Principles of Astrophysics and Cosmology

Welcome Back to PHYS 3368

Friedrich Wilhelm Bessel
July 22, 1784 – March 17, 1846

Announcements

- Reading Assignments: Chapter 4.1 - 4.3.
- Problem Set 6 is due Wednesday, March 4th, 2015.
- Next lab is Monday, March 16th. Be sure to report to FOSC 032 that day.
- Midterm Exam 1 is in class on Wednesday, March 18th. It will be open book, open note and cover chapters 1 - 3.
- Dark Sky viewing has been postponed due to weather. Check your email for details on rescheduling possibilities.
- Office hours this week will be held by Matt Stein, FOSC 139 on Wednesday from 4 - 5 pm and Friday 11 am - noon.
- Dr. Cooley will be out of town Thursday, March 5 - Friday, March 20th. If you need to reach her during that time, please send email.

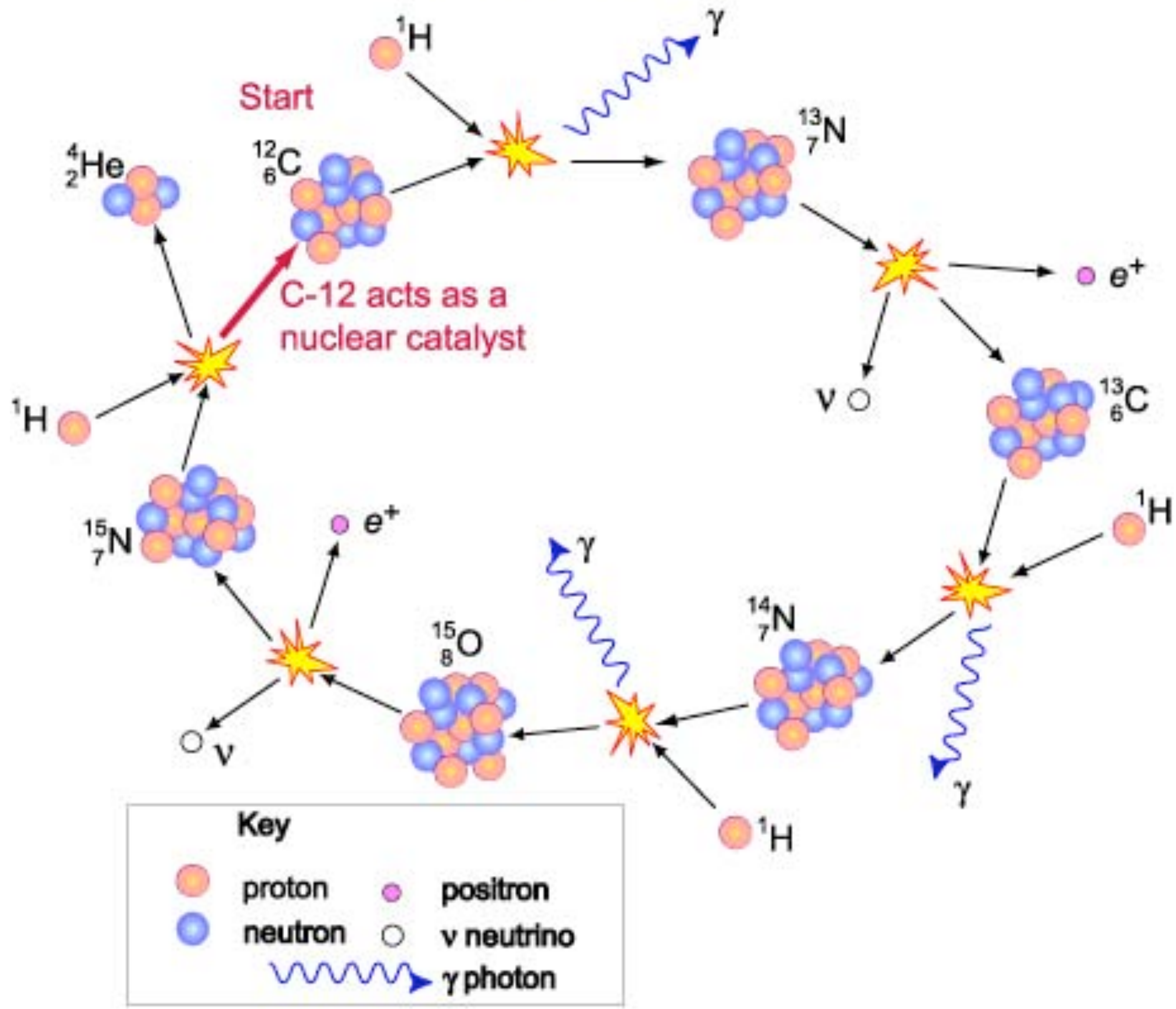
Goals for Today's Class

- Are there other nuclear reactions besides p-p for which we should account?
- Are there other means of energy transport besides radiative transport?
- What is the fate of a main sequence star?
- Why do we have to bring statistical quantum mechanics into the mix?

The CNO Cycle

- The main nuclear reaction sequence in the sun is the p-p cycle which we discussed last week.
- Other nuclear reactions do occur and produce neutrinos that are detectable on Earth.
- In stars more massive than the sun, H is converted to He via the CNO (carbon, nitrogen, and oxygen) cycle.

