Helium Burning

Lars Bildsten (Lecturer)
and
Bill Wolf (TA)

Helium Burning Outline

- Simple Physics of Heat Loss from a Star in Hydrostatic Balance
- Ignition of Helium Burning and the Resulting "Main Sequence"
- In Class LAB
- Lifetimes on the Helium Main Sequence and Final Composition
- In Class LAB
- Explaining the Longer problem for the 90 minute lab.

Hydrostatic Balance

- We assume that the star is in Hydrostatic balance,

$$\frac{dP}{dr} = -\rho g \rightarrow P_c \approx \frac{GM^2}{R^4}$$

- When ideal gas pressure is dominant

$$kT_C \approx \frac{GM\mu m_p}{R}, \text{ where } \mu = \text{mean molecular weight}$$

- The mean molecular weight is 0.6 for solar, and 4/3 for pure helium=>Hotter at the same M and R for pure He than for H/He

Mass-Luminosity Relation

- Given an opacity, the luminosity due to radiative diffusion is roughly

$$L \approx 4\pi R^2 \frac{c}{3\kappa\rho} \frac{daT^4}{dr}$$

- When the opacity is solely from electron scattering, this gives

$$L \propto M^3 \left(\frac{\mu^4}{1+X} \right)$$

- So a factor of 40 increase in L when the star goes from H/He mixture to pure Helium.

