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Evolution of Low Mass Stars (Cont'd):

Helium Flash:

With growing Core mass, the temperature of the core rises. This happens in the relativistic degenerate core (when $\rho \gtrsim 10^6 \, g \, cm^{-3}$). When the core mass is $M_c \simeq 0.45 \, M_\odot$, we have $T_c \simeq 10^8 \, K$, which is high enough to ignite Helium burning.

He burning results in an increase in the temperature. However, there will be no corresponding increase in the pressure for a fully degenerate matter. Thus the matter cannot expand and cool; temperature increase results in an increase in the rate of energy production, which in turn increases the temperature further and leads to a runaway process. This is the so-called "Helium Flash".

The runaway behaviour of temperature in this phase can be quantified as follows. The rate of change of T is given by:

$$C_V \frac{dT}{dt} = \varepsilon \quad (C_V\text{: specific heat per unit mass})$$

Where:

$$C_V = C_{V,ion} + C_{V,e^-}$$

For a fully ionized situation, the pressure from α particles is:

$$\boxed{C_{V,ion} = \frac{3}{2}\frac{k_B}{4m_u}}$$

On the other hand for the degenerate electron gas:

$$\boxed{C_{V,e^-} \simeq 1.35 \times 10^{14}\, T_9\, x(1+x^2)^{\frac{1}{2}}\, \rho^{-1}}$$

Here:

$$x = \left(\frac{\rho}{9.74 \times 10^5\, \mu_e\, g\, cm^{-3}}\right)^{\frac{1}{3}} \quad , \quad T_9 \equiv \frac{T}{10^9 K}$$

For Helium burning we have:

$$\varepsilon \simeq 5.1 \times 10^8\, \rho^3\, Y^2\, T_9^{-3}\, \exp\left(\frac{-4.4027}{T_9}\right)\ erg\, g^{-1}\, s^{-1}$$

Starting with (say) $T_9 = 0.15$, $\rho = 2 \times 10^5\ g\, cm^{-3}$, $\mu_e = 2$, $Y = 1$

we can find the increase in T. We should stop when the electrons become degenerate. This occurs when:

$$\frac{\rho}{\nu_e} \simeq 6 \times 10^{-9} \, T^{3/2}$$

At this point thermal de Broglie wave length of electrons becomes smaller than their mean separation. Once the degeneracy is removed, the core expands and the increase in the temperature stops. The star then settles for the values appropriate for stable Helium burning.

Helium flash is an extremely short phase. It lasts for ~6 days. The temperature is nearly constant up to about 5.7 days, and then shoots up rapidly.

Evolution after the Helium Flash:

Until the onset of Helium **burning**, the total luminosity of the star increases with increasing core mass (recall that core contraction and envelope expansion during the red giant phase, while T_e being nearly constant). After the temperature shoots up in the Helium flash phase and removes degeneracy, the core expands and the envelope contracts. This results in an appreciable decrease in the luminosity (as also discussed in the case of high mass stars).

The Helium burning now stabilizes in the core, and the evolution is similar to the initial evolution of the star, with Helium burning replacing Hydrogen burning. Broadly speaking, the star at this stage can be thought of as made of a Helium burning core and a Hydrogen envelope. We discussed the evolution of such star before, and its evolutionary trajectory in the H-R diagram is shown in the figure on page 119.

From that figure, we would expect the star with a Helium burning Core and a Hydrogen envelope to move to the left in the H-R diagram toward the Horizontal Branch. The subsequent evolution parallels the original departure from zero age main sequence, and the star moves back to the red giant branch. This is usually called an Asymptotic Giant Branch, which is close to the original giant branch but at a slightly higher T_e. The star will the evolve toward the white dwarf stage.

The time scale for the horizontal branch is given by:

$$t_{HB} \sim \left(\frac{M}{M_\odot}\right)\left(\frac{L_\odot}{L}\right) 10\ Gyr$$

Stars with a mass less than approximately $(1.8-2.2)\,M_\odot$ experience Helium flash and have a luminosity $\sim 50\,L_\odot$ while on the horizontal branch. The Helium Core of these stars have mass $\sim 0.45\,M_\odot$. Approximately, half of this

Helium is converted into Carbon and the other half to Oxygen. Thus, the time scale for the horizontal branch is given by:

$$t_{HB} \approx 7.2\times10^{-4} \frac{0.45\, M_\odot c^2}{50\, L_\odot} \approx 0.5\ \text{Gyr}$$

This is much shorter than the main sequence, which lasts ≈ 10 Gyr for a $M_\odot$ star.