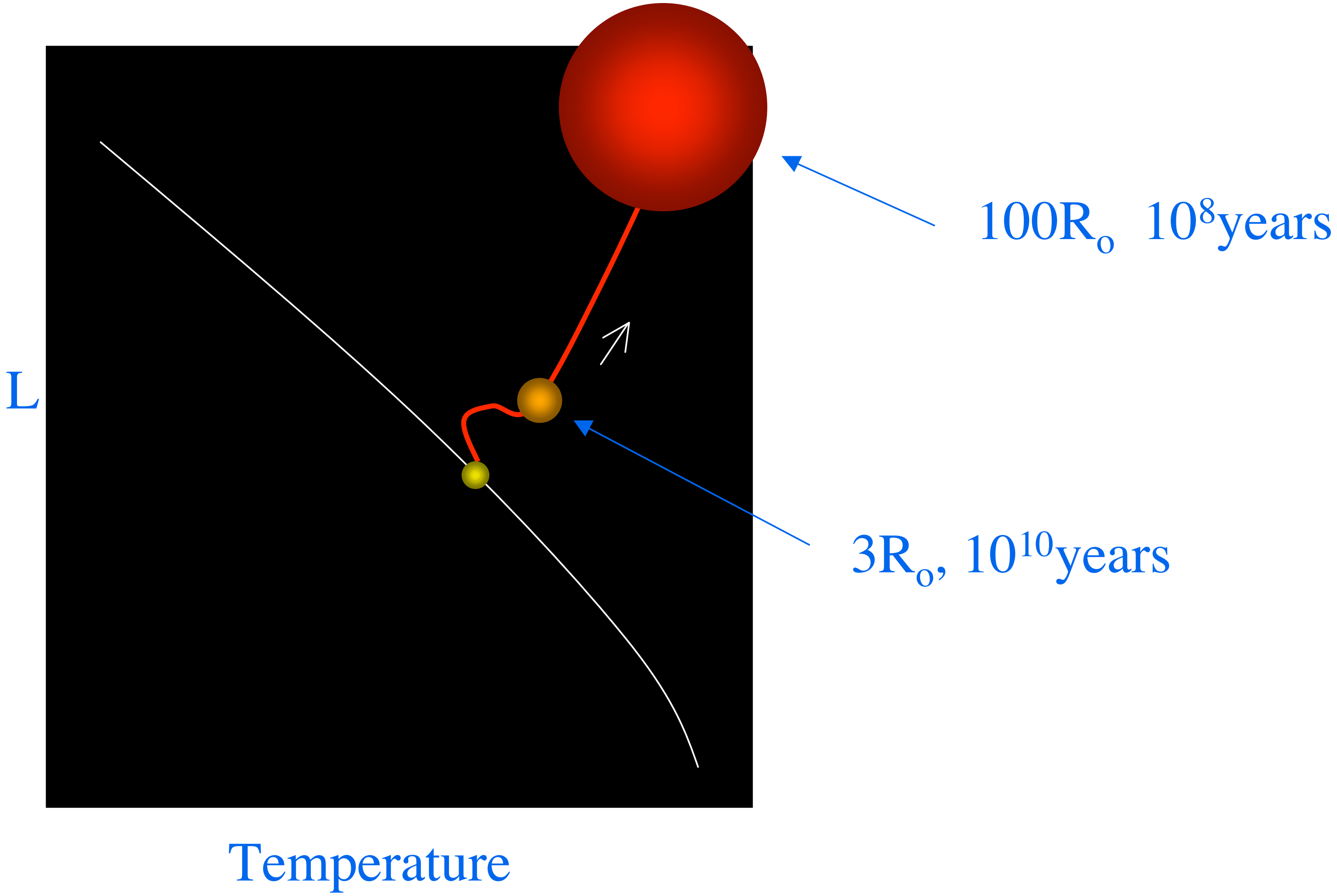
Announcements

- Next Session
  - Stellar evolution
    - Low-mass stars
    - Binaries
    - High-mass stars
  - Supernovae
  - Synthesis of the elements
- Note: Thursday Nov 11 is a campus holiday

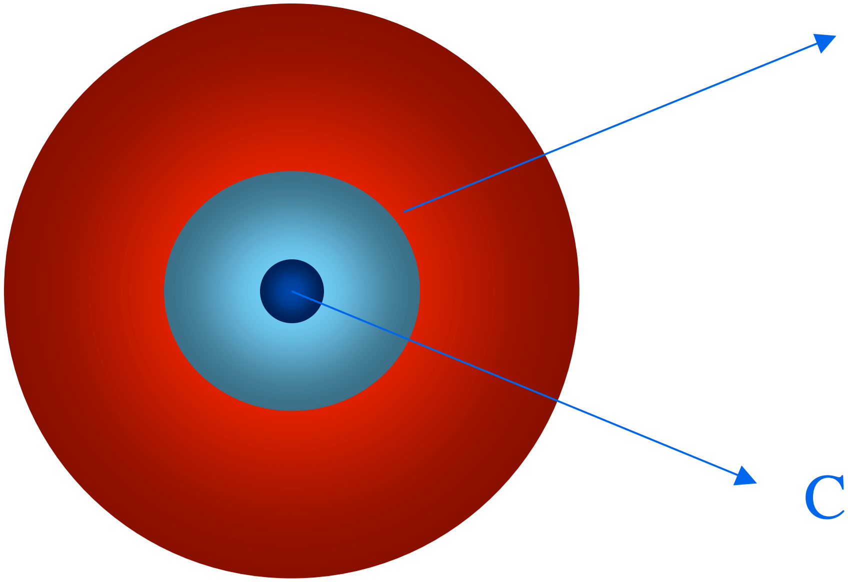
Red Giant



$100R_o$ 10^8years

$3R_o$, 10^{10}years

Red Giant



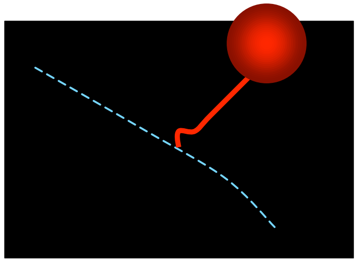
Hydrogen fusion shell

Contracting helium core

Electron Degeneracy

- Pauli Exclusion Principle says that you can only have two electrons per unit 6-D phase-space volume in a gas.

$$\Delta x \Delta y \Delta z \Delta p_x \Delta p_y \Delta p_z$$



Red Giants

- RG Helium core is support against gravity by electron degeneracy
- Electron-degenerate gases do not expand with increasing temperature (no thermostat)
- As the Temperature gets to 100 x 10^6K the “triple-alpha” process (Helium fusion to Carbon) can happen.

Helium fusion/flash

Helium fusion requires two steps:

$He^4 + He^4 \rightarrow Be^8$

$Be^8 + He^4 \rightarrow C^{12}$

The Berylium falls apart in 10^{-6} seconds so you need not only high enough T to overcome the electric forces, you also need very high density.