Kippenhahn and Weigert

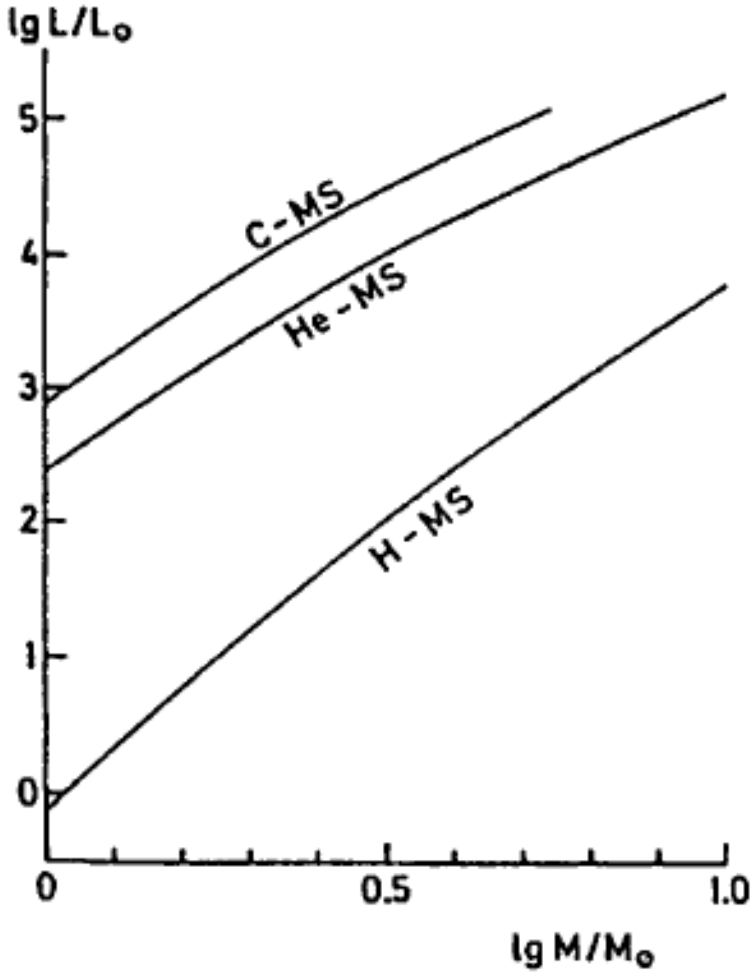
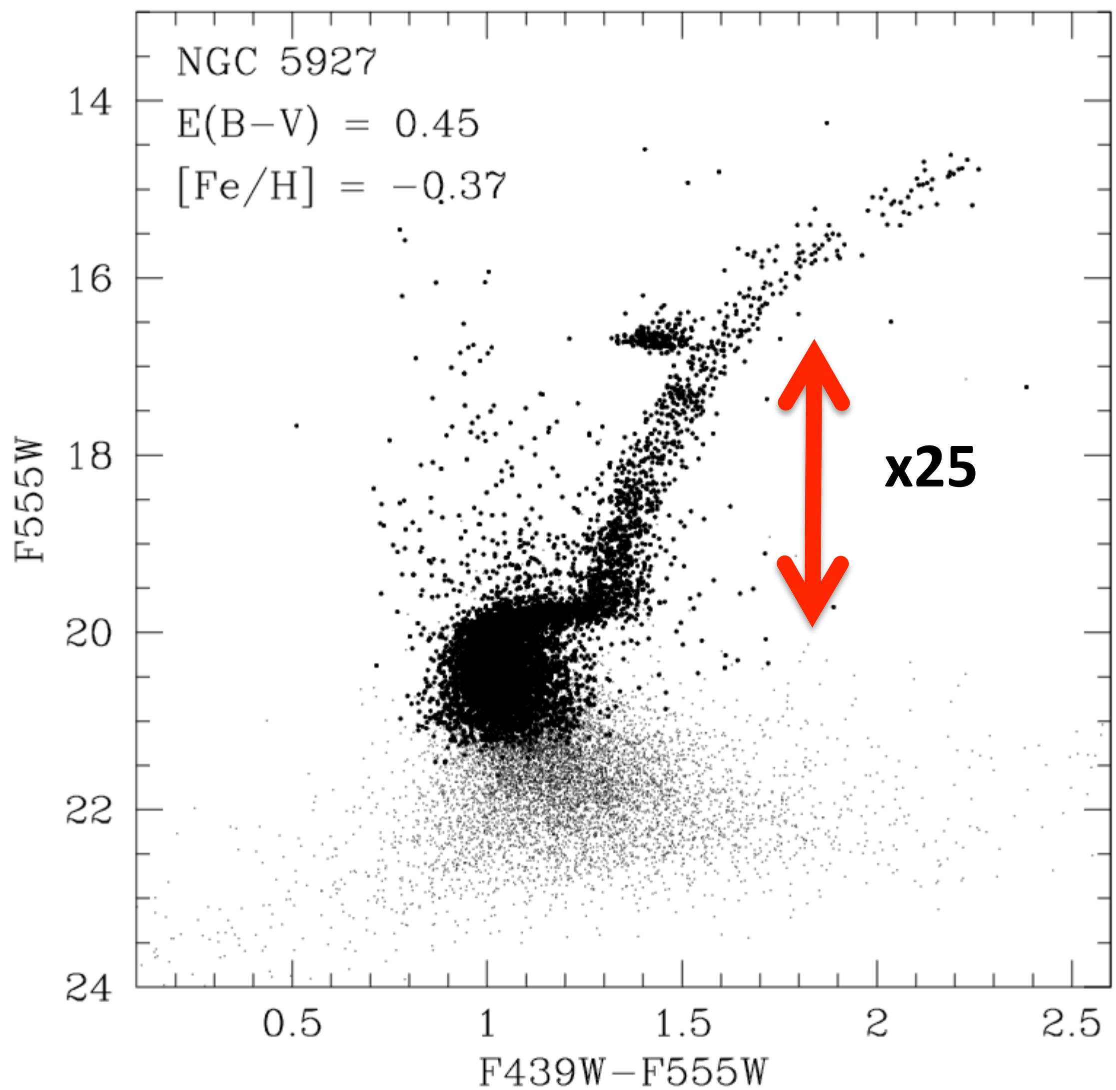


Fig. 23.2. Mass–luminosity relations for the models of the hydrogen, helium, and carbon main sequences of Fig. 23.1

