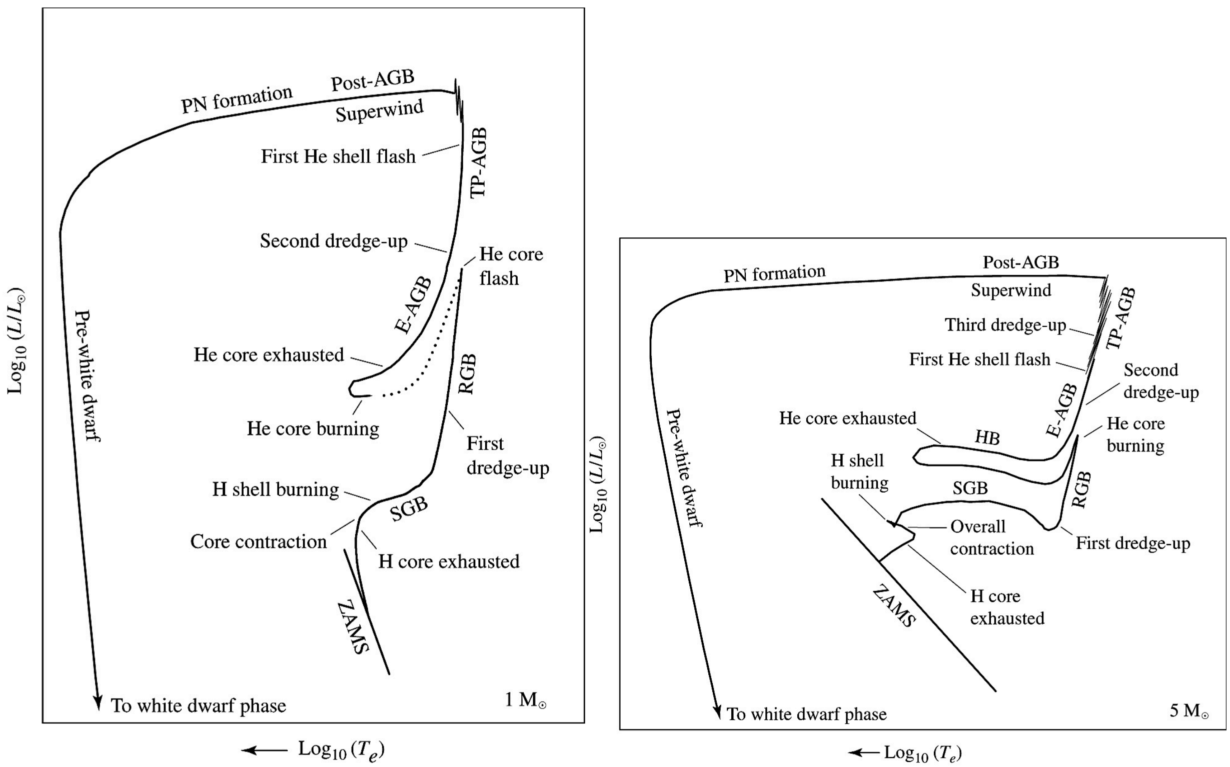
Astronomy 404
November 1, 2013
Chapter 13. Main Sequence and Post-Main Sequence Stellar Evolution



The evolution of a star depends on its mass. Above are the evolutionary tracks for 1 $M_\odot$ and 5 $M_\odot$ stars.

As the hydrogen is exhausted (turned into helium) in the core:
* 1 $M_\odot$ star's He core contracts, raising the temperature of the H-burning shell and producing more energy than the H core on the main sequence; the higher energy output drives the expansion of the envelope; the luminosity goes up but the stellar effective temperature goes down; the star enters the **sub-giant branch (SGB).**
* 5 $M_\odot$ star's entire star contracts; at first the radius goes down, but the gravitational energy release drives up the luminosity, and the stellar effective temperature goes up; then a H-burning shell around the He

core is ignited, the high energy output drives the envelope expansion, and the star enters the SGB.

