ASTR 501 Stellar Physics Midterm

Falk Herwig, Fall 2024

Instructions: You may use any resources available to you *except ChatGPT or any other LLM*, and *you must work alone* to avoid an academic integrety violation. You have 2.5 hours to complete the exam. Start a notebook in your `/home/user/githubname_config` directory on the Astrohub Outrach Hub using the `EtaMu` image from the Spawner Menu, and save your work there. Name your notebook `FirstName_Midterm_a.ipynb`. Save repeatedly. When you are finished, consider restarting the kernel and run the notebook one more time to make sure any calculations or analysis works when executing the notebook. Save again, and download the notebook to your laptop. Then upload it in direct message to me on Mattermost. Questions 1 though 3 *must* be completed in the exam period before you leave. For question 4 and 5 you have a chance to complete them after the exam period (take-home component). If you want to take advantage of this option you must submit these problems in a separate notebook `FirstName_Midterm_b.ipynb` by 10pm on the day of the exam, and I will in that case *only* grade these two questions in your take-home submission, and you will incur on each of these problems a 5 point penalty. If you attempt to finish all questions in the exam period, manage your time well. Good luck!

Question 1 (30 points)

Figure 1 shows the evolution of a low-mass star in two complementary diagrams.

1. Figure 1 shows the evolution of a low-mass star in two complementary diagrams.
   (a) Explain what is shown in each panel of the figure. (5 points)
   (b) Identify and describe the important phases of low-mass stellar evolution marked by the colored circles and bars. For each phase: (25 points)
      - Identify the type of nuclear burning taking place
      - Describe where in the star this burning occurs
      - Explain the general properties of the abundance profiles in the star
      - Discuss any abundance changes that may be observed at the surface

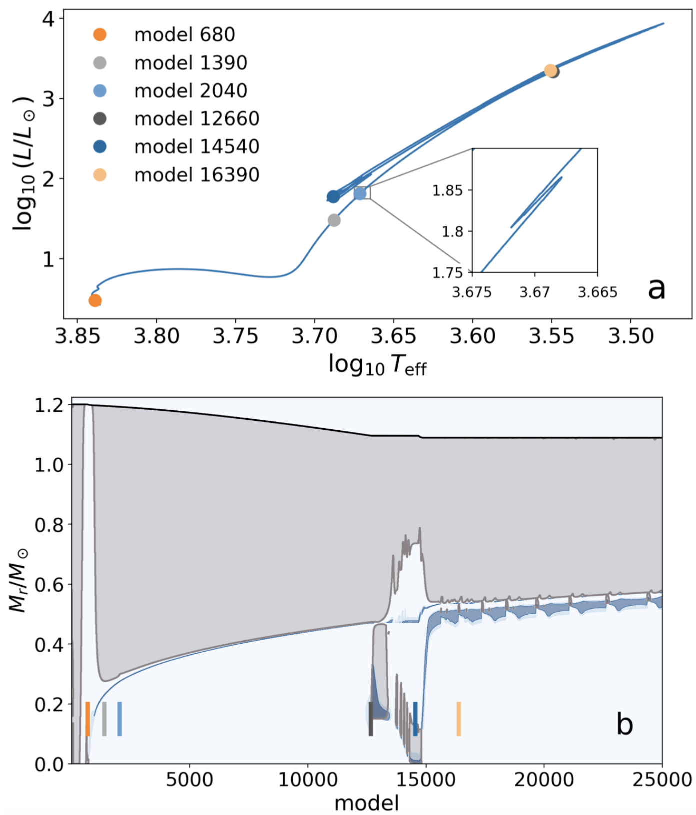

Figure 1: Top panel: HRD of a low-mass star with evolutionary points marked. Bottom panel: Kippenhahn diagram with corresponding evolutionary points marked on the time axis.