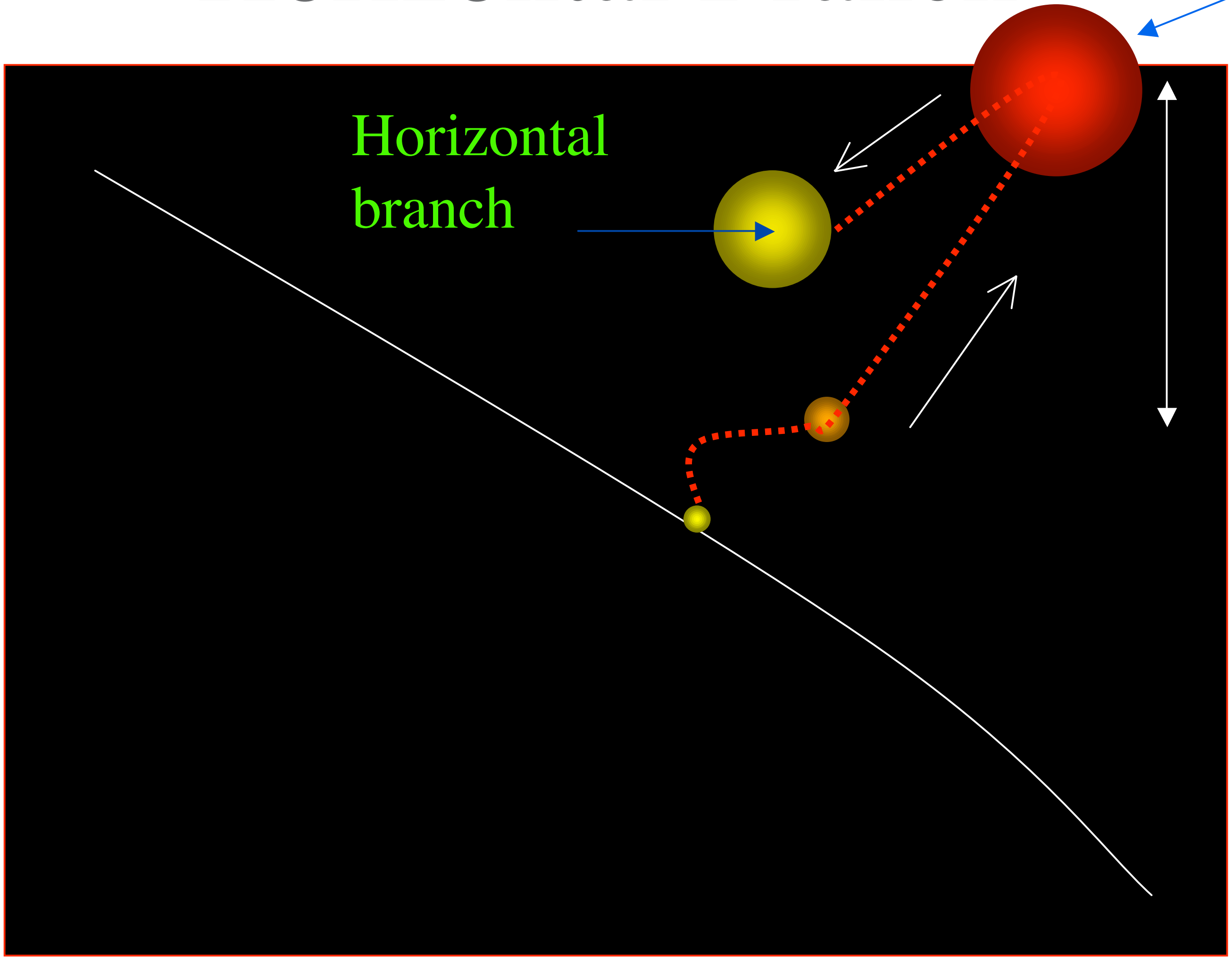
Helium Flash

- The Temp and Density get high enough for the triple-alpha reaction as a star approaches the tip of the RGB.
- Because the core is supported by electron degeneracy (with no temperature dependence) when the triple-alpha starts, there is no corresponding expansion of the core. So the temperature skyrockets and the fusion rate grows tremendously in the `helium flash’.

Helium Flash

- The big increase in the core temperature adds momentum phase space and within a couple of hours of the onset of the helium flash, the electrons gas is no longer degenerate and the core settles down into `normal’ helium fusion.
- There is little outward sign of the helium flash, but the rearrangment of the core stops the trip up the RGB and the star settles onto the *horizontal branch*.

Horizontal Branch



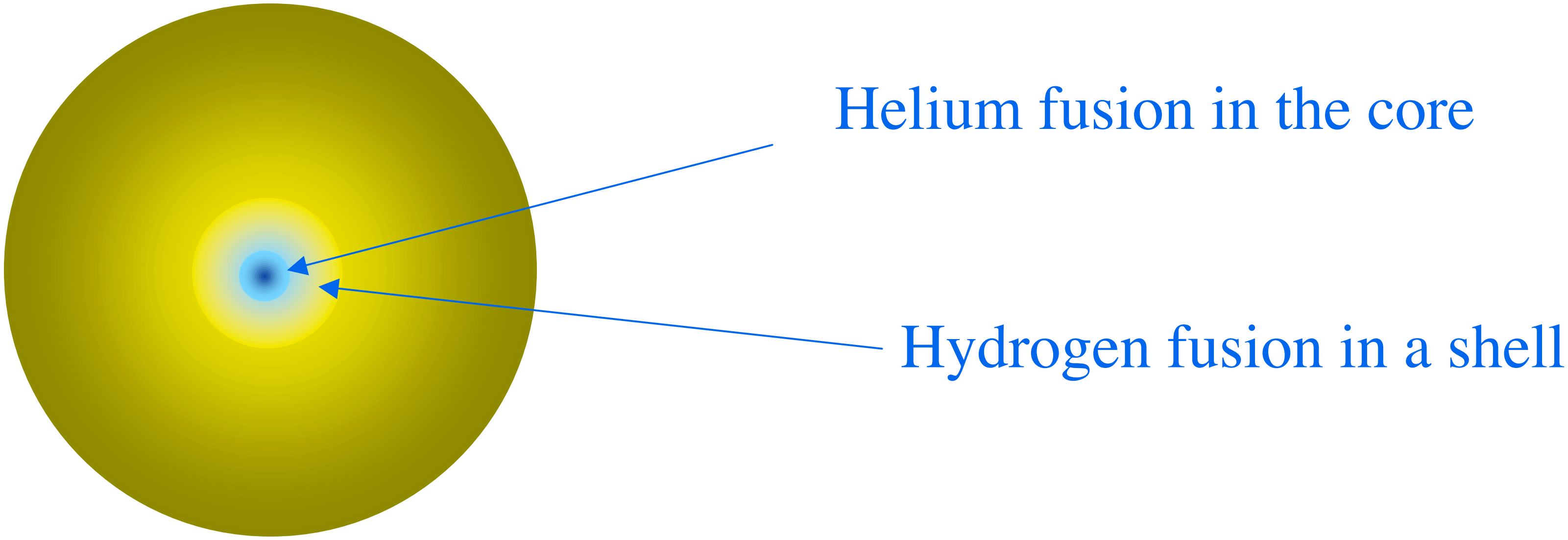
Helium flash

Horizontal branch

RGB

Horizontal Branch

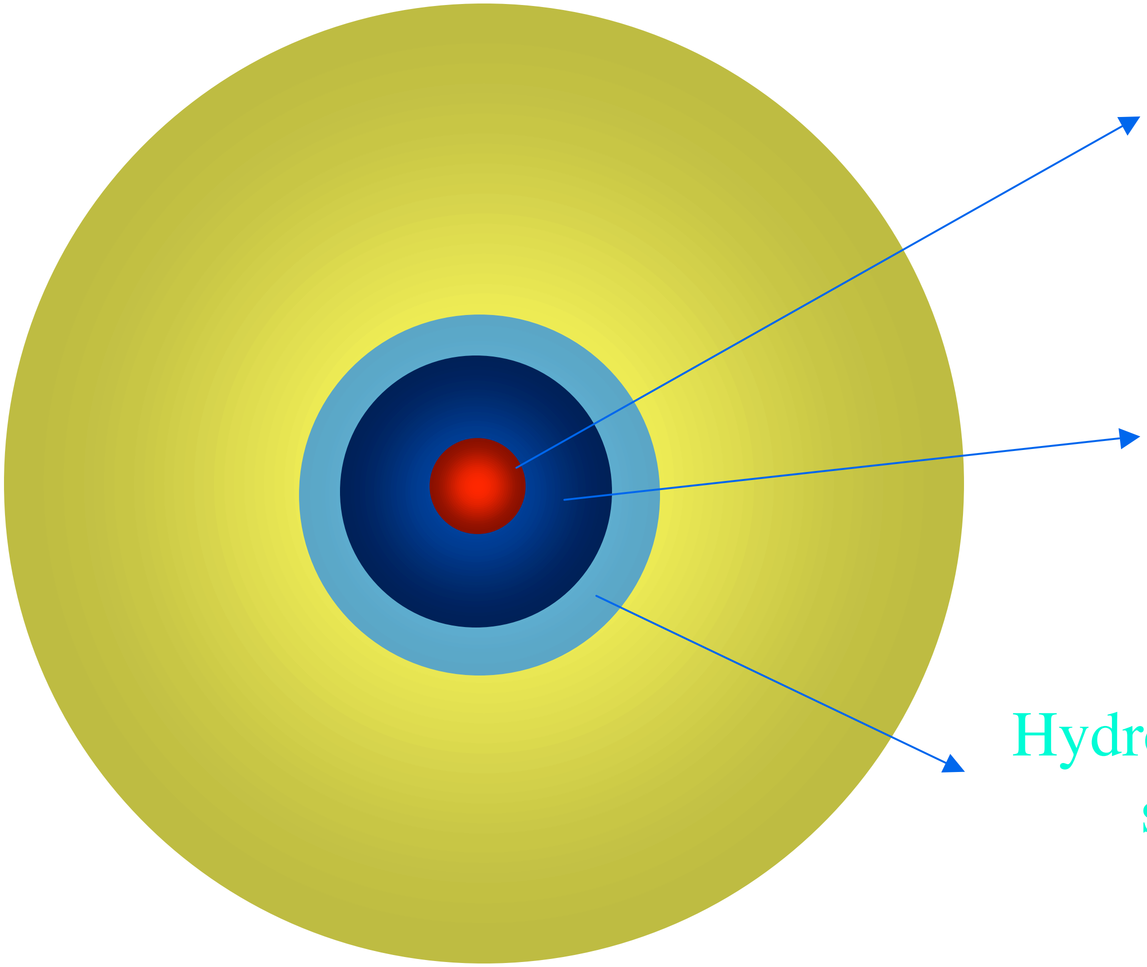
- Stars on the horizontal branch have similarities to main-sequence stars



The Second Ascent Giant Branch

- Horizontal-branch stars (like main-sequence stars) begin to use up their fuel in the core.
- In this case, the star is building up a Carbon core. *For stars near $1M_o$ the temperature never gets high enough for Carbon fusion.*
- The core begins to contract, releasing gravitational potential energy and increasing the fusion rates in the He and H fusion shells. Does this sound familiar?