The expansion of stellar envelope takes energy, so the SGB luminosity may go up or down, depending on how much energy is spent on the envelope expansion.

As the temperature drops along the SGB, the opacity goes up, especially with the abundant H^-, leading to a convective envelope; the convection transports energy and makes radiation easier to escape the star, so the luminosity goes up; the star now enters the **red giant branch (RGB).**

The convective envelope can extend deep into the H-burning shell, and bring processed material up to the stellar surface and change the stellar surface abundance. In this **first dredge-up**, the abundances of Li and C go down, and abundances of ^{3}He and ^{14}N go up.

At the tip of RGB:
* < 1.8 $M_\odot$ star has a temperature inversion at its core because degenerate electrons provide the pressure (independent of temperature) and energy is lost from them thermal gas through escaping neutrinos; when the core's temperature (10^8 K) and density (10^7 kg m^{-3}) are high enough, He-burning (triple-α process) is ignited; as the reaction rate is highly dependent on temperature, the ignition is almost explosion, generating a luminosity as high as 10^{11} $L_\odot$; this **helium flash** lasts for only a few seconds and the energy produced is used to expand the core and lift degeneracy; once the core expands the density drops and the energy production rate drops. The helium flash does not produce appreciable effects on the stellar surface. It is difficult to model/computer the helium flash, so the model stops here.
* 5 $M_\odot$ star's core is not as degenerate as a low-mass star; at the tip of the RGB, its core is already burning He via triple-α process, turning He into C and O; the high energy production rate of He-burning causes the core to expand, and the density to drop; the lower density leads to

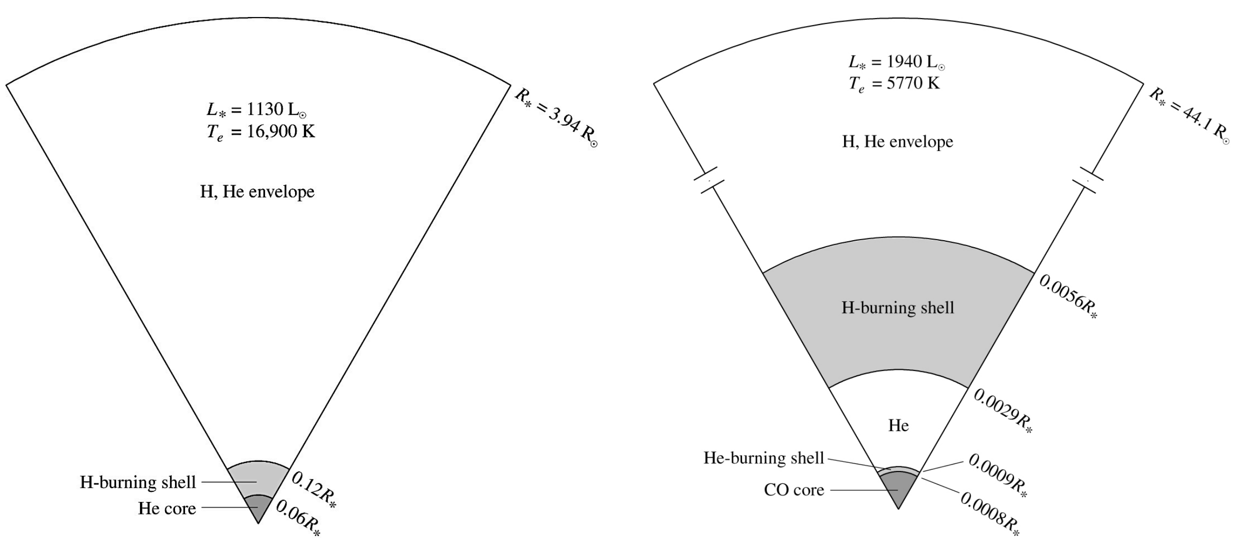
lower energy production rate and a lower luminosity; as the luminosity drops and the envelope contracts, the stellar effective temperature rises; the star enters the **horizontal branch**; at the blue end of the horizontal branch the star burns He in the core steadily just like the H-burning main sequence stars; this is the He-burning main sequence.