They neglected to include the change in the mean opacity in going from H==>He when it's electron scattering

$$\kappa = 0.2(1 + X)\ \mathrm{cm}^2\ \mathrm{g}^{-1}$$

Reality in a Cluster



Helium Burning Reactions

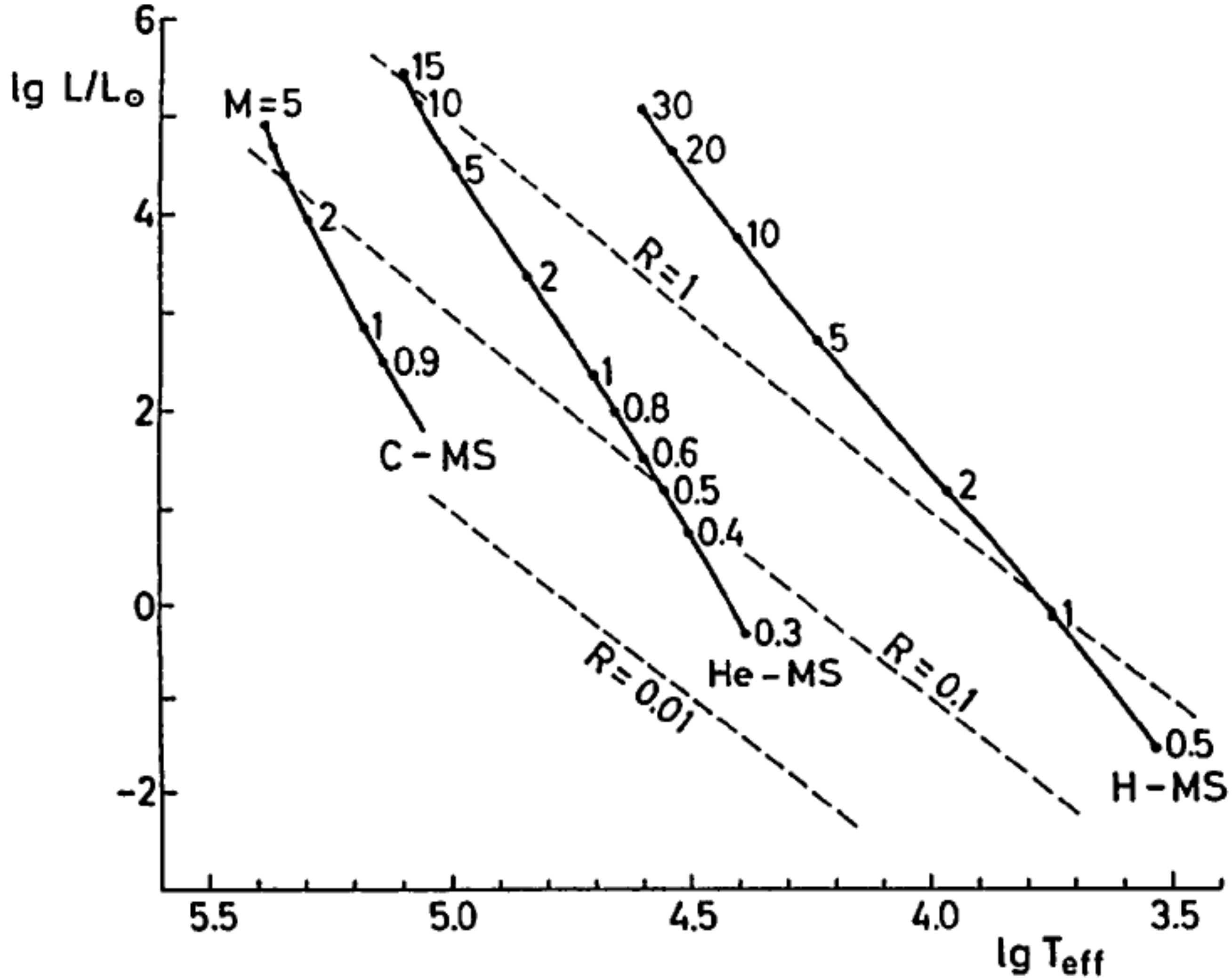
- The rate from the triple-alpha process to ^{12}C is reasonably well described by