Asymptotic Giant Branch



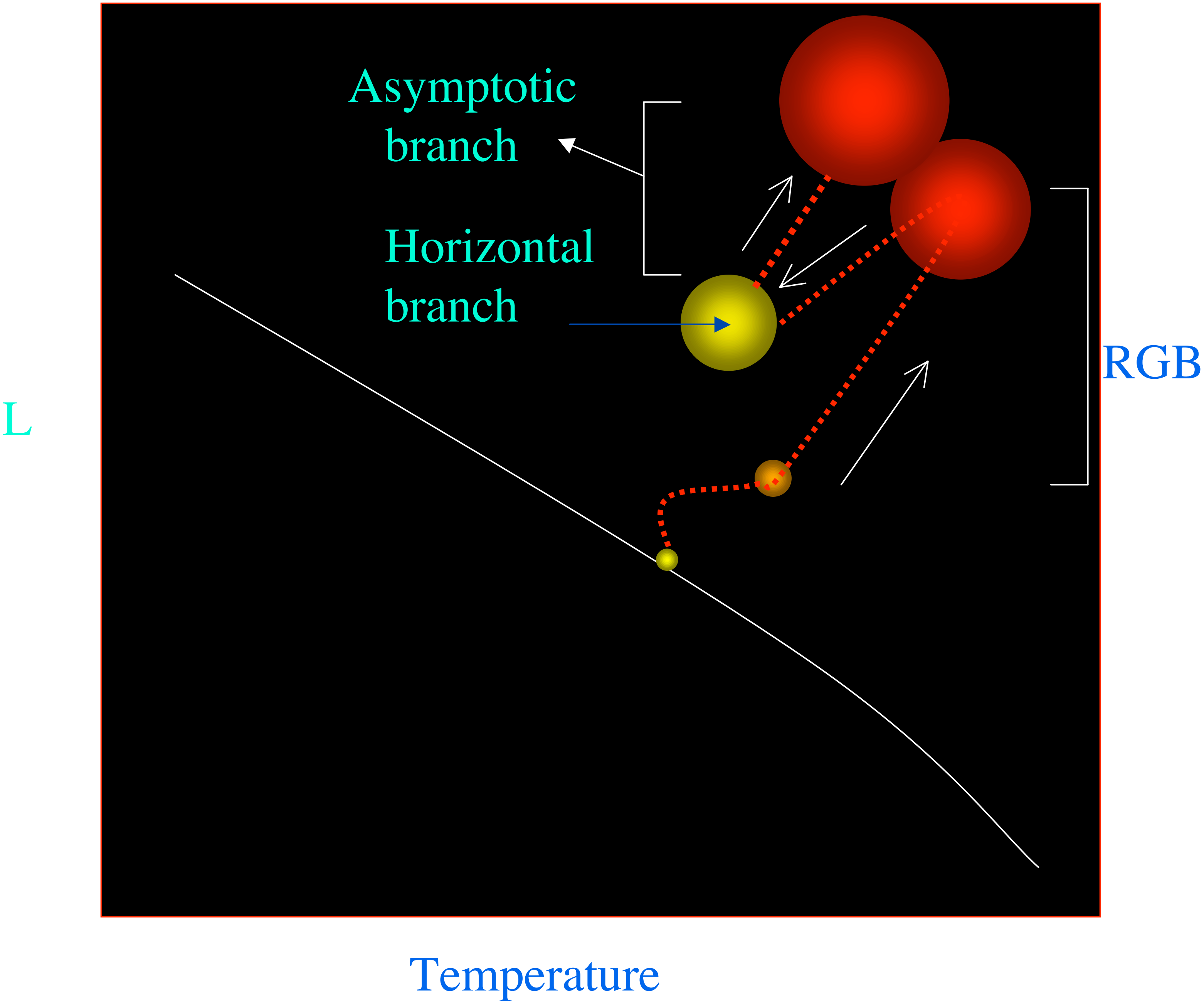
Carbon Core

Helium fusion
shell

Hydrogen Fusion
shell

Asymptotic Giant Branch

- This is like the transition from the main sequence to the Red Giant Branch.
- Stars evolve off the HB up and right in the HR-Diagram on a track parallel and above the RGB. Now, the energy generation is much more erratic. The triple-alpha process rate scales with T^{30}(!). AGB stars undergo `Shell flashes’.