Question 2 (15 points)

Consider a region deep within a white dwarf star where the gas is completely ionized. The conditions are: $T = 10^7$ K, $\rho = 10^6$ g/cm^3, composition: pure carbon ($A = 12$, $Z = 6$)

1. Calculate the average distance between ions. Also calculate the average distance between electrons. (5 points)

2. Estimate the thermal de Broglie wavelength for the ions. Also calculate it for the electrons. You can assume that the thermal de Broglie wavelength is given by $\lambda = h/\sqrt{2\pi m k T}$. (5 points)

3. Based on your answers to (a) and (b), are the ions degenerate? What about the electrons? (5 points)

Question 3 (30 points)

Analyse the abundance profiles given in Figure 2 for a region of a star. Answer the following questions:

1. What type of star and what evolutionary phase is shown in the top panel? Explain your answer in terms of the general features of the abundance profiles shown. What is the range of initial masses and what is the approximate initial metal content in terms of $Z = 1 - X - Y$. Provide supportive arguments for your answer. (5 points)

2. What is the cause of the isotopic abundance features (local decrease/increase, maxima) of isoptes at mass $0.6181\mathrm{M}_{\odot}$ in the top panel? (5 points)

3. What is the cause of the isotopic abundance features (local decrease/increase, maxima) of isoptes at mass $0.6176\mathrm{M}_{\odot}$ in the top panel? What is the broader role of these features in stellar nucleosynthesis? (5 points)

4. Explain why in the top panel in a very narrow mass region at just above $0.6175\mathrm{M}_{\odot}$ the ^{13}C abundance is larger than the ^{14}N abundance, and why the ^{14}N abundance has a substantial maximum just above $0.6176\mathrm{M}_{\odot}$? (5 points)

5. Relate the abundance features shown in the bottom panel to the features in the top panel. What does the second panel show? Why do you think where the isotopes selected that are shown? (5 points)

6. Interpret details of the heavy element abundance features in the bottom panel, specifically around the peaks. (5 points)

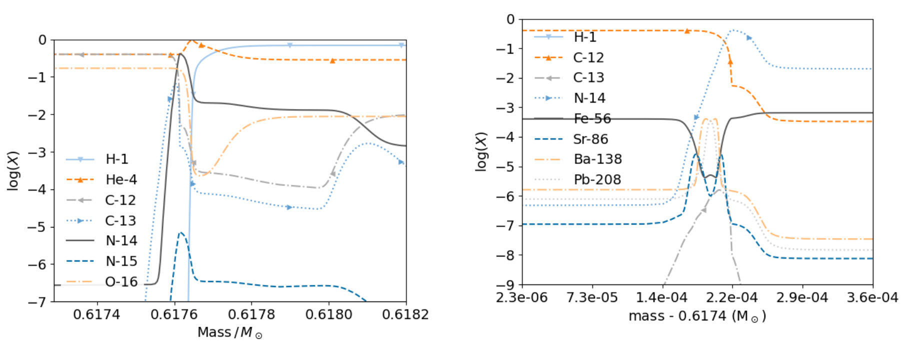

Figure 2: Abundance profiles in a region of a star at two different times.

Question 4 (25 points)

1. Using the NuGrid stellar evolution and nucleosynthesis library, find a stellar model at the time of O burning. A model in stellar evolution is meant to be a time step with a model number of a stellar evolution sequence with given initial mass and metallicity. Say which model you are using by marking its location (e.g. with a vertical line) in a Kippenhahn diagram that shows the entire evolution of the respective stellar evolution sequence. (5 points)
2. Show the location (e.g. make a filled red dot) of the model in the Herzsprung-Russell diagram and ρ_c - T_c diagram. (5 points)
3. Show an appropriately zoomed-in abundance profile plot that shows the location of all burning shells active at that time. Include for each burning shell abundance profiles of one or two major burning products. Explain which abundances are the products (or ashes) of which nuclear burning process. (10 points)
4. Mark the mass regions (e.g. horizontal line or transparent box) that are convective at the time shown. Find the convection zones by plotting a profile of the radiative and adiabatic temperature gradients. (5 points)

Question 5 (25 points)

A stellar evolution stratification of a thermal pulse in a low-Z super-AGB star is shown in Figure 3. Note that the mass coordinate where the nuclear energy generation ϵ_{nuc}[1] peaks is where H has reached through a connection of the convective envelope with the pulse-driven convection zone (as indicated by the mixing diffusion coefficient). We are looking at a H-ingestion into a He-burning convective shell event. H is burning at He-burning temperatures! We know from the figure what the nuclear luminosity is at this location.