$$\epsilon_{3\alpha} = 5.3 \times 10^{21} \left(\frac{\rho}{10^5 \, \mathrm{g\,cm^3}} \right)^2 \left(\frac{10^8 \, \mathrm{K}}{T} \right)^3 \exp\left(-44/T_8\right) \, \mathrm{erg\,g^{-1}\,s^{-1}}$$

- Balancing with heat loss $L_{\rm nuc} \approx \epsilon(\rho_c, T_c) M \approx L$ determines the central temperature, T_c, and the radius

$$T_c = 1.33 \times 10^8 \, \mathrm{K} \left(\frac{\mathcal{M}}{\mathcal{M}_\odot} \right)^{0.17} \quad \mathcal{R} = 0.116 \, \mathcal{R}_\odot \left(\frac{\mathcal{M}}{\mathcal{M}_\odot} \right)^{0.83}$$

Where the Stars Appear on HR



Kippenhahn & Weigert

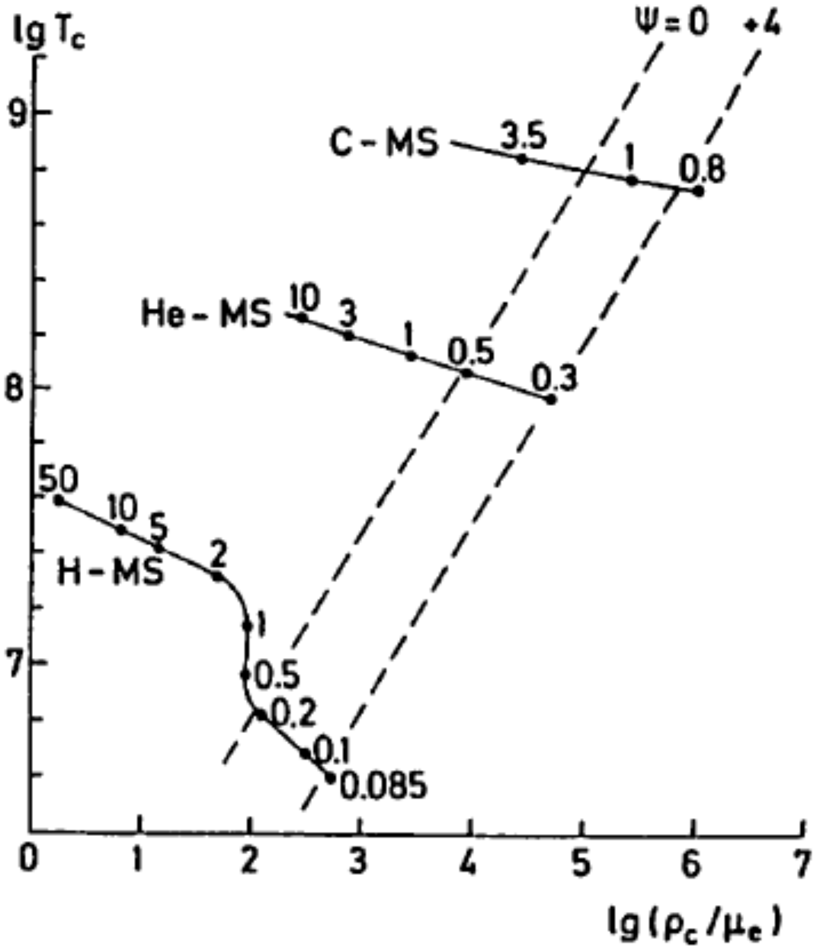
Mini-Lab

- Pick a random number between zero and one and use it to determine the mass of 'your star' uniformly between 0.2 and 4.0 solar masses
- Using the pre-main sequence models available to you, find the ZAMS, ie., the first time that L_{nuc}=L or when the core helium abundance has dropped by 10%
- Tell us L, T_{eff}, T_c, rho_c, size of convective core. Email your answers to Bill Wolf at wmwolf@physics.ucsb.edu