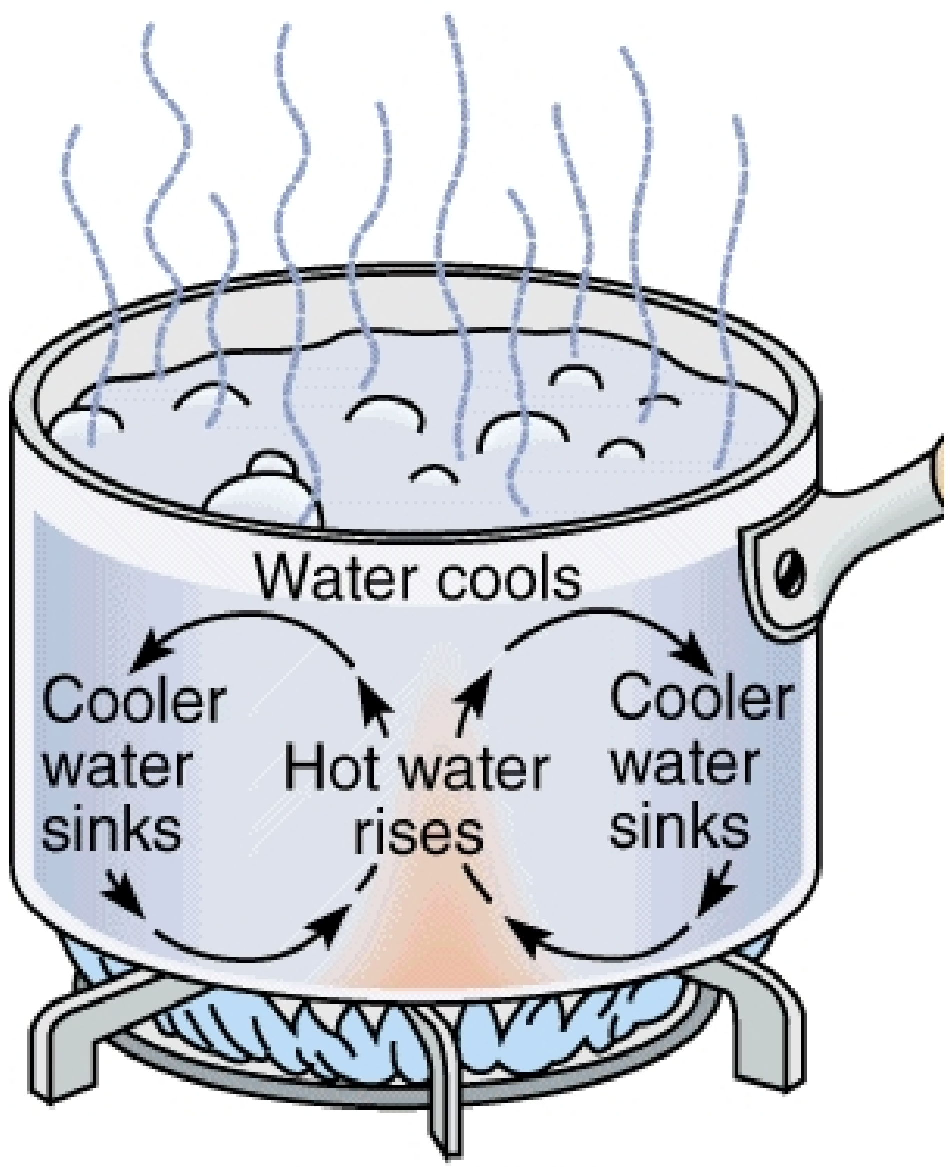
The CNO Cycle



$$
\begin{aligned}
{}^{12}\mathrm{C} + \mathrm{p} &\rightarrow {}^{13}\mathrm{N} + \gamma \\
{}^{13}\mathrm{N} &\rightarrow {}^{13}\mathrm{C} + e^{+} + \nu_e \\
{}^{13}\mathrm{C} + \mathrm{p} &\rightarrow {}^{14}\mathrm{N} + \gamma \\
{}^{14}\mathrm{N} + \mathrm{p} &\rightarrow {}^{15}\mathrm{O} + \gamma \\
{}^{15}\mathrm{O} &\rightarrow {}^{15}\mathrm{N} + e^{+} + \nu_e \\
{}^{15}\mathrm{N} + \mathrm{p} &\rightarrow {}^{12}\mathrm{C} + {}^{4}\mathrm{He}
\end{aligned}
$$

The Coulomb barrier is higher than p-p, but the first step is not a weak interaction. Thus, CNO dominates over p-p in stars with higher core temperature ($M > 1.2\ M_{sun}$).

Convection



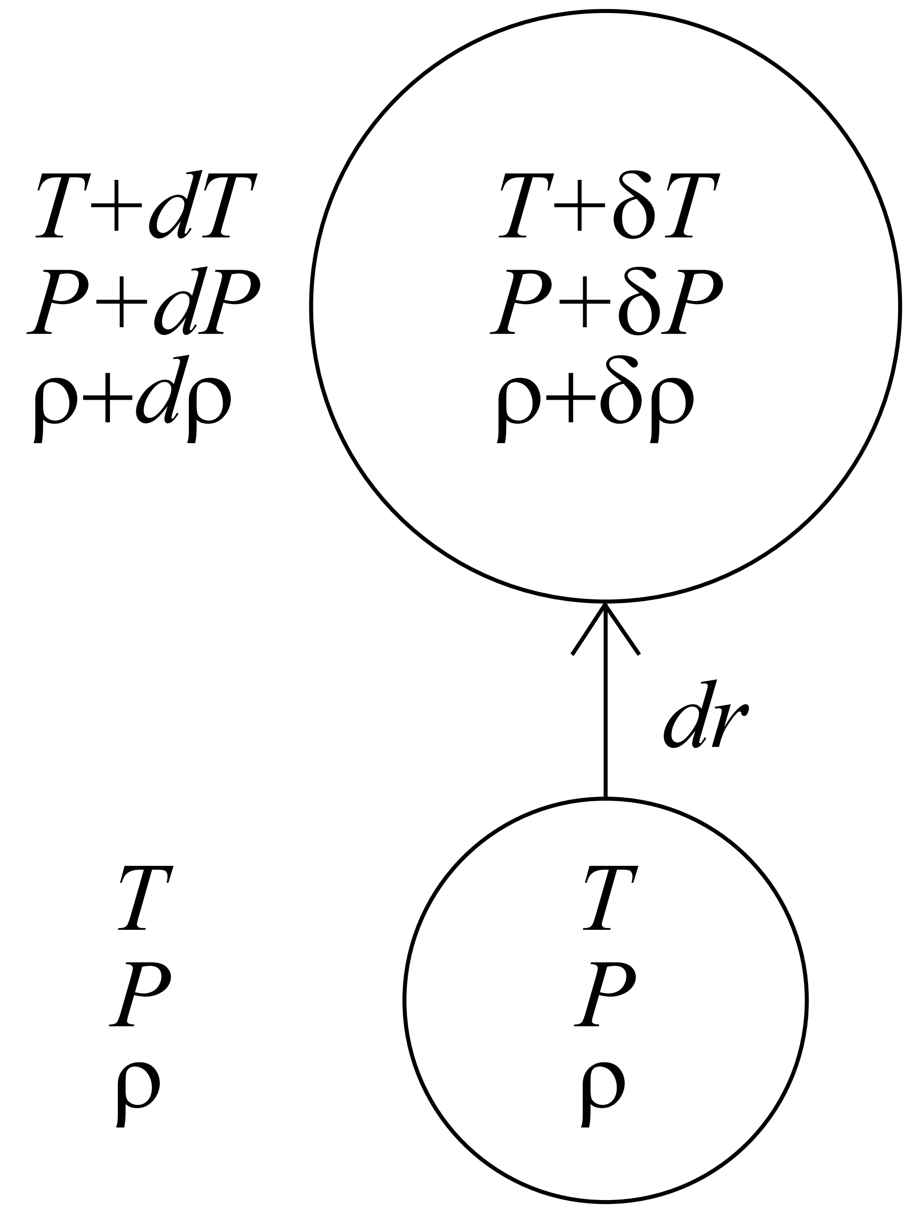
What is convection?