1. Estimate from the information given if the situation shown is potentially at risk of becoming dynamically unstable, and how unstable could it become. For this, calculate the nuclear heating time scale, which is how quickly the nuclear luminosity adds energy comparable to the internal energy for a representative location, i.e. the location of maximum nuclear energy generation. (10 points)
2. Note that layer is convective as can be seen from the diffusion coefficient profile. Assume that the mixing length scale in the diffusion approximation is 5 Mm. Estimate the convective turnover time scale. (5 points)
3. Compare the nuclear heating time scale with the convective time scale and draw conclusions as to what could happen in this stellar model. (5 points)

[1] ϵ_{nuc} really should have been called L_{nuc} because it has according to the Figure 3 labels the units of a luminosity.

Note: You will have to make some additional assumptions. Clearly state these assumptions and explain what their implications are, i.e. what effect do they have on the estimate. (5 points)

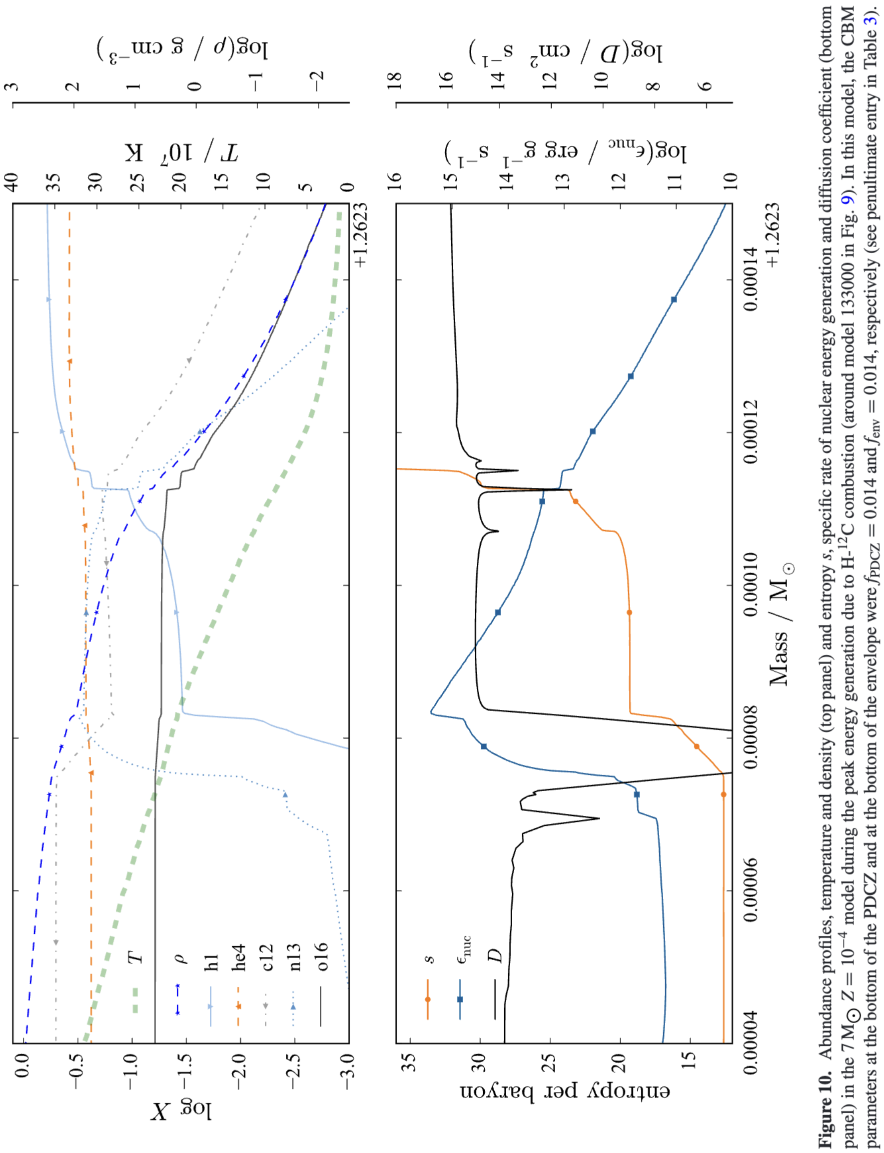

Figure 3: Profiles of various quantities in a super-AGB star during a thermal pulse. From Jones et al. (2016).