In the horizontal branch, as He turns into C-O in the core, the core contraction raises the temperature of the He-burning shell, and the increased energy output forces the material above the shell to expand and cool, resulting in a temporary turn-off of the H-burning shell.

As He is exhausted in the core, the CO core contracts and the stellar evolution track is similar to that following the exhaustion of the H-burning core. The CO core contraction raises the temperature and density of the He-burning shell. The increased energy production forces the envelope to expand and the star enters the **early asymptotic giant branch (E-AGB)** stage.

During the E-AGB stage, the convection in the stellar envelope causes the second dredge-up of product of H-burning, e.g., He and N.

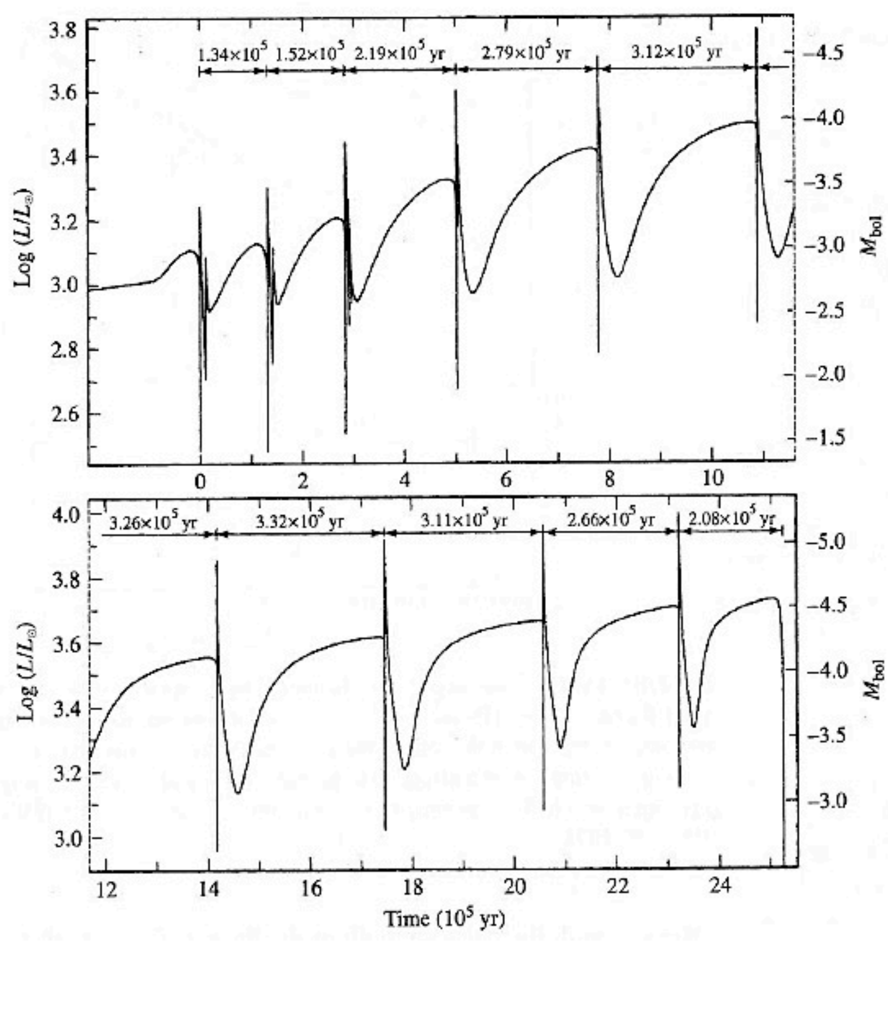
Structure of a 5 $M_\odot$ star
@ onset of H-burning shell and @ E-AGB (He-burning shell)



The upper portion of the AGB is called **thermal pulse AGB (TP-AGB)**. Here the star has a H-burning shell, which deposits He into the He-rich layer whose base is degenerate. When the temperature at the base of the He layer is high enough, a **helium shell flash** occurs, driving the H-burning shell outward and causing it to cool and turn off. When the He-shell burning is turned off, the envelope contracts and the H-burning shell is turned on again...