- The mechanical transport of energy.
- Fluid moves, carrying thermal energy
- Convection does not (normally) produce net motion of fluid.
- Convection can change temperature and density profile.

When does convection occur?

- Consider a small fluid element that is displaced upward. The element will adiabatically expand to match the pressure at the new location. Causes density and pressure within the element to change.

- If new density is higher than surrounding density, $\rho + \delta\rho > \rho + d\rho$, the element will sink back down. If the density is lower, $\rho + \delta\rho < \rho + d\rho$, the element will continue to rise leading to convection.



- If convection occurs, it drives down the temperature gradient. Stellar structure codes need to check for convection and modify if the temperature gradient occurs.

Where does convection occur?

- In cool regions of stars where atoms and molecules exist.
  - Outer layers of intermediate-mass main sequence stars and red giants.
  - Cores of massive stars.
  - Our Sun is convective in the outer 28% of its radius.

- Convection mixes materials at different radii. Once it sets in, it works towards equilibrating temperatures.

Stellar Evolution

- Up to this point we have considered only the simple case of static equilibrium. We now know this can not exist.
- Nuclear reactions at central regions and convection change conditions over time and at some point the hydrogen fuel in the core of the star is used up.
- Unavoidably, stars **evolve** with time.

Life History of Star

Mass	Core Details	Comments
$> 0.08M_{sun}$	Low mass ball of gas, not hot enough for hydrogen fusion	Stars in this mass range are not stars, but brown dwarfs of spectral type L and T.
$0.08M_{sun} < M < 0.5M_{sun}$	Fusion of H -> ^{4}He. Star is never hot enough to fuse ^{4}He to ^{12}C or ^{16}O.	Stars in this mass range are M on the main sequence. End up white dwarfs made of helium.
$0.5M_{sun} < M < 5M_{sun}$	Fusion of H -> ^{4}He -> ^{12}C and ^{16}O. Center is not hot enough to fuse ^{12}C and ^{16}O.	Stars in this mass range are A, F, G and K on the main sequence. End up white dwarfs made of ^{12}C and ^{16}O.
$5M_{sun} < M < 7M_{sun}$	Fusion of H -> ^{4}He -> ^{12}C and ^{16}O -> ^{20}Ne and ^{24}Mg.	Stars in this mass range are B on main sequence. End up as white dwarfs made of ^{20}Ne and ^{24}Mg.
$M > 7M_{sun}$	Fusion of H -> ^{4}He -> ^{12}C and ^{16}O -> ^{20}Ne and ^{24}Mg -> heavier elements .	Stars in this mass range are O on the main sequence. End up as neutron stars or black holes.

Stellar Evolution

Properties of stars on the main sequence of the HR diagram change little during the hydrogen-burning stage. Thus, they make only small movements on the HR diagram.

The main sequence lifetime, t_{ms}, is dependent on stellar mass.

Recall:

$$L \sim M^{\alpha}$$

Values of α:

$\alpha = 3.5$ for 2-20 M_{sun}
$\alpha \sim 1$ for >20 M_{sun}

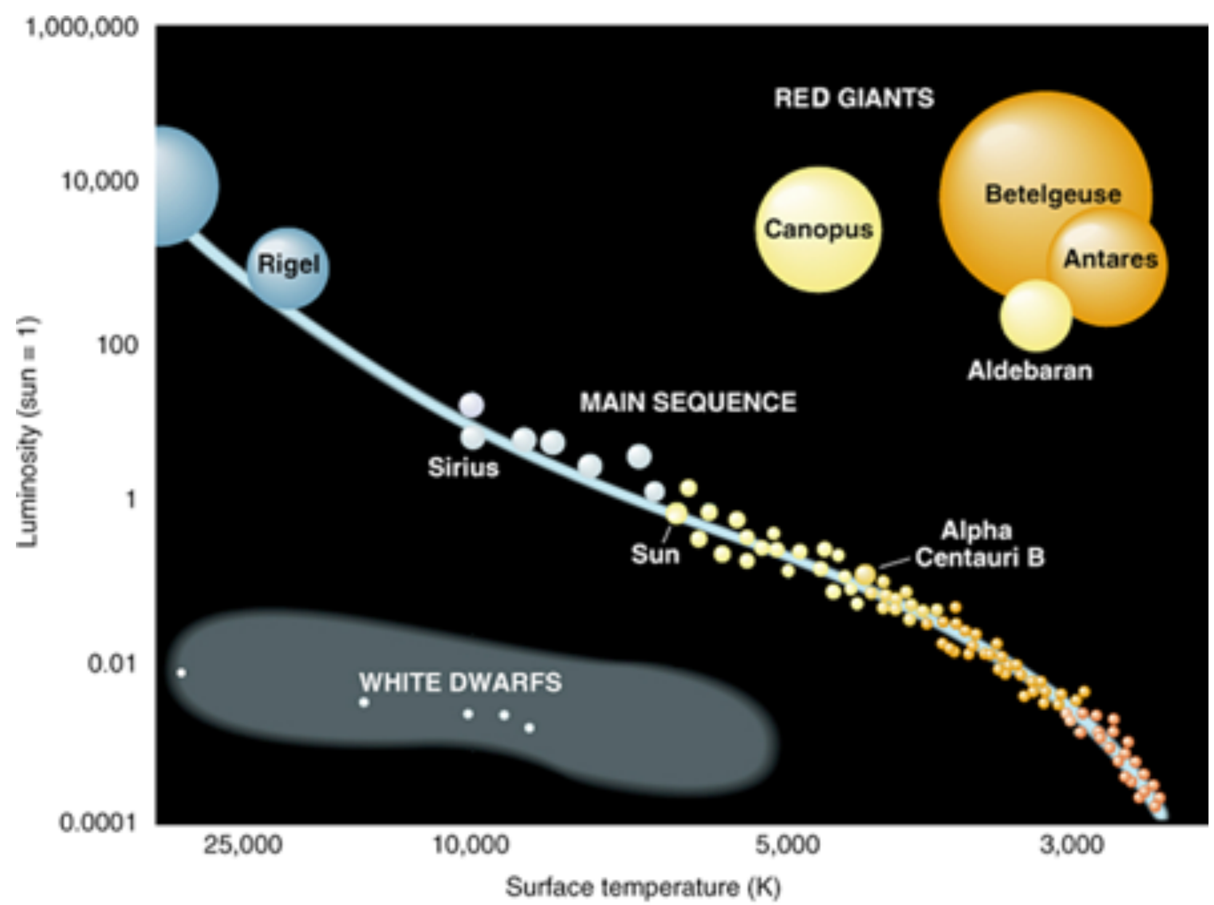


Figure 1 - The Hertzsprung-Russell Diagram. Dim cool stars are at the lower-right, bright hot stars are at the upper-left. The sizes shown for the stars are suggestive, not exact.

The energy radiated away in nuclear reactions is proportional to mass.

$$Lt_{\rm ms} \sim E \sim M$$

$$t_{\rm ms} \sim \frac{M}{L} \sim M^{1-\alpha}$$

Implications: The more massive the star, the shorter t_{ms}.

<u>Examples:</u> Stars with initial solar abundances and various masses

$$0.5M_\odot \rightarrow \sim 5 \times 10^{10}\mathrm{yr};$$

$$1.0M_\odot \rightarrow \sim 10^{10}\mathrm{yr};$$

$$10M_\odot \rightarrow \sim 2 \times 10^{7}\mathrm{yr}.$$

What is the age of the sun? Ans. ~ 5 billion yrs old

This comes to us by radioactive dating the oldest astroids. It is thought that the solar system (sun, planets, astroids, etc) all formed as one unit. Additional evidence from Earth. The oldest rocks are about 4.6 billion years old.

The sun is thus about half way through its lifetime on the main sequence.

Most Massive Stars:

For the most massive stars, $\alpha \sim 1$.

$$t_{ms} \propto M^0$$

Lifetime on the main sequence becomes independent of mass.

$$> 30 M_\odot \rightarrow \sim 3 \times 10^6 \mathrm{yr}$$

Lifetime of most massive stars is short compared to the age of the universe (14 billion years). This implies star formation is ongoing.

Even when on the main sequence, a star can move in the HR diagram because its luminosity and surface temperature can change. This causes the main sequence to have a finite width on the HR diagram.

Stars move off the main sequence when most of the hydrogen in the core has been converted to He.

Hydrogen then burns in a shell surrounding the core.

Stellar models predict a huge expansion of outer layers.

Gravitational contraction and hydrogen shell burning result in increased L. Moves star up the HR diagram.

Increase in radius lowers T_E. Moves star to right on HR diagram.

This is known as the Red Giant phase. It is not intuitive, but is well understood and predicted by the stellar equations.

Red giant stage last ~ 1 billion years for M_{sun} and ~1 million years for $10M_{sun}$.