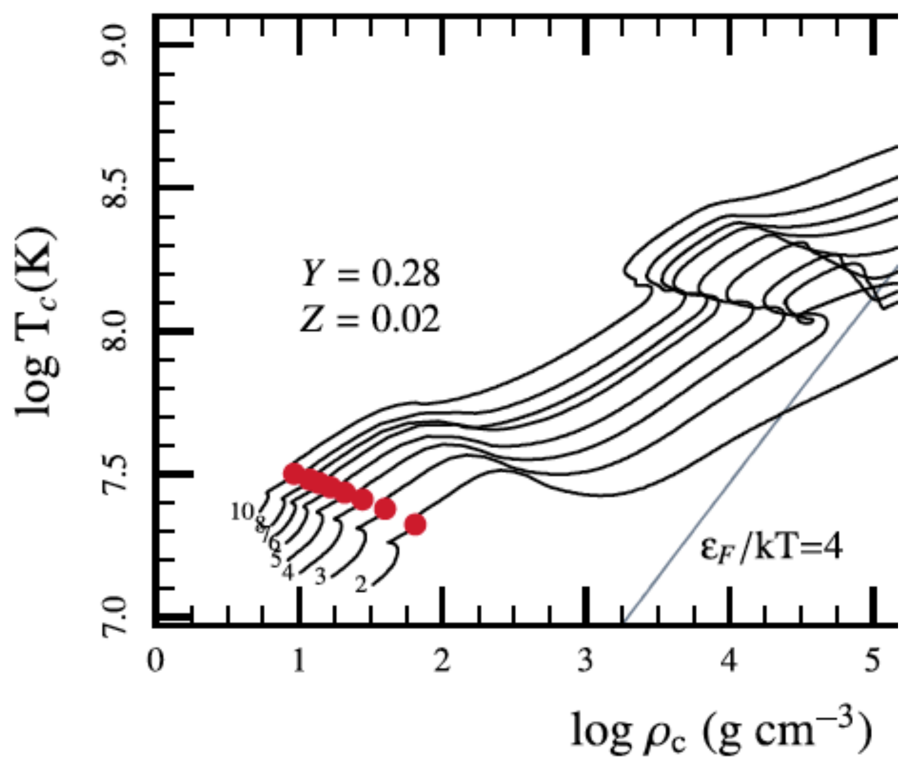
Results and Discussion

- Collect data from the room and present (Bill)
- Discuss any odd cases (did everybody ignite?)
- Compare to next plot

Results Discussion



Kippenhahn & Weigert



Paxton et al. 2011

Core Convection

- The strong temperature sensitivity of helium burning (in excess of T^{20}) leads to reaching L_{nuc}=L in a small volume=> High Flux=> Temperature gradient in excess of the adiabatic gradient and hence a convective core.
- Convection speeds are estimated by $F \approx \rho v_c^3 \approx L/4\pi r^2$

$$\left(\frac{v_c}{c_s}\right)^3 \sim \frac{L}{GM^2/R}\frac{R}{c_s} \sim \frac{10^{35}\mathrm{erg\ s^{-1}\ 70s}}{4\times 10^{49}\ \mathrm{ergs}} \sim 10^{-13}$$

- Though the motion is very subsonic, the eddy turnover time is still of order a month, so that the entropy and composition within the convective core are very uniform.
- Determines the lifetime of core Helium burning, since this sets the amount of available fuel

Continued Mini-Lab

- Now run your model until the central helium abundance falls to zero.
- What is
  - Time to complete the burning
  - C/O mix at this point in time.
- Once your core has burned out, keep running to see IF you can get helium to burn in the shell just above the C/O core

