Maxilab: Constructing and evolving a double white dwarf merger remnant

- The goal of this lab is to construct the remnant of a double white dwarf merger after it has dissipated its rotational kinetic energy and become quasi-spherical. This process converts the disrupted less massive WD into a hot extended envelope on top of the (more or less) undisturbed more massive WD.

- We'll begin by modeling a 0.2 + 0.3 Msol double helium WD merger, so we'll need to construct a 0.5 Msol pure helium object, with a 0.3 Msol degenerate core and a 0.2 Msol puffy envelope that does not exert much pressure on the core.
  - We'll relax the composition using flags in **`star_job`** and **`controls`**, similar to what we did in the first minilab. Some of the flags in **`controls`** are missing, so you will have to fill them in.
  - Entropy relaxation is currently not a standard option in MESA, so we'll have to write our own entropy relaxation routine in **`run_star_extras.f`**.

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- Open **`run_star_extras.f`** and read through the new energy routine.

- Outside of $M_{transition}$ = 0.3 Msol, the target entropy is set to something high so that the outer 0.2 Msol gets expanded out.

- Inside of $M_{transition}$, we want the inner material to approximate an isothermal degenerate WD core. But we have to do this relaxation in two steps. This is because of the negative specific heat of ideal gas stars. When you add heat to a star like the Sun, it expands, and the temperature drops! So cooling the inner core actually makes the temperature increase at first.
  - Instead, we first cool the inner material to a low entropy until it becomes degenerate.
  - When it becomes degenerate "enough", the specific heat becomes what you're used to in everyday life, and cooling makes the temperature drop. We parametrize how degenerate is "enough" with $\eta_{transition}$, where η measures the ratio of the electron chemical potential to the thermal energy.
  - Once the inner material becomes degenerate, we can set a target temperature instead of entropy. This command is left blank for you to fill in.
  - (The **`exp_cr`** is the exponential function from **`crlib`** so that the answer is bit-for-bit.)

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- The relaxation equation I'm using is not fundamental, but it has the spirit of an entropy equation

$$\epsilon_{\text{heat}} = T\frac{ds}{dt} \sim T\left(\frac{s_{\text{target}} - s}{t_{\text{relax}}}\right)$$

- And something similar for the temperature part. Not physically important, but it helps to use something with the right units to get a roughly correct order of magnitude for easier convergence.

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- Once everything is in place, including filling in the missing inlist commands, **`./mk`** and **`./rn`**.

- If everything goes smoothly, save the model when it is relaxed and restart from it with the appropriate flags turned on and off. But how do you know when it is relaxed?
  - One thing to check is that the extra heat being added becomes very small.
  - So, make a new profile plot window with **`inlist_pgstar`** showing the extra heat being added vs. mass.
  - After the model reaches a relaxed state, you should see the extra heat being ~0, except for very near the boundary between the hot envelope and cold core. That's because the relaxation routine is counteracting thermal diffusion across this boundary, which is trying to smooth the sharp transition.

- Once you've reached this state, the model should be relaxed. Now you can set your inlist to save at a recent model number and **`./re`** from a photostep just before this model so that **`MESA`** saves the relaxed model.

- Finally, you can turn on and off the relevant flags to evolve your relaxed model without extra heating and with burning and neutrino-cooling back on, and **`./rn`** the relaxed model.

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- Your model should redistribute entropy and start to contract as it cools. The temperature and density of the material at the base of the hot envelope rise until burning is ignited.

- Let's get a better idea of the progress of the burning as it flashes inwards.
  - Specifically, let's track the mass location where the maximum value of burning is taking place and add it to the **`pgstar`** history window.
  - First, find out if something like that exists in the default **`history_columns.list`** (search for "nuc" or "eps" using your favorite search method).
  - As it turns out, the variable we want is commented out by default, so we need to work with a non-default copy. So, copy **`history_columns.list`** over to your work directory (**`MESA`** looks for this file in your work directory first before using the version in the **`defaults`** directory), and uncomment the variable back in.
  - Unfortunately, doing so changes the **`history.data`** file in the **`LOGS`** directory, so we have to get rid of it and start with a fresh **`history.data`**. So stop the run and delete the old **`LOGS/history.data`**. To see the history of the new variable, add it to **`inlist_pgstar`** as the new **`History_Panels1_other_yaxis_name(3)`**, and **`./re`** from a recent photostep.

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- How many flashes does it take before the burning wave reaches the center? How long does it take?

- After the burning wave reaches the center, what happens? What does it look like (how bright, how hot), and how long does it live like this?

- Eventually this phase ends, and it cools down as a C/O white dwarf. Let's compare the resulting WD to the WDs from our minilab.
  - Put in a condition to stop the WD when the central temperature reaches 2 x 10^7 K. You can't do this too early because the temperature is below 2 x 10^7 K during the burning phase.
  - What is the total ^{4}He mass at the end of the day? How does it compare to the results from the minilab? Report your values on the Google spreadsheet.

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- Now that you've expertly modeled the evolution of a 0.2 + 0.3 Msol double helium WD merger, let's try another set of parameters. For simplicity, let's stick with double helium WDs, so both initial components should be between 0.15 and 0.5 Msol or so, giving total masses between 0.3 and 1.0 Msol.
  - Warning: the higher the mass, the longer it will take to run! If you decide to go above a total mass of 0.7 Msol, use coarser resolution controls.

- Different masses will entail changing the various parameters in the extra energy routine, specifically $M_{transition}$, $\eta_{transition}$, highentropy, and lowentropy. Getting the last 3 correct for your particular choice of masses will probably require some trial and error. Since it's annoying to change them in **`run_star_extras.f`** and recompile for each trial, let's find a way to change them at run-time, without the need to recompile.
  - This is done by using **`x_ctrl(:)`**, which you can change in your **`inlist`** at run-time.
  - You will need to decide which **`x_ctrl`** matches which variable (e.g., **`x_ctrl(1)`** might be your $M_{transition}$), and use them in **`run_star_extras.f`** by accessing **`s%x_ctrl(1)`**.
  - Remember to keep careful track of which **`x_ctrl`** changes which variable!
  - You may find it useful to look at a profile plot of η to pick a good $\eta_{transition}$. So add this profile to your profile plot of **`extra_heat`** to help you pick a winner.

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- If you've made a couple helium WD merger remnants and there's still time, you can try and make a double C/O WD merger remnant in a similar manner.
  - Unlike with pure helium compositions, relaxing to a pure C/O composition is non-trivial.
  - You'll have to do something similar to what we did in the first minilab. Namely, let the material cool down until its degenerate, and only then relax the composition and entropy to what you desire.
  - Also, because of the slow speed of the inwardly moving burning wave, stick with low total masses < 1.2 Msol or so (e.g. 0.5 + 0.6 Msol).

- As it turns out, the C/O WD merger remnant evolution is very similar to the lab yesterday. Alternatively, you can try to model the remnant of a helium + C/O WD merger (i.e., a puffy helium layer on a cold degenerate C/O core).
  - Relaxing a non-pure composition is a little different. You will need the **`relax_initial_composition`** flag and its associated flags in **`star_job`**, and you'll need to give it a file with a compositional profile. This is more complicated, but the comments near the relevant flags in **`star_job.defaults`** will help explain things.

- How do these remnants evolve differently from double helium WD merger remnants? What different phases do they go through? Are they longer or shorter?