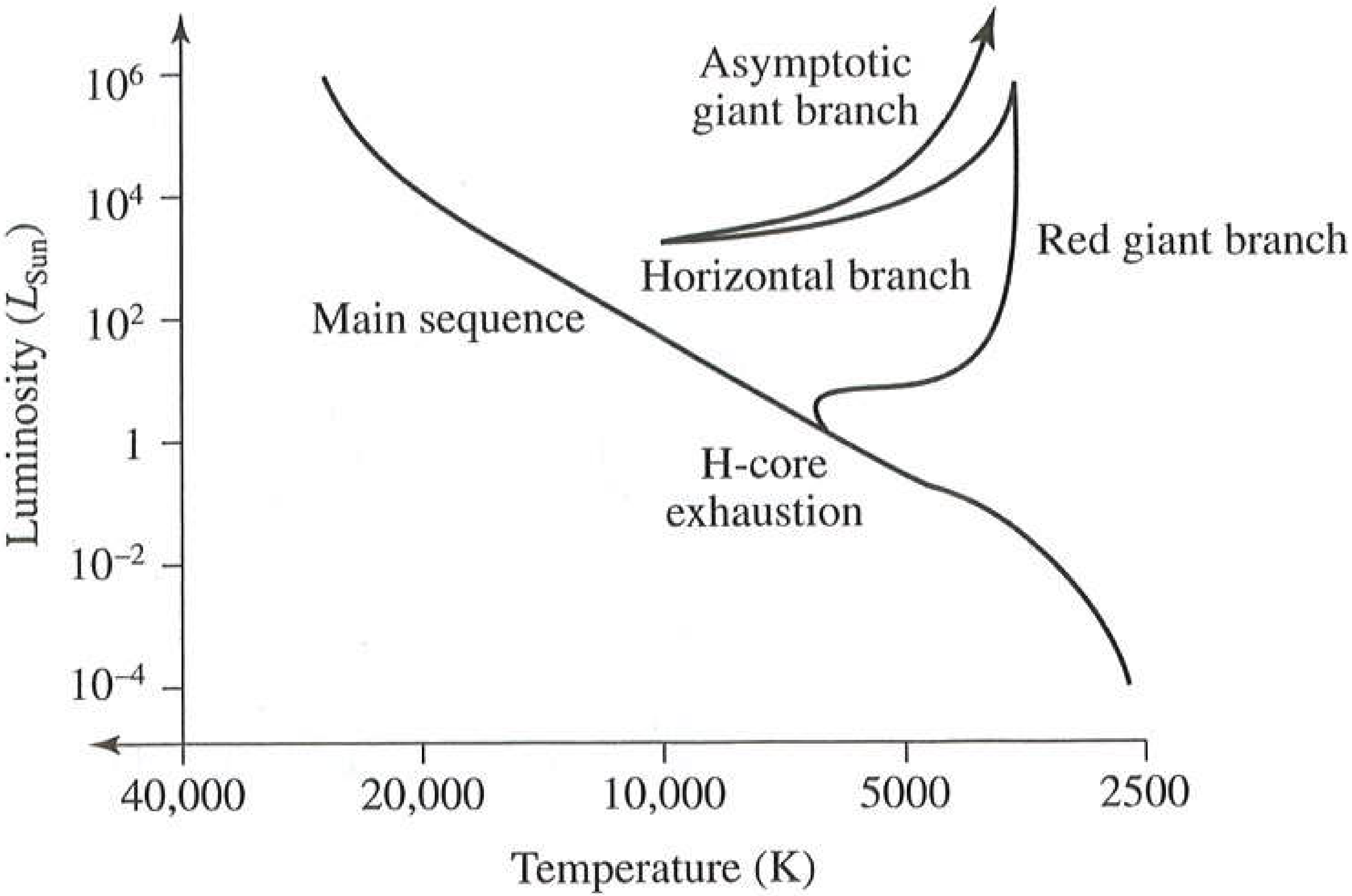
To model how stars age, one needs to track changes in abundances as a function of position within the star.

- This changes the energy generation profile and thus all the other profiles.
- Regions with convection have uniform abundances - convection occurs on timescales much faster than composition changes due to nuclear burning.

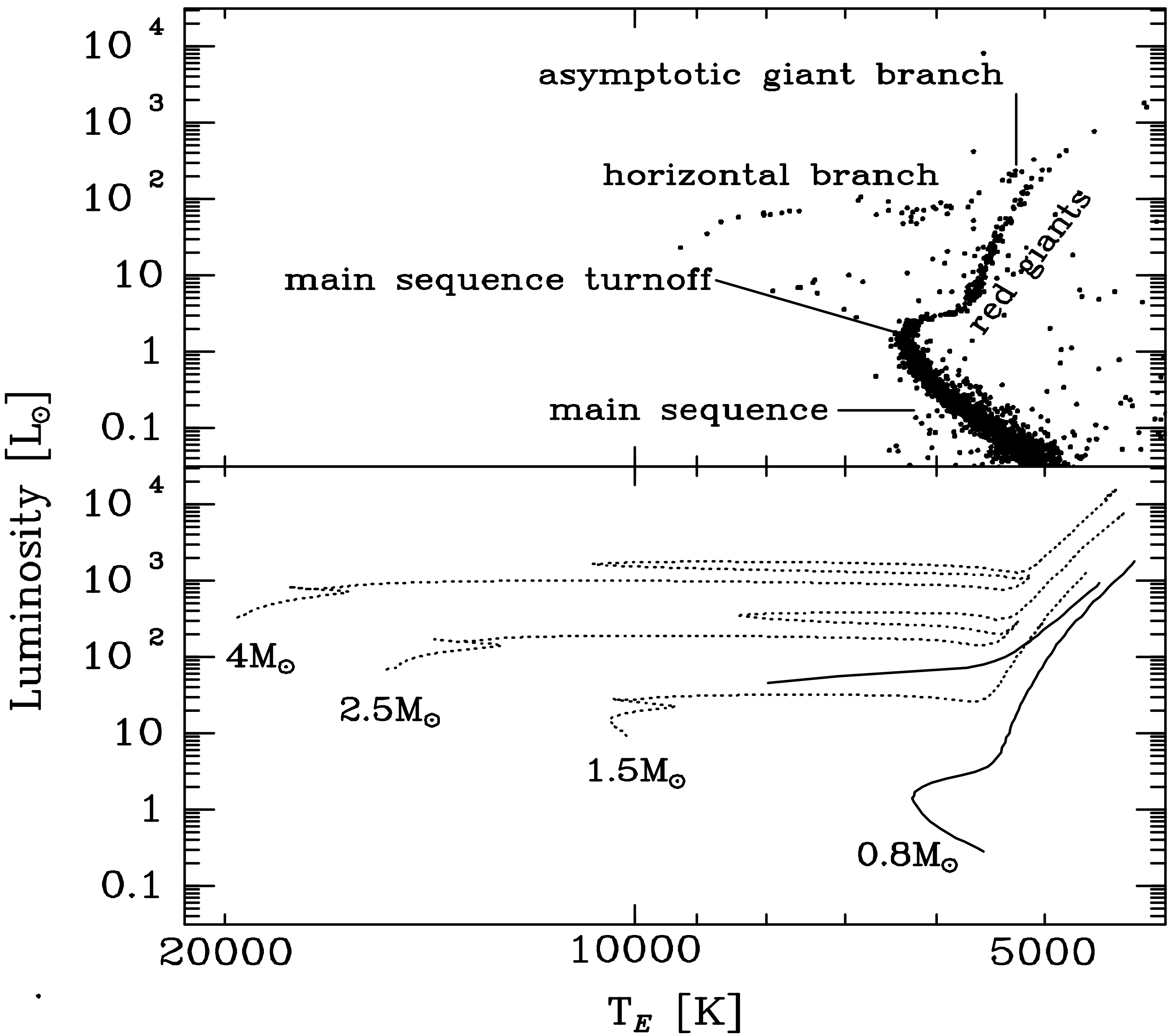
All large motion on the HR diagram corresponds to changes in location or type of nuclear burning.

