Compton Lecture #3: The Life and Times of Low Mass Stars

- Welcome!
- On the back table:
  - Lecture notes for today's lecture
  - Extra copies of last week's are on the back table
  - Sign-up sheets – please fill one out if you're not already on the Compton Lectures mailing list

Stars: Their Life and Afterlife

The Life and Times of Low Mass Stars

Brian Humensky

68th Series, Compton Lecture #3

October 25, 2008

Outline

- Preliminaries
- Evolution along the main sequence
- Evolution beyond the main sequence
- White dwarfs, Novae and Type Ia supernovae

Key Points to Take Away

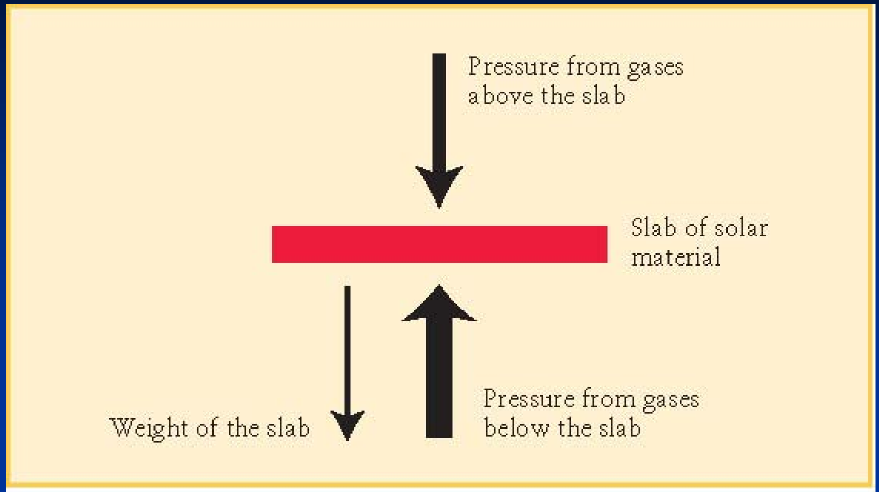
- Stellar evolution is dominated by initial mass
  - composition plays a secondary role
- Fusion is the primary energy source
- Stars spend most of their time on the main sequence, burning hydrogen
- Stellar evolution driven by search for hydrostatic equilibrium
  - exciting things happen when stars fall out of equilibrium
- Stellar interiors behave like ideal gases in *most* circumstances
- In key cases, have a degenerate gas instead with very different properties
- Final states: 85% of stars will end as red dwarfs, most of the rest will end as white dwarfs. A few "lucky" stars go supernova:
  - Massive stars go through core collapse → neutron stars or black holes
  - White dwarfs in close binary systems suffer thermonuclear explosion → total disruption

Preliminaries

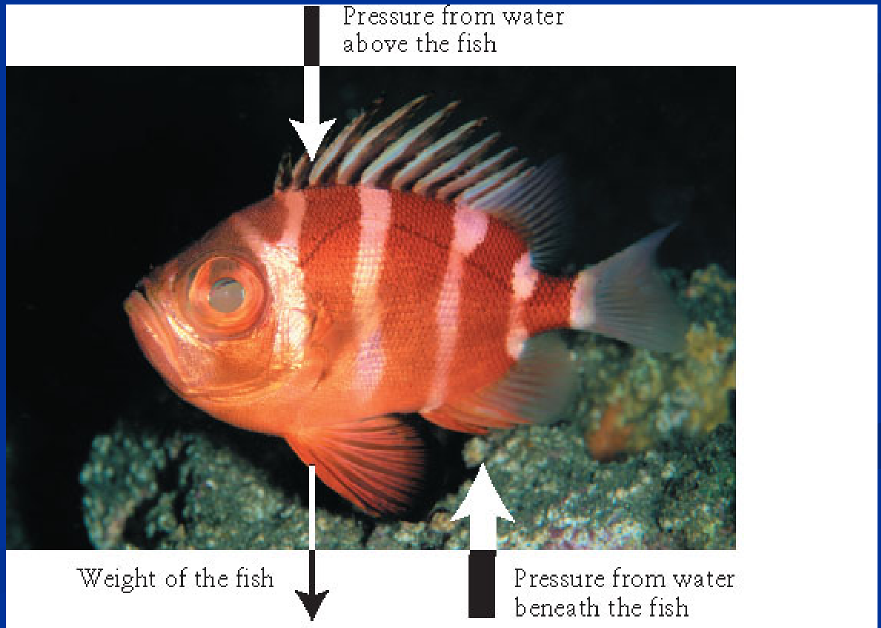
Hydrostatic Equilibrium

- Hydrostatic equilibrium is the balancing of the downward pull of gravity by a pressure gradient
  - Gravity + $P_{above} = P_{below}$

- Loss of hydrostatic equilibrium leads to exciting events in the life of a star



(a) Material inside the sun is in hydrostatic equilibrium, so forces balance



(b) A fish floating in water is in hydrostatic equilibrium, so forces balance

Fusion is the primary power source

- Only power source capable of sustaining stellar structure against gravity for the time scales needed.
  - $4\ ^{1}H \rightarrow\ ^{4}He$ + neutrinos + gamma rays
- $E = mc^2$ in action!
  - 0.7 % of mass of hydrogen ions is converted to energy during fusion into helium.

Stellar Interiors (usually) Act Like Ideal Gases

- In an Ideal Gas, there is a simple relationship between pressure, temperature, and density:
  - Pressure $\propto$ Density * Temperature
- This implies:
  - As a gas expands, it cools
  - As a gas is compressed, it heats up
- In a star, this provides a safety valve:
  - If the rate of fusion rises, the temperature tends to rise
  - The temperature rise increases the pressure, expanding the gas just enough to cool the gas back down and stabilize the rate of fusion
  - Thermal equilibrium is maintained

Stellar Evolution is Dominated by Mass…

Mass Range ($M_\odot$)	Lifetime Range	Final State
$\lesssim 0.08$	Failed star	Brown Dwarf
0.08 – 0.4	$\gg$ 100 Gyr	Red Dwarf
0.4 – ~8.0	$\gg$ 100 Gyr - ~100 Myr	White Dwarf*
~8.0 - ~20-30	~100 Myr - ~ 4 Myr	Neutron Star
$\gtrsim$ 20-30	$\lesssim$ 4 Myr	Black Hole

* White Dwarfs in binary systems may explode as Type Ia supernovae, leaving no compact object behind

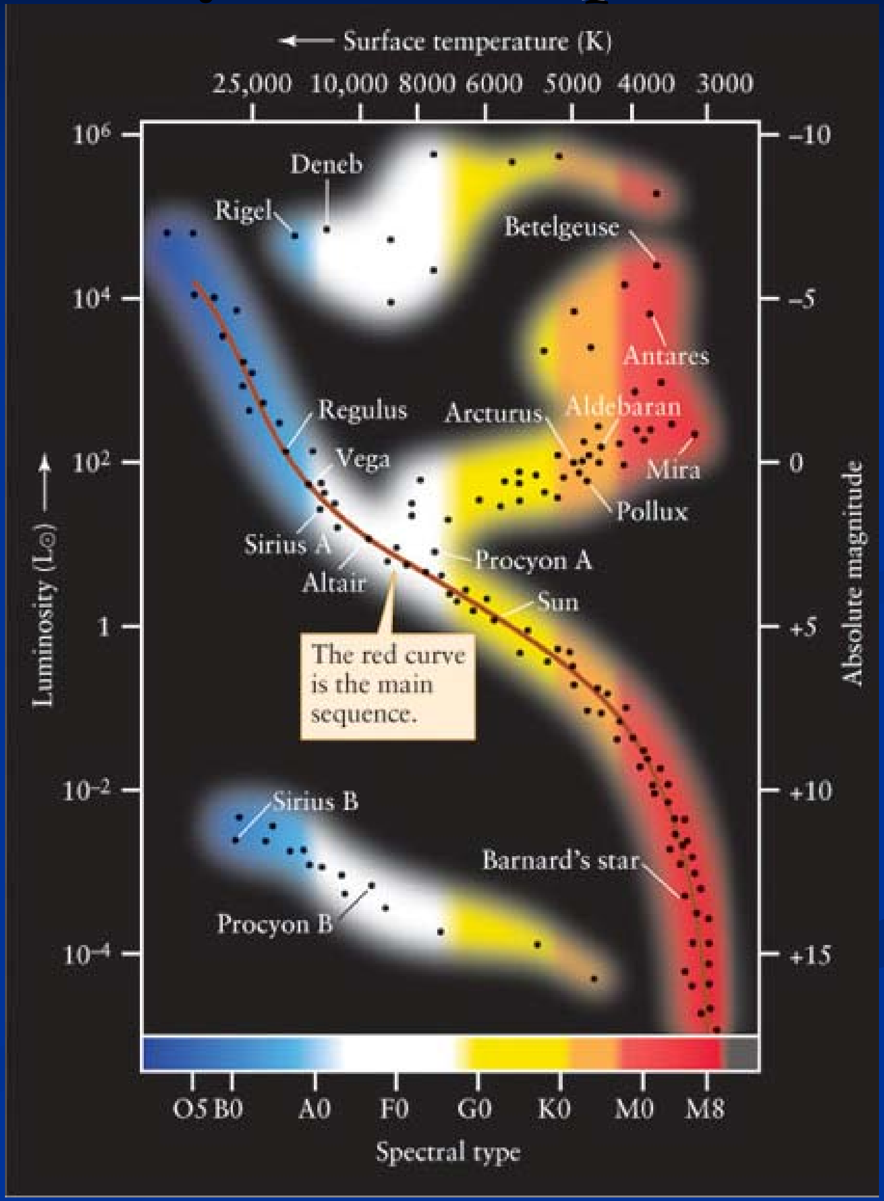
…but Composition Also Plays a Role

- Our Sun is a pretty typical star – starting composition
  - 74% hydrogen
  - 25% helium
  - 1% metals (elements heavier than helium)
- Stars that begin with extra helium:
  - Hydrogen burns faster → lifetime is shorter
  - Outer layers are less opaque → star is brighter & hotter
- Stars that begin with extra metals:
  - Little effect on fusion rates
  - Outer layers are more opaque → star is dimmer & cooler

Evolution Along the Main Sequence

Hertzsprung-Russell Diagrams Show the Relationship between Luminosity and Temperature

- The Main Sequence curves from lower-right to upper-left (cool/dim to hot/bright).
- Stars do NOT travel along the Main Sequence!
  - Their location on the Main Sequence is determined by their mass.
  - Stars form a "sequence" of colors/luminosity as a function of their mass.
- Note the enormous range of luminosities!
- Stars spend most of their lifetime on the Main Sequence.