The period between thermal pulses is a function of stellar mass, ranging from 10^3 yr for a 5 $M_\odot$ star to 10^5 yr for a 0.6 $M_\odot$ star.

Long period variables (LPVs) and **Mira variables** are examples of AGB stars.



During the TP-AGB phase, a convection zone is developed between the He-burning shell and the H-burning shell. The convection brings the He-burning product to the surface. This is the **third dredge-up**, which enriches the surface with C and cause C/O > 1. The star becomes a **carbon star**.

^{99}Tc (technetium) is unstable with a half-life of 200,000 yr, but it is present in the spectrum of TP-AGB stars. It must have been freshly made. Tc is produced by **s-process**, in which heavy nuclei are built up by absorbing neutrons one by one slowly. A nucleus may decay into other nuclei before absorbing another neutron in the *slow* s-process, as opposed to no time to decay in the rapid **r-process.**

Mass loss and post-AGB evolution

All stars less massive than ~ 8 $M_\odot$ evolve into white dwarfs. When they are in AGB and post-AGB phase, they lose mass in the form of "superwind" with mass loss rates as high as 10^{-4} $M_\odot$/yr.

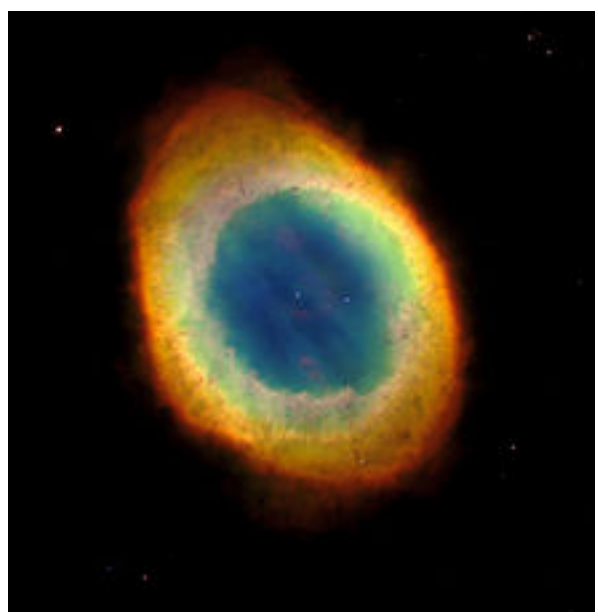
Without mass loss rate, 4-8 $M_\odot$ stars would have their degenerate cores exceeding the Chandrasehkar Limit and collapse into neutron star. The fact that they evolve into white dwarfs requires that they do lose mass via superwinds.

The 1-5 $M_\odot$ stars develop degenerate C-O core, while the more massive stars develop degenerate ONeMg cores. These degenerate cores become white dwarfs.

Most known white dwarfs have masses ~0.6 $M_\odot$ because high-mass white dwarfs are scarce due to the IMF and the stars with very low masses have not evolved into white dwarfs yet. With the mass loss during the AGB phase, most stars with masses of 1 to a few $M_\odot$ end up in ~0.6 $M_\odot$ white dwarfs.

Planetary Nebulae

The mass loss from AGB stars form planetary nebulae. The superwind is followed by a fast wind, which sweeps up the superwind to form a shell, which is photo-ionized by the hot central star to become a visible planetary nebula.



Planetary nebulae are very dusty. They contain clumps of molecular material mixed with dust.

The surface of the dense clumps can be photoionized by the central star to form the tadpole-like structure (below-left). Deep images of planetary nebulae can reveal extended history of mass loss from the star throughout its evolution (below-right).