- Main sequence turns off — core burning shutting down
- Red giant branch — inert He core, H shell burning
- Horizontal branch — He core burning, H shell burning
- Asymptotic giant branch — inert C+O core, He shell burning, H shell burning.

HR Diagram Schematic



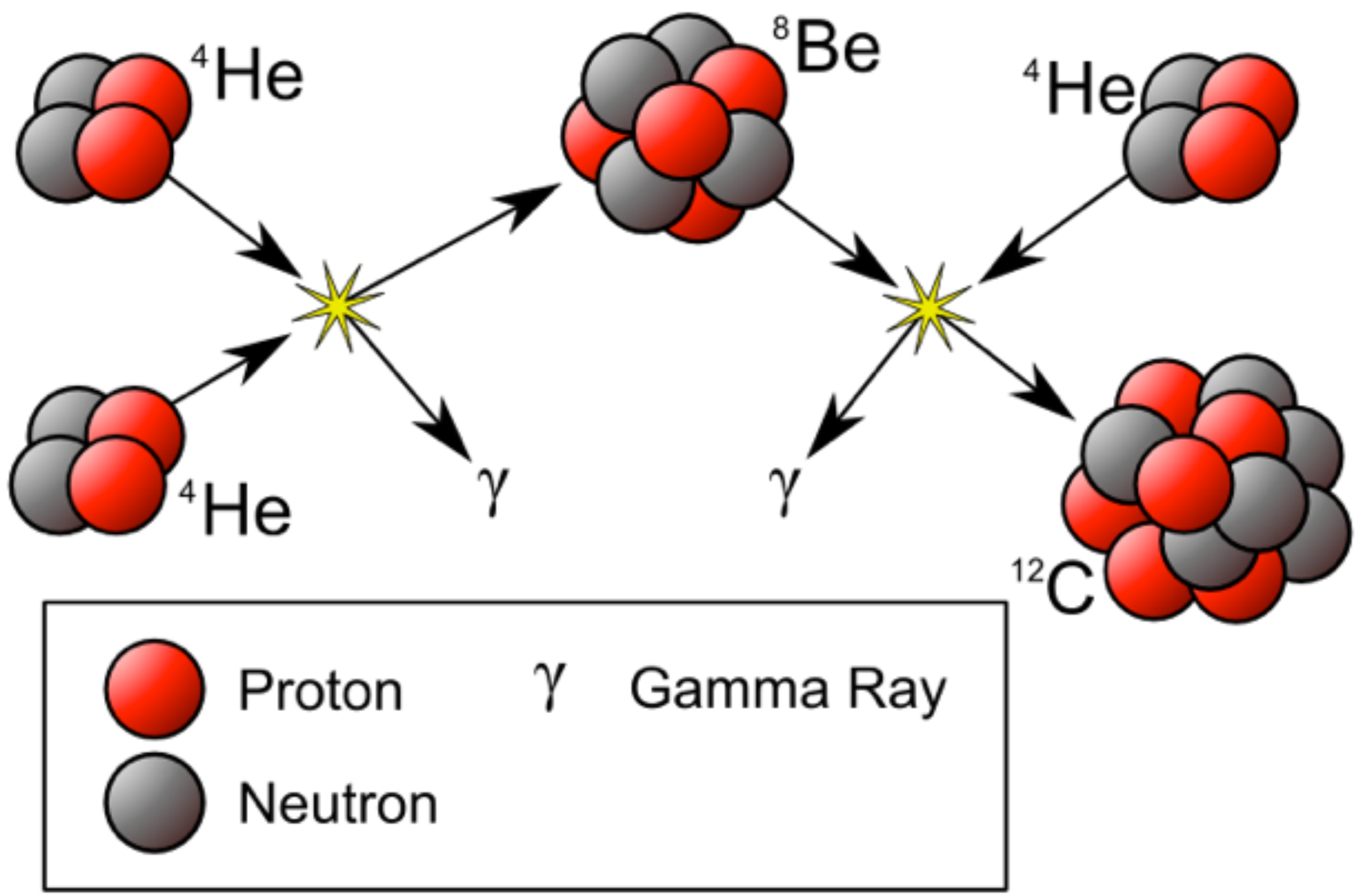
H-R Diagram for M3



The Red Giant Phase

As the red giant phase progresses, the He core contracts and heats up. When it reaches T~10^8 K and $\rho \sim 10^4$ g cm^{-3}, He burning begins.

triple-alpha reaction: $^4\mathrm{He} + ^4\mathrm{He} + ^4\mathrm{He} \rightarrow ^{12}\mathrm{C} + \gamma(7.275\mathrm{MeV})$



In addition to carbon, oxygen and neon can also be synthesized.

$$^4\mathrm{He} + ^{12}\mathrm{C} \rightarrow ^{16}\mathrm{O} + \gamma$$

$$^4\mathrm{He} + ^{16}\mathrm{O} \rightarrow ^{20}\mathrm{Ne} + \gamma$$

Remember, hydrogen is still burning around the core.

Horizontal Branch

He ignition begins, the star quickly moves to the horizontal branch.

- Horizontal branch evolution lasts ~ 1% of main sequence lifetime.

Asymptotic Giant Branch

- When He is exhausted, core contracts (again) until the surrounding shell of He ignites. H continues to burn around the He shell. Star moves to asymptotic giant branch during this double burning period.

Evolved Stars

Surface gravity of giant stars is low.

- strong winds and high rates of mass loss
- AGB stars can experience thermal pulses, periods of high helium shell burning. These drive mass loss.

Giant stars are highly convective.

-Results in a dredge-up of newly synthesized elements from core to outer layers. Expelled by wind.

For stars < 8 M_{sun}, at the end of AGB, leaves a hot helium/carbon/oxygen core and other layers are blown off.

-Excitation of gas loss from star by hot remnant (white dwarf) produces a planetary nebula.