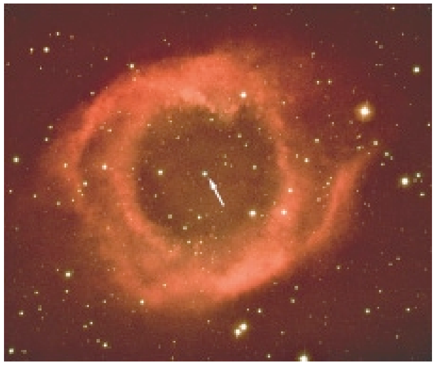
L

Asymptotic branch

Horizontal branch

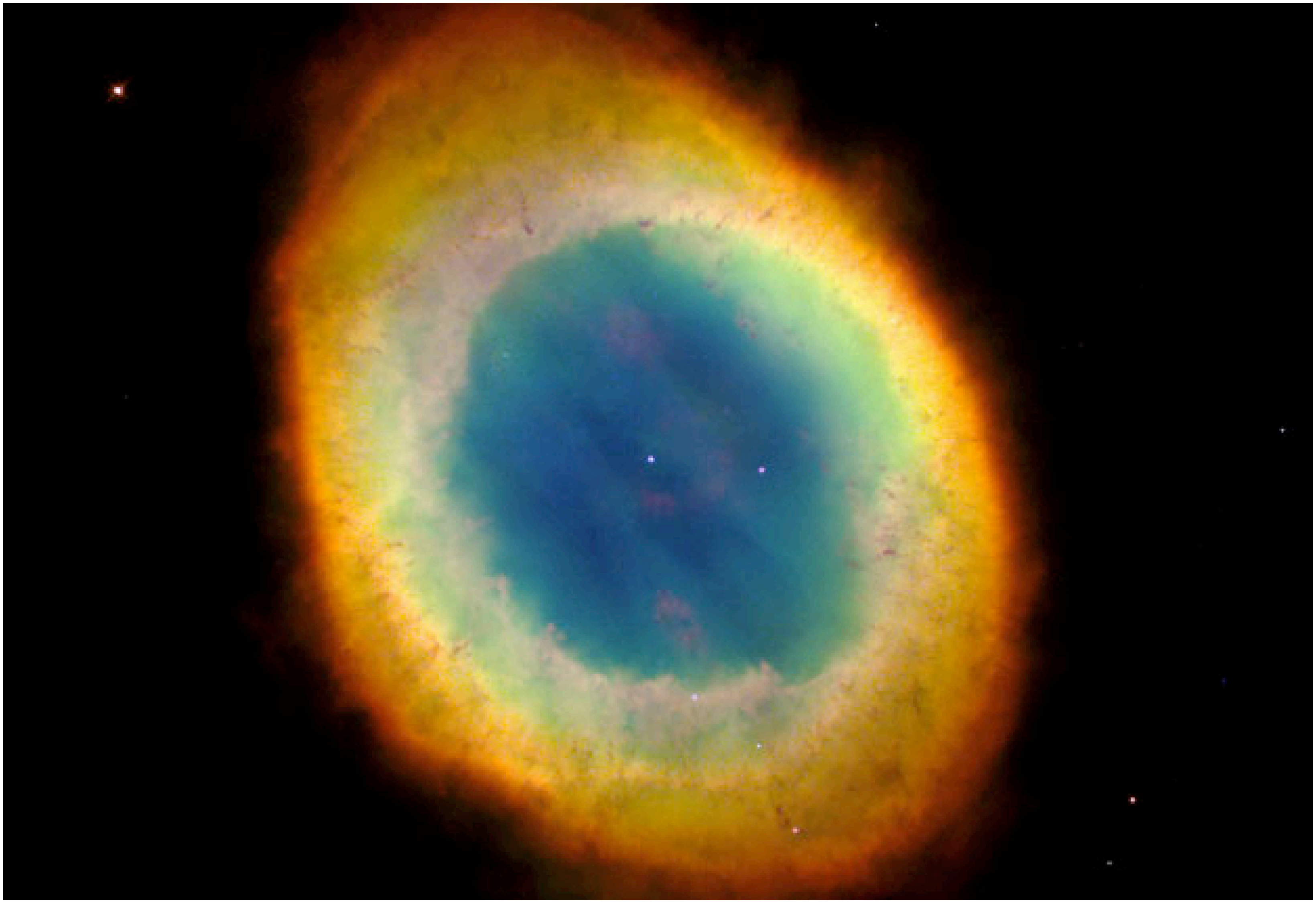
RGB

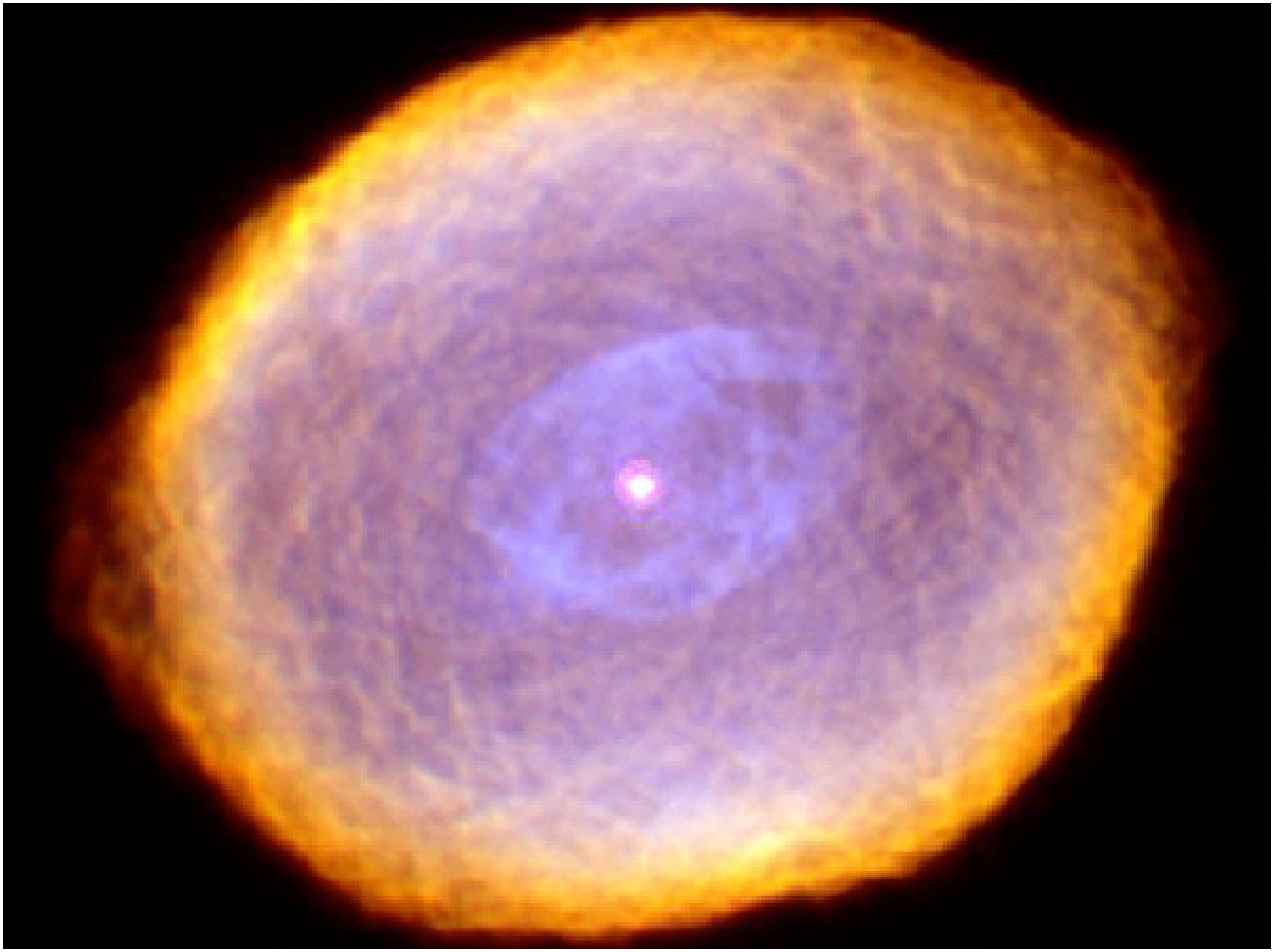
Temperature

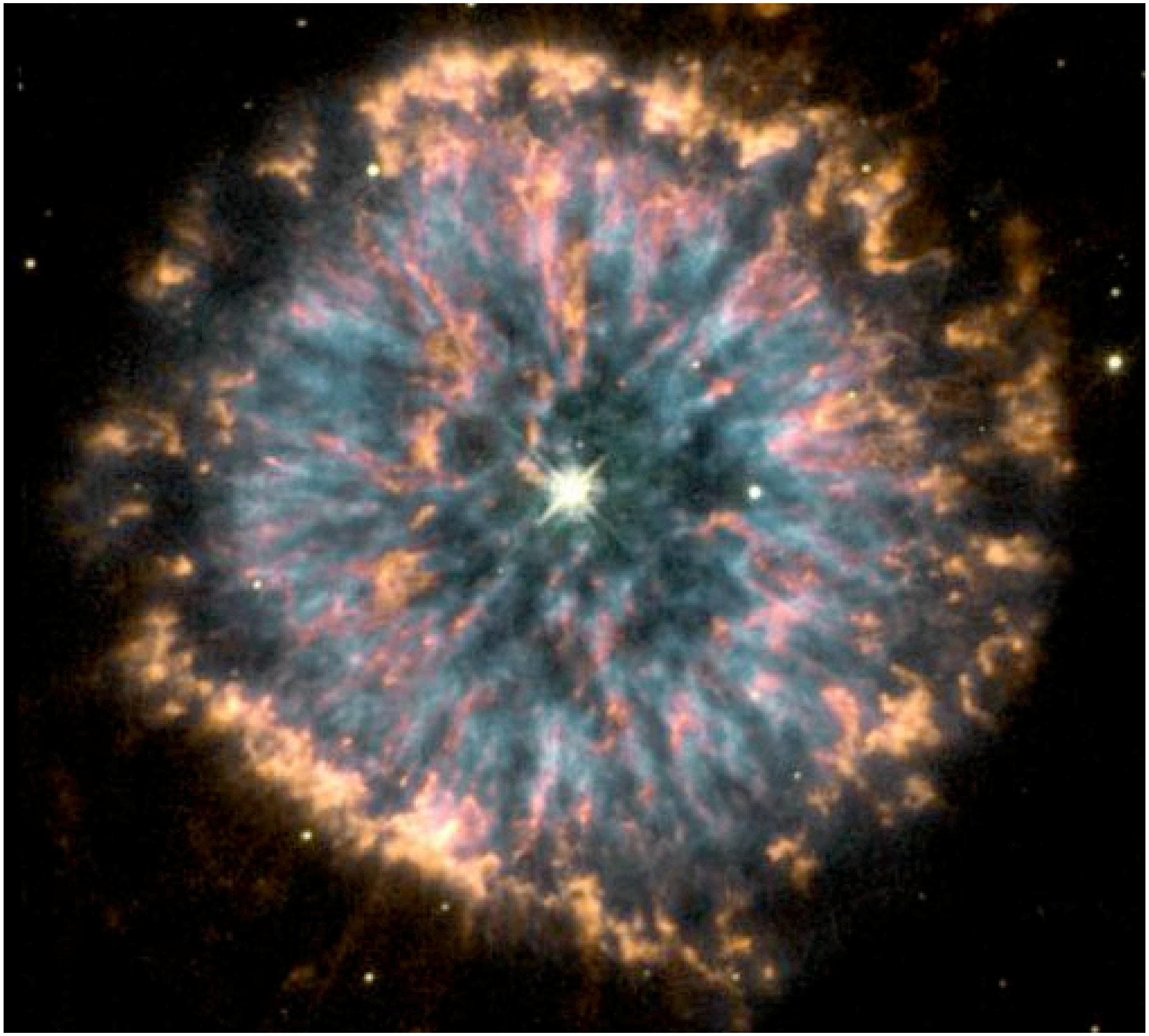


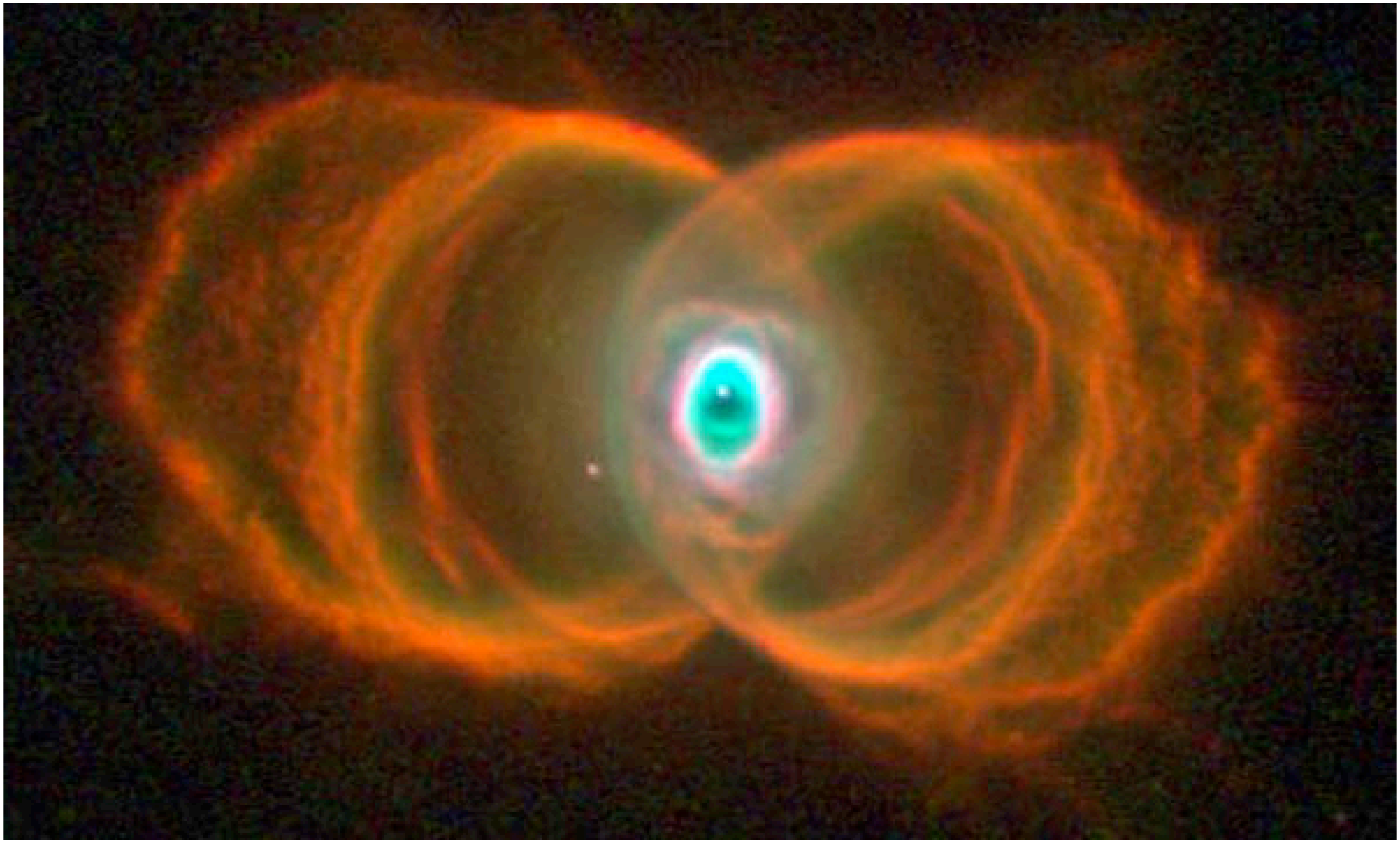
Planetary Nebula Stage

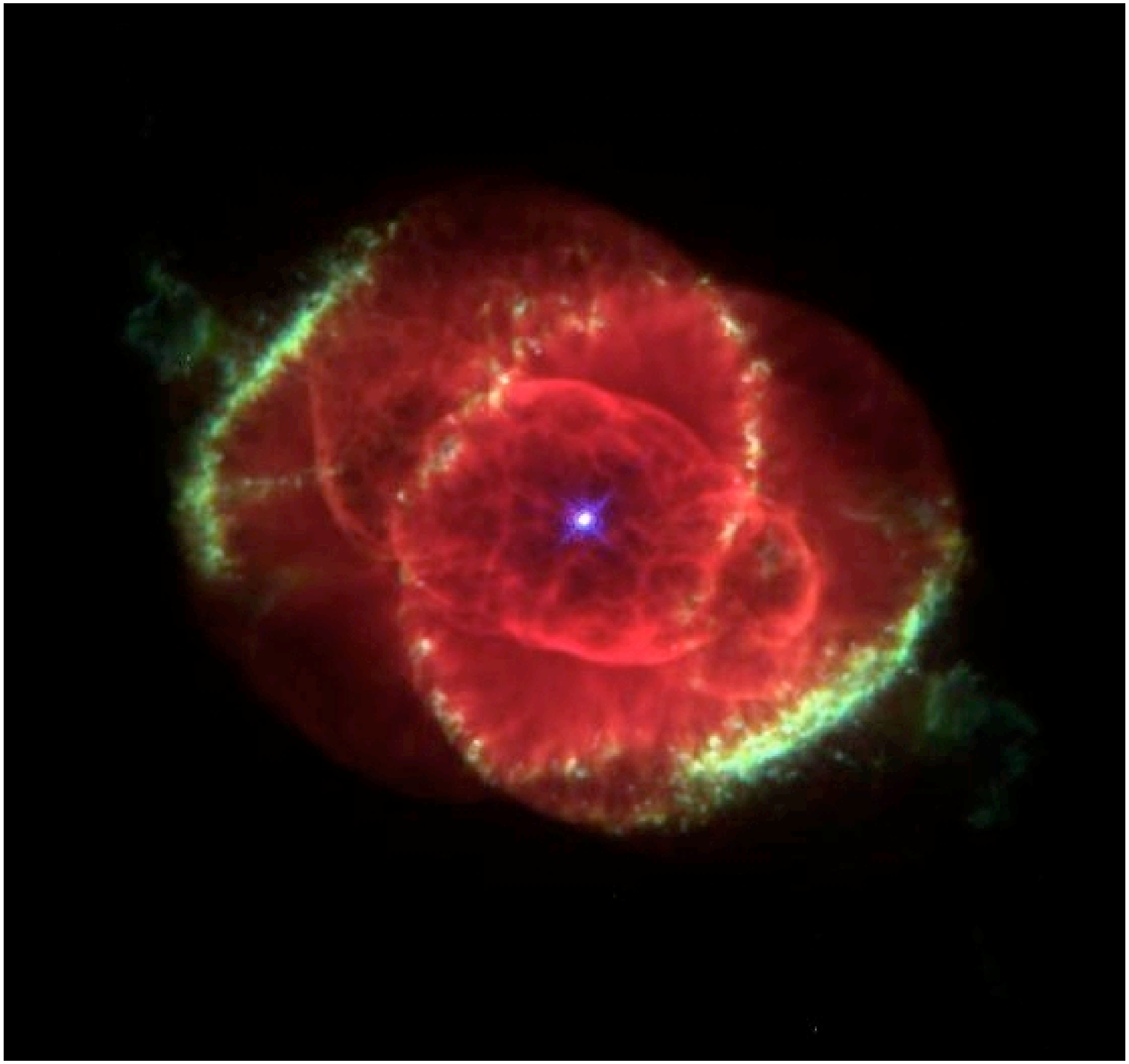
- The trip up the AGB (or `second ascent giant branch') gets terminated when the star's outer envelope becomes detached and begins to drift off into space. (!!)
- The former envelope shines in the light of emission lines.
- As the envelope expands and becomes transparent the very hot core of the AGB star can be seen at its center.





