection scenarios - what scenario gives us the largest possible mass for the convective core on the CHeB?

Solutions

Lots of cases covered! A directory of solutions for all cases is found in the `conv_boundaries_2022/lab3_4M_solutions` folder for all cases. The case numbering is off from the lab due to two additional cases for resolution. The python plot scripts adjust them to match the lab case numberings, so even if you don't have python on your machine, you can 1) view the files to see the re-ordering and 2) view the saved pdf figures that show the results... also, as with the prior labs, bonus exercises are not included in the solutions directory due to a scrambled TA that ran short on time to submit the full lab by the deadline (please forgive me... crazy summer lol)

BONUS TASKS

Bonus 1: can we afford reduced mass resolution?

This case is the same as case 1, but let's see how the results compare if we reduce mass resolution.

Use the `inlist_project` file you saved for case 1 and add the control `mesh_delta_coeff=2`. You may want to follow the checklist items here too to remember that this case uses different mass resolution than case 1! That way you won't over-write your case 1 LOGS files! **Note:** It might be best to first make a copy of `inlist_project_case1` to `inlist_project_bonus1`, then edit that file. Then either copy `inlist_project_bonus1` to `inlist_project` or edit the pointer inlist file your `inlist` reads in.
Try running this case and compare to Case 1!

What is the age at TACHeB compared to before? How does the growth of the convective core look compared to before?

Bonus 2: time resolution

Same as above, but instead of mass, let's do time resolution. Change `time_delta_coeff=1` in your `inlist_project` controls and comment out the `mesh_delta_coeff=2` control. Follow the checklist to update the files saved for this case, as well as the tips mentioned in the previous bonus task. Run the code.
How long does it take? What is the age at TACHeB compared to case 1 and case 2a? How does the convective core compare?
Be sure to make a copy of the edited `inlist_project` to `inlist_project_case2b` ;)
For the following cases, we will use time_delta_coeff=2 to make the run-time faster!

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 Here to return to Case 2.

1 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 to go back to Case 1.