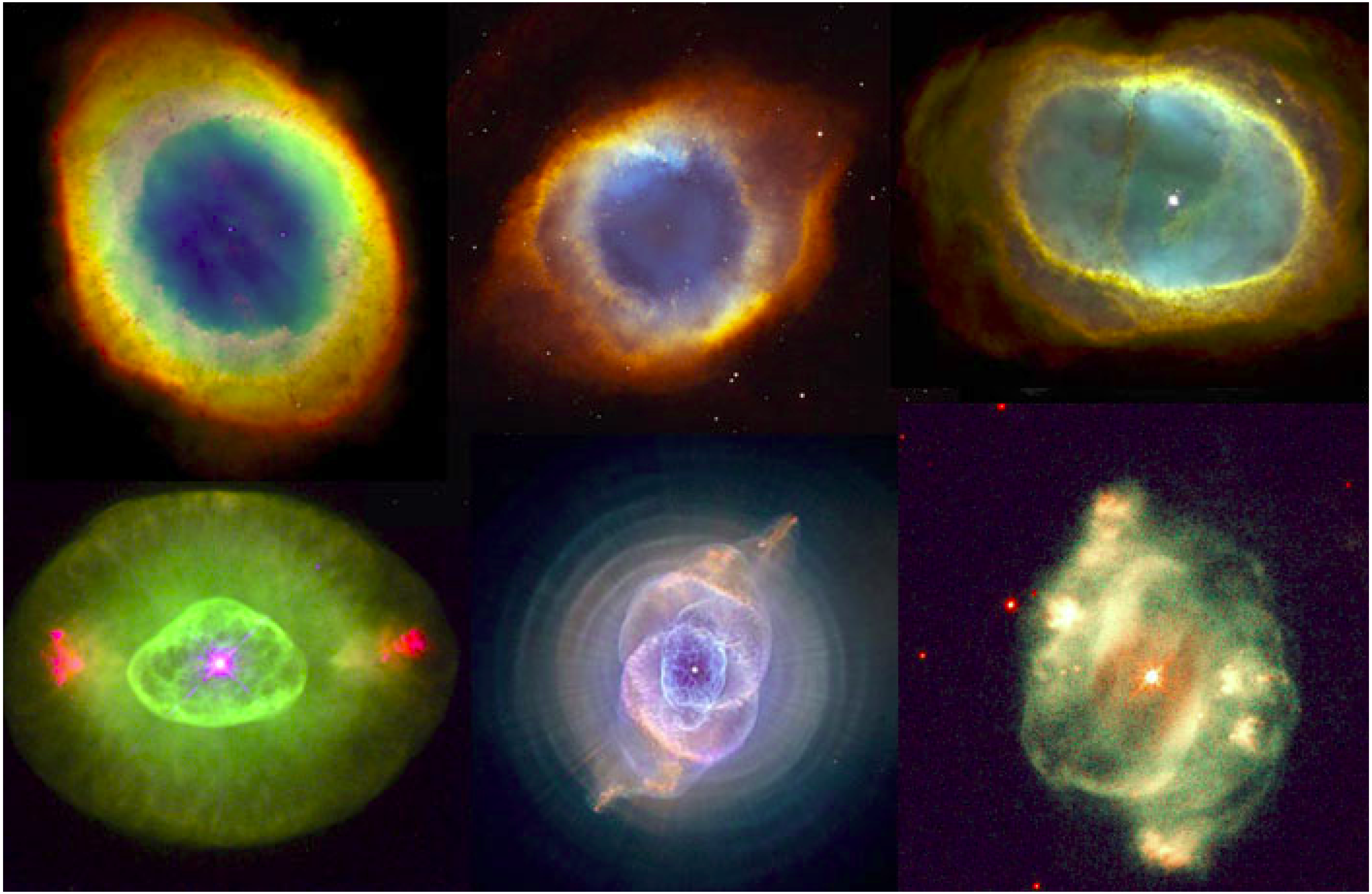
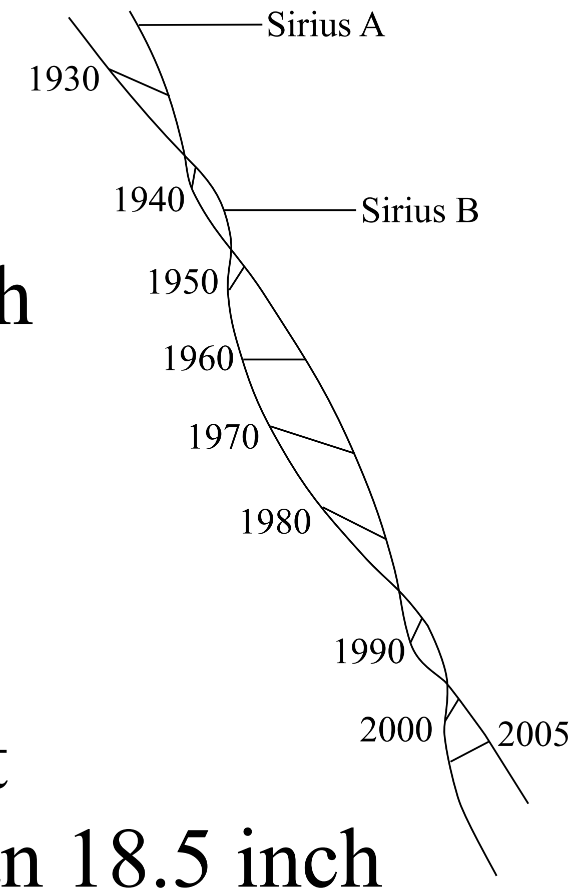
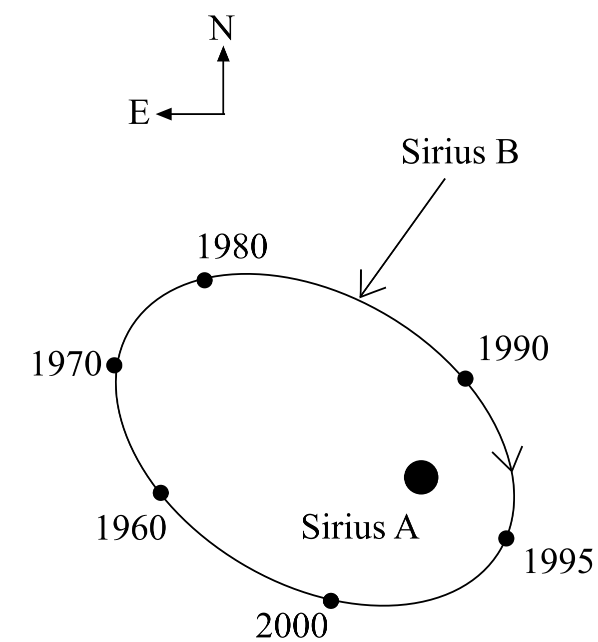