Results and Discussion

- Who got what outcomes ?
- Lifetime vs. mass…

Long Lab After Coffee

- For the long lab, you will fully explore Helium burning, but in this case for real stars that start with Hydrogen burning
-

Long Lab: Part One (20 minutes)

- Pick a mass randomly between 1 and 5 solar masses.
- Run the model through the Hydrogen burning Main sequence and stop it once Helium burning has started in the core of the star.
- Report L, T_{eff}, T_c, rho_c, size of convective core. Email your answers to Bill Wolf at wmwolf@physics.ucsb.edu
- Plot L(m) and comment on the role of H burning when the Helium is also burning.

Coffee!

Long Lab: Part One (20 minutes)

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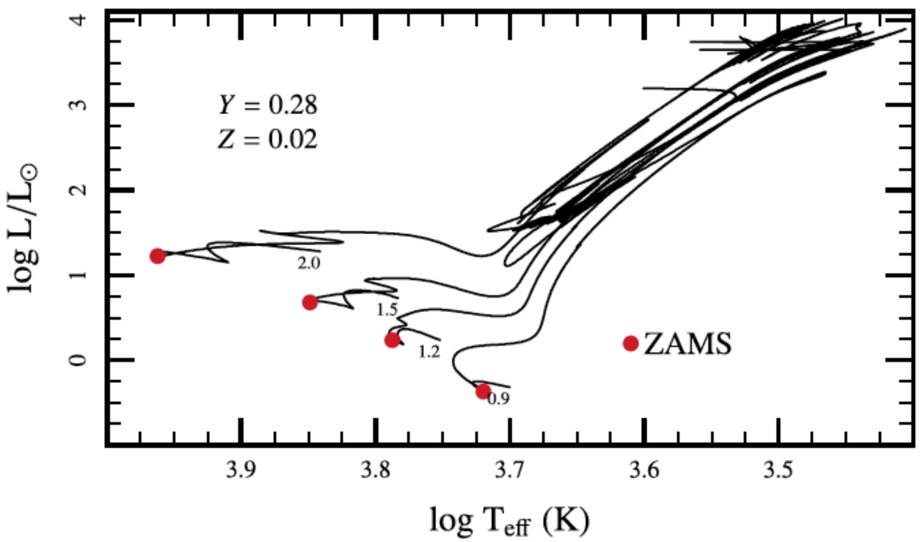
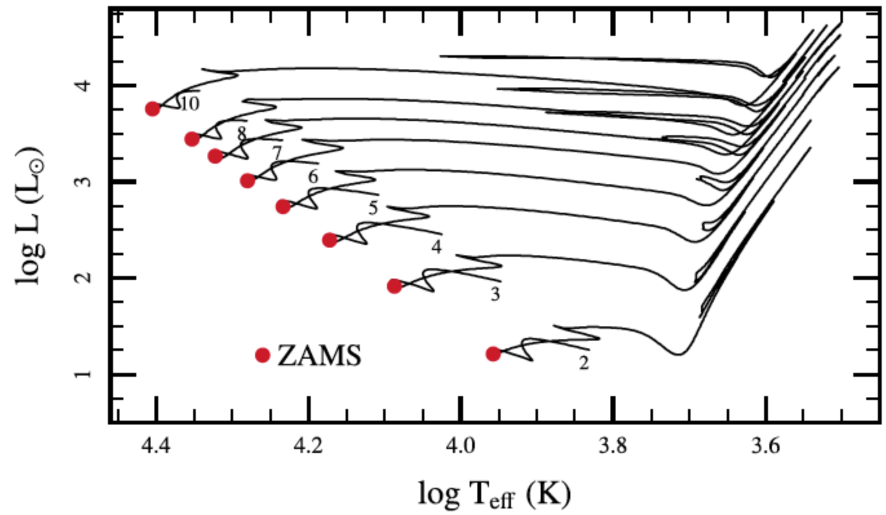