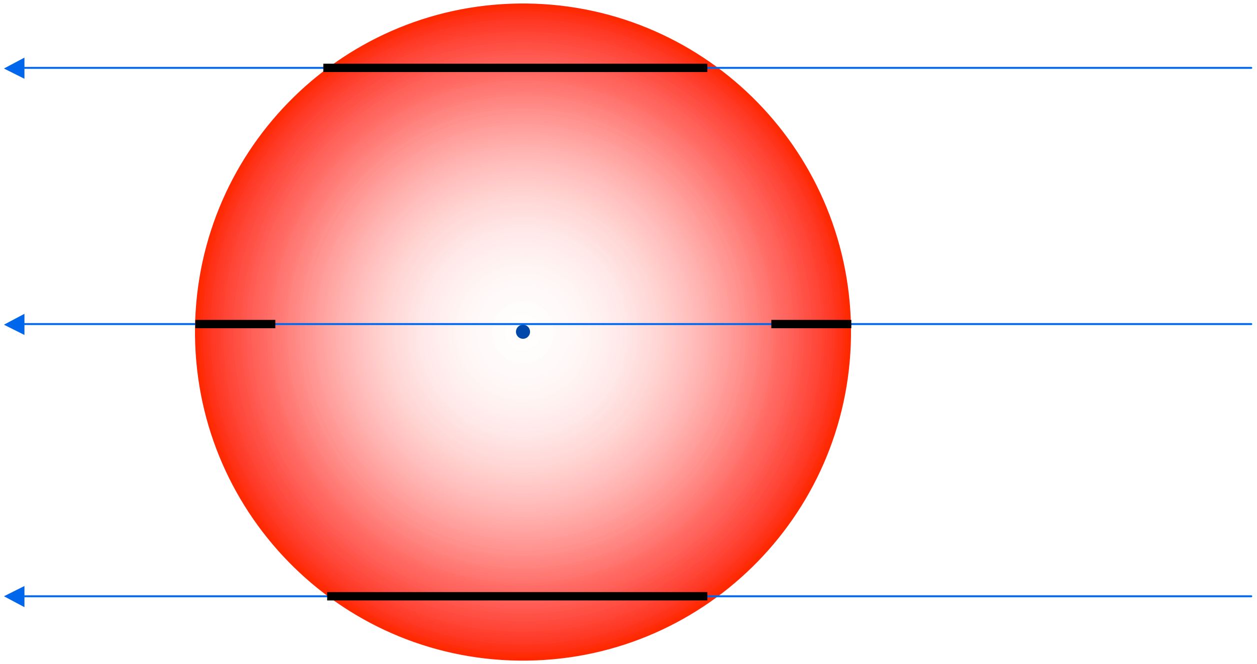






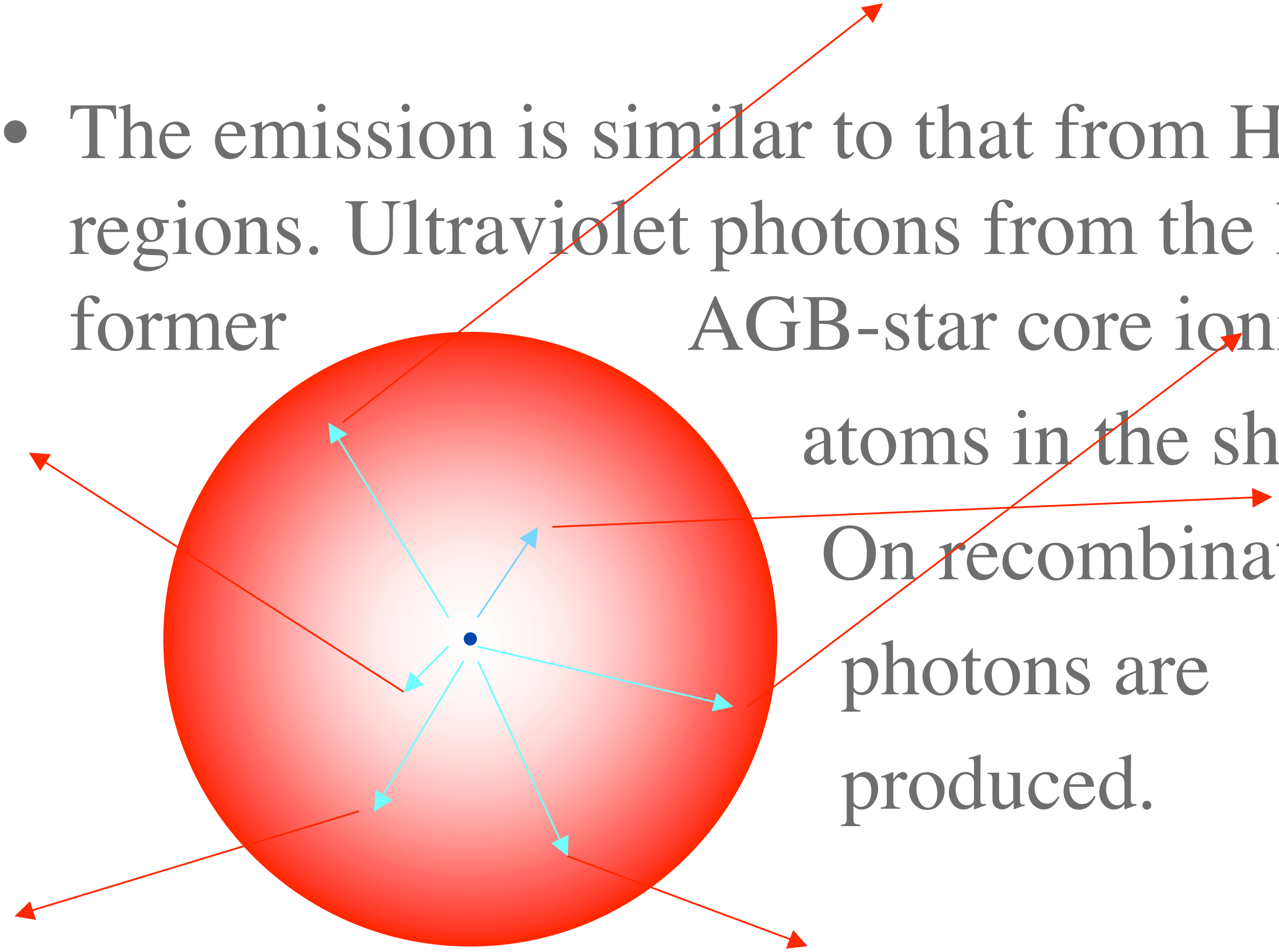
Planetary Nebulae

- The outer envelope expanding out as a shell appears as a ring in the sky.



Planetary Nebulae

- The emission is similar to that from HII regions. Ultraviolet photons from the hot former AGB-star core ionize atoms in the shell. On recombination, photons are produced.



Planetary Nebulae Shells

- The ejection mechanism for the shell is a combination of winds from the core, photon pressure, perhaps the shell flashes and the large radius of the star.
- The shell expands into space at relatively low speed (20 km/sec).
- Approximately 50% of the AGB star mass is ejected.

Planetary Nebulae Shell

- The shell expands and is visible for about 30,000 years growing to a size of more than a light year.
- The shell is enhanced in the abundance of He, Carbon, Oxygen (because of convection during the AGB phase). This is one of the means by which `Galactic Chemical Evolution' proceeds.
- There are about 30,000 PN in the Galaxy at any time.

Planetary Nebulae Central `Star'

- The object in the center of the nebula is the former core of the AGB star.

  (1) It is hot! T>150,000k initially

  (2) Supported by e- degeneracy

  (3) Mass ~ $0.6M_o$

  (4) Radius ~ 6000km (Earth)

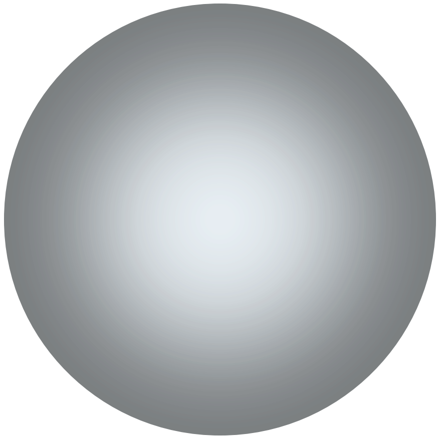
  (5) Density ~ 10^9 kg/m^3

  A thimble of material at this density would weight about 5 tons on Earth.

Planetary Nebulae Central `Star’

- The central `star’ isn’t a star because it has no energy source. This is a white dwarf.
- Supported against gravity by e- degeneracy.
- Lots of residual heat, no energy source, a white dwarf is like a hot ember. As it radiates energy into space, the white dwarf cools off.
- There is an upper limit to the mass of a WD set by e-degeneracy. $1.4M_o$ is the Chandrasekar Limit.