Figure 4.2 Several examples of planetary nebulae, newly formed white dwarfs that irradiate the shells of gas that were previously shed in the final stages of stellar evolution. The shells have diameters of $\approx 0.2 - 1$ pc. Photo credits: M. Meixner, T.A. Rector, B. Balick et al., H. Bond, R. Ciardullo, NASA, NOAO, ESA, and the Hubble Heritage Team

White Dwarfs

Sirius B is a white dwarf companion to Sirius A.





In 1844 German astronomer Friedrich Bessel deduced the existence of a companion star from changes in the proper motion of Sirius.

In 1862, astronomer Alvan Clark first observed the faint companion using an 18.5 inch refractor telescope at the Dearborn Observatory.

In 1915 Walter Adams observed the spectrum of the star, determining it was a faint whitish star. This lead astronomers to conclude it was a white dwarf.

Matter at Quantum Densities

As stars evolve, they contact and the density of the core increases. At some point the distance between the atoms is smaller than their de Broglie wavelengths. At that point, we can no longer use classical assumptions.

Recall: **de Broglie Wavelength**

$$\lambda = \frac{h}{p} = \frac{h}{(2mE)^{1/2}} \approx \frac{h}{(3mkT)^{1/2}}$$

Since,

$$p = mv$$

$$p = \sqrt{2mE}$$

$$E_K = \frac{1}{2}mv^2$$

$$v = \sqrt{\frac{2E}{m}}$$

$$E \sim \frac{3kT}{2}$$

mean energy of a particle

Question: Which will reach the quantum domain first, electrons or protons?

Although both electrons and protons share the same energy, electrons have smaller mass and longer wavelengths. The electron density will reach the quantum domain first.

When the inter particle spacing is of order 1/2 a de Broglie wavelength, quantum effects will become important.

$$\rho_q \approx \frac{m_p}{(\lambda/2)^3} = \frac{8m_p(3m_e kT)^{3/2}}{h^3}$$

Calculate the quantum density at the center of the sun (T = 15 x 10^6 K).

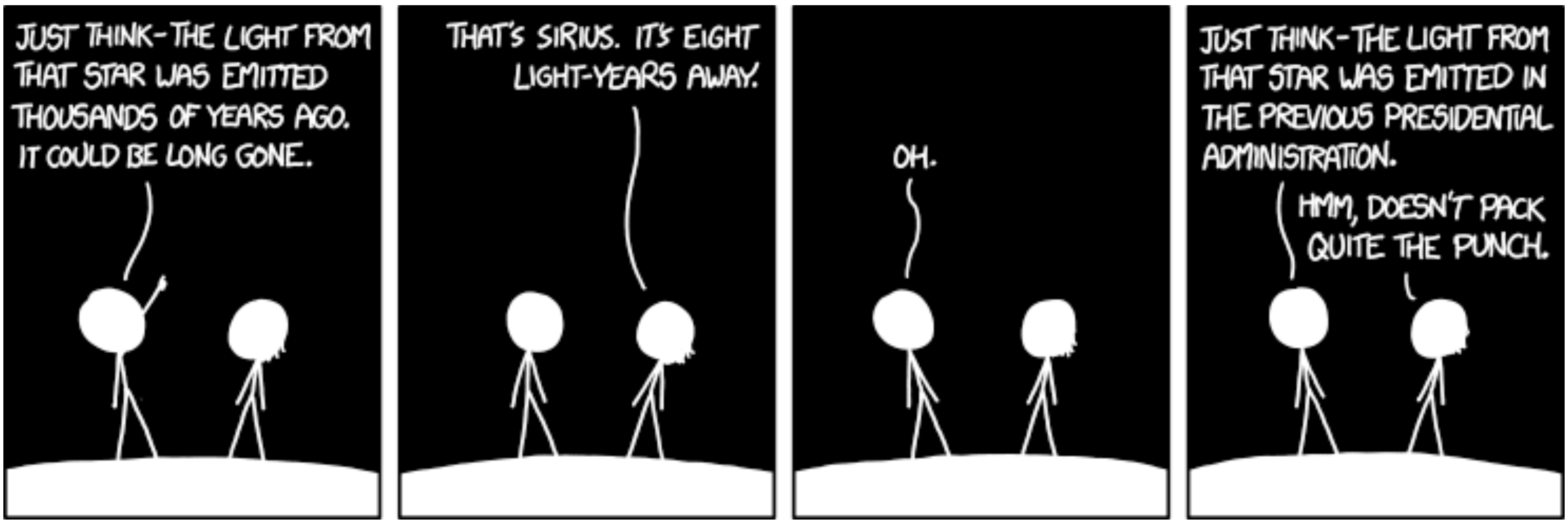
$$\rho_q \approx \frac{8 \times 1.7 \times 10^{-24}\ \mathrm{g}\ (3 \times 9 \times 10^{-28}\ \mathrm{g} \times 1.4 \times 10^{-16}\ \mathrm{erg\ K^{-1}} \times 15 \times 10^6\mathrm{K})^{3/2}}{(6.6 \times 10^{-27}\ \mathrm{erg\ s})^3}$$

$$p_q = 640\ g\ cm^{-3}$$

The core density of the sun is 150 g cm^{-3}.
Much below the quantum regime.

Next up - Stellar Evolution!

Stay Tuned!



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