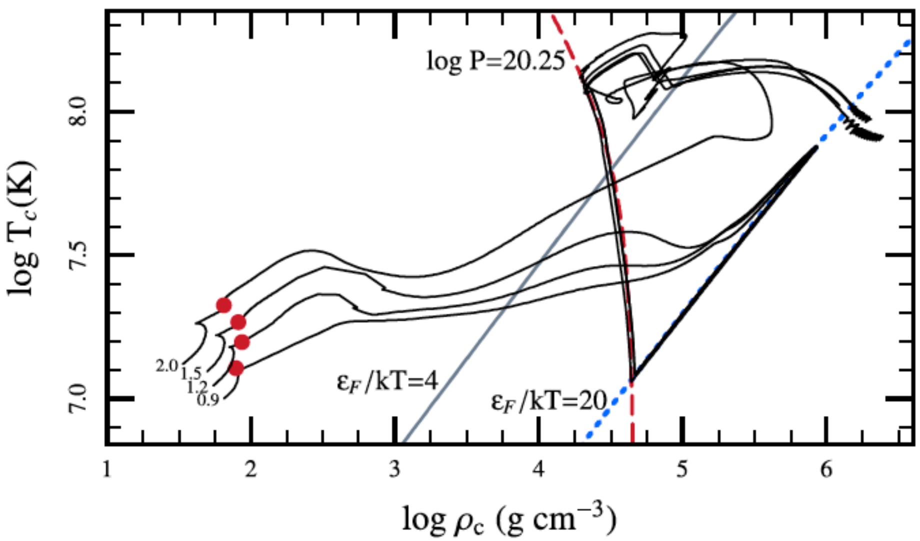
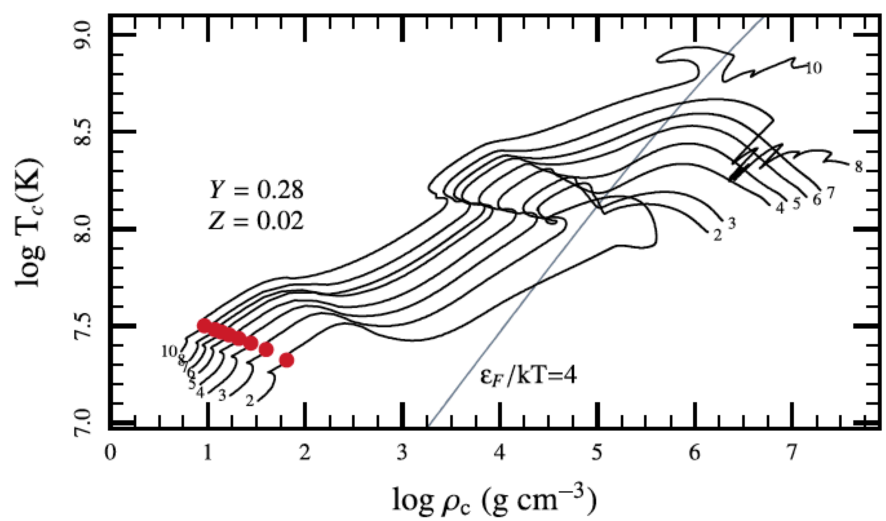
Anydbody Find a Core Flash?









Open Discussion (10 minutes)

Long Lab: Part Two (15 minutes)

- Now Continue running your star (or a surrogate) through the end of Helium Burning in the core.
- Report 1. duration of helium core burning, 2. amount of Hydrogen burned during this phase, and 3. final carbon/oxygen mix. Email your answers to Bill Wolf at wmwolf@physics.ucsb.edu

Open Discussion (10 minutes)

Long Lab: Part Three (15 minutes)

- Now Continue running your star (or a surrogate) and plot as a function of time:
  - Mass of the C/O core
  - Hydrogen shell and Helium Shell Burning Luminosity
- Halt the model when it undergoes the first 'thermal pulse' of unstable Helium shell burning.

Open Discussion (10 minutes)