White Dwarf

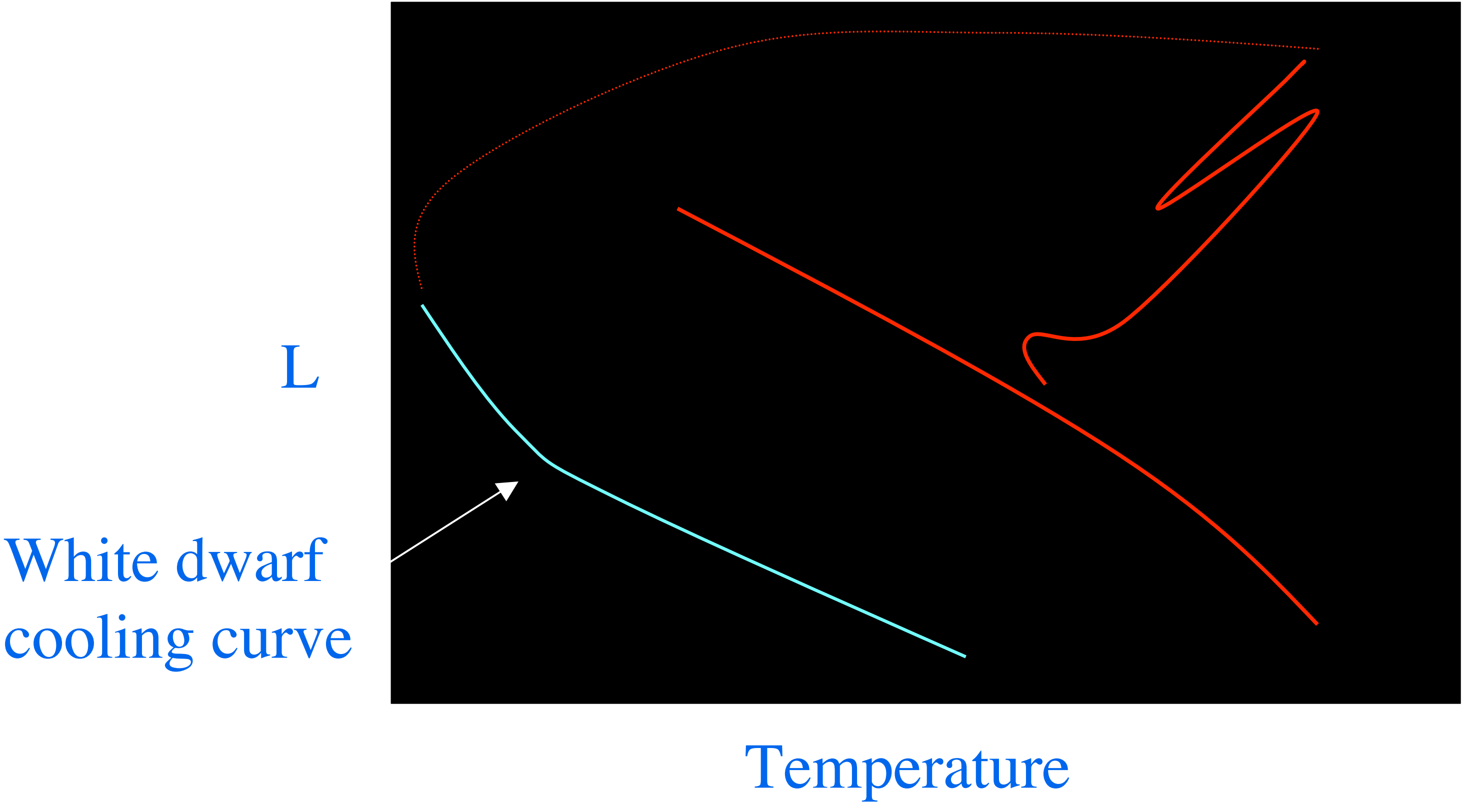


- Energy source: none
- Equilibrium:
  e- degeneracy vs gravity

- Size: 6000km (Earth)

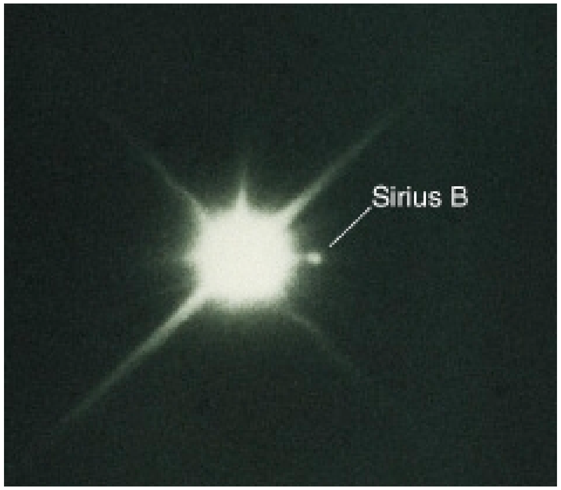
White Dwarfs

- WDs appear in the HR-Diagram in the upper left and VERY rapidly evolve downward and to the right.



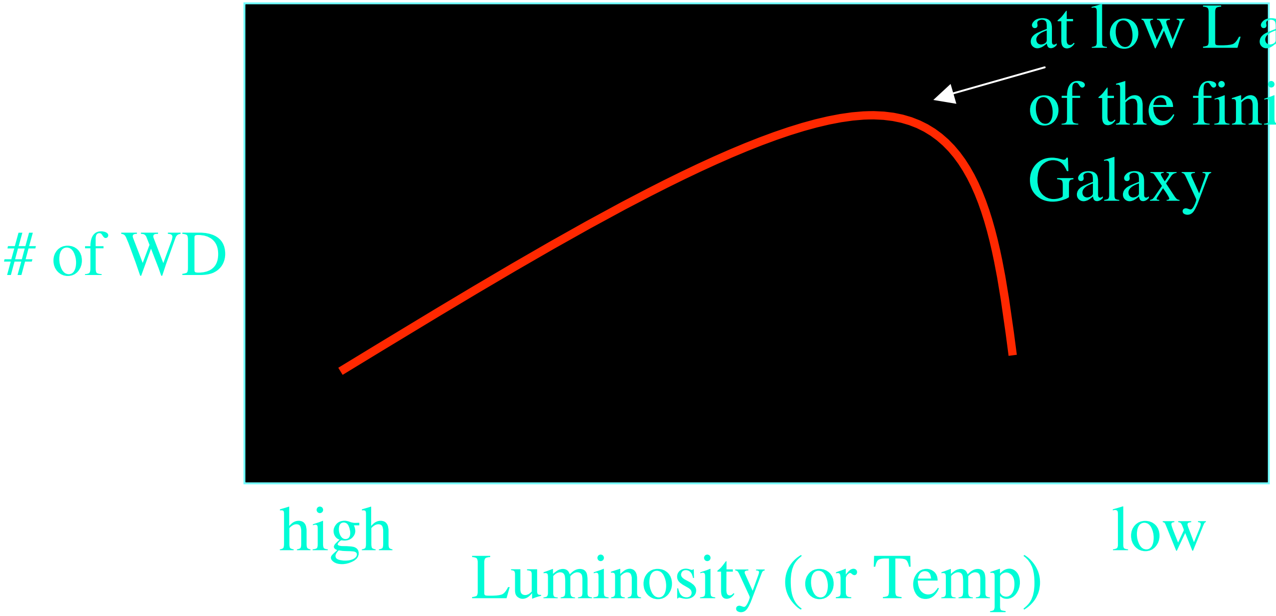
White Dwarfs

- At least 15% of the stellar mass in the solar neighborhood is in the form of WDs. They are very common, though hard to see.



White Dwarf Cosmochronology

- The WDs in the solar neighborhood have an interesting story to tell:



This drop off in WDs at low L and T is because of the finite age of the Galaxy

White Dwarfs in the Galaxy

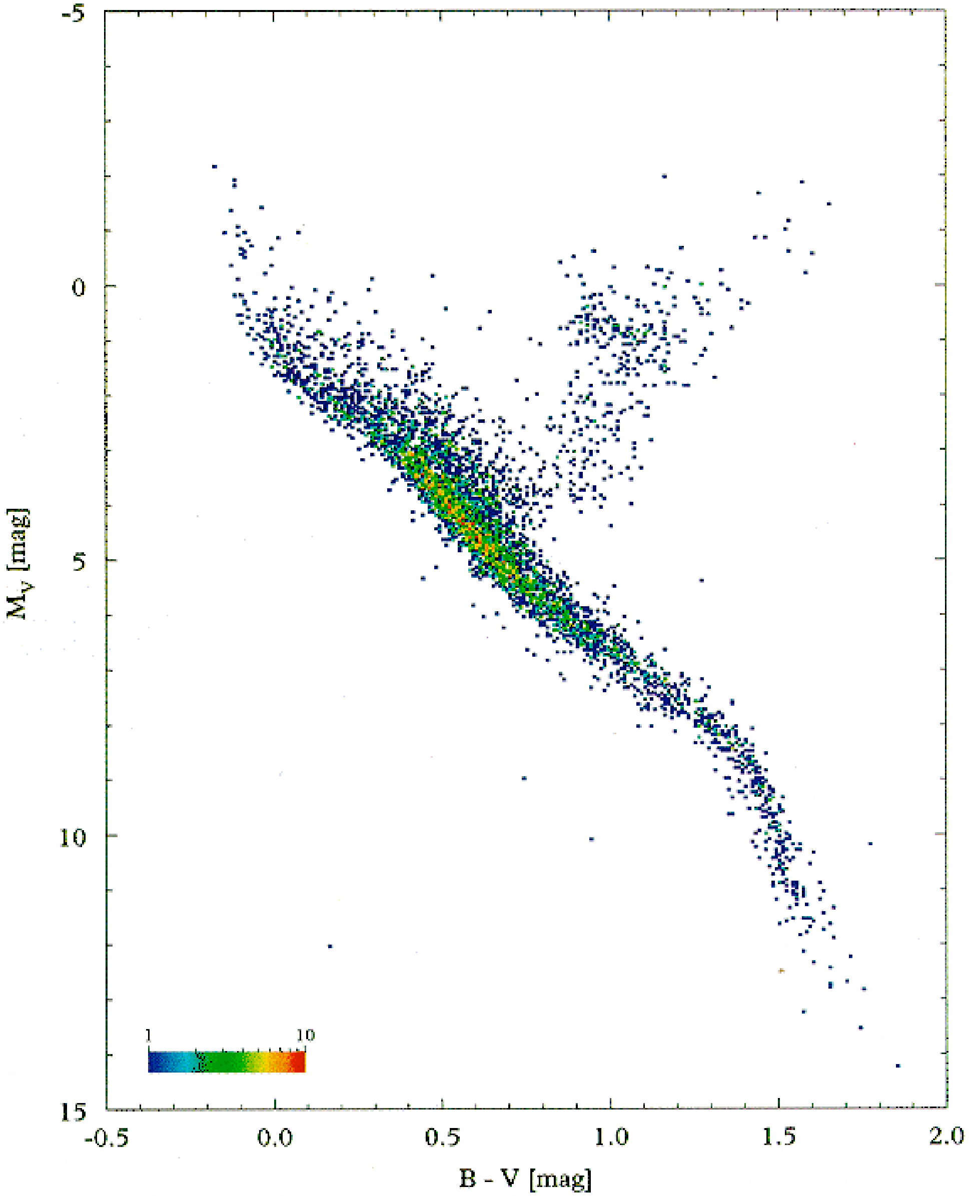
- We think that all stars with initial main-sequence mass less than around $7M_o$ become white dwarfs.
- When we look at the number of WDs at different luminosity (or temperature) there are some interesting bumps and wiggles AND a dramatic dropoff at the Luminosity that corresponds to a cooling age of 11 Gyr.

Evolution of $1M_o$ Star

Protostar	Grav. contraction	5×10^7 years
Main Sequence	Core H fusion	10×10^9 years
Red Giant	Core contraction and shell H fusion	5×10^8 years
Horizontal Branch	Core He fusion and shell H fusion	5×10^7 years
AGB	Core contr + He fusion + H fusion	1×10^6 years
White dwarf	none	A very long time

Evolution of $1M_o$ Star

- The time spent in a particular evolutionary phase is related to the number of stars of that type we see in the sky of that type. (although you have to be careful)
- When the Sun is an AGB star, its envelope will extend out to the orbit of Mars, the H-fusion shell will reach the orbit of the former Earth.
- $1M_o$ main-sequence star becomes a $0.6M_o$ WD made mostly of C with a little H, He.



-5
0
5
10
15
M_V [mag]
-0.5
0.0
0.5
1.0
1.5
2.0
B - V [mag]
1
10

Evolution of $4M_o$ Stars

- For stars less than $6M_o$ these last slides describe the evolution pretty well. There are some differences in the details that depend on the initial main-sequence mass.
- For stars that start with $4M_o$, it gets hot enough in the cores to (1) avoid the helium flash and (2) to start carbon fusion.
- The WD remnant contains Ne, Mg and Si and the amount of enriched material returned to the ISM is larger.

Do we have all this right?

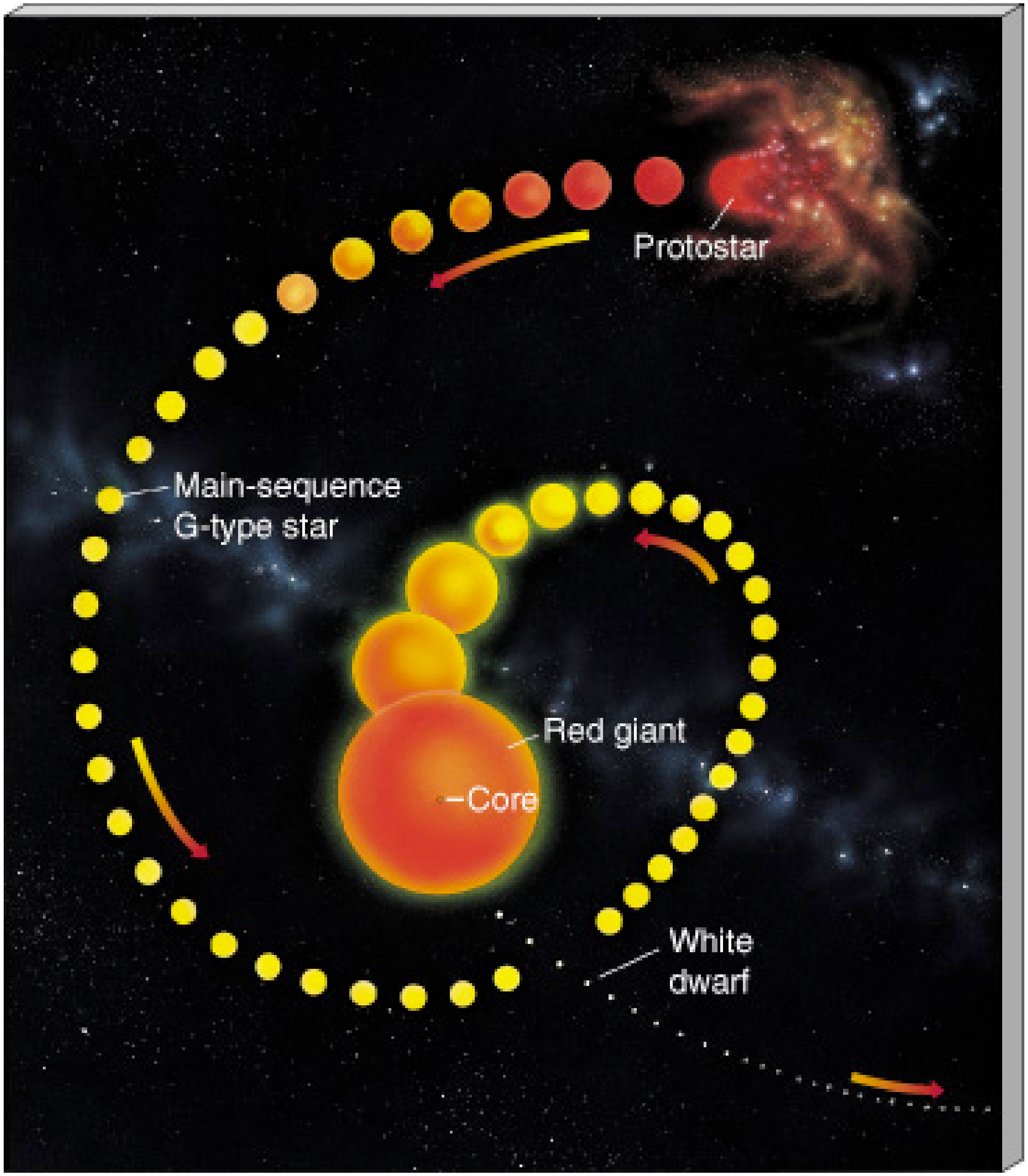
- How do we check all this out?

  (1) Star clusters are perfect because they contain stars in many of the evolutionary phases. Can test timescale, surface temperature and luminosity predictions. After 30 years of testing, it looks like we understand the basic evolution of stars very well.

  (2) My personal favorite test is the measurement of radioactive Tc in AGB stars.

Technecium$_{43}$

- Tc is an element with no stable isotopes and the longest-lived isotope (Tc^{98}) has a half-life of 4.2 million years.
- Models for AGB stars, predict that Tc will be synthesized inbetween shell flashes and convected to the surface.
- In 1952 Tc was detected for the first time in a star and now is routinely found in the spectra of AGB stars. This is direct proof of nucleosynthesis in stars and a powerful verification of stellar models.


Protostar
Main-sequence G-type star
Red giant
Core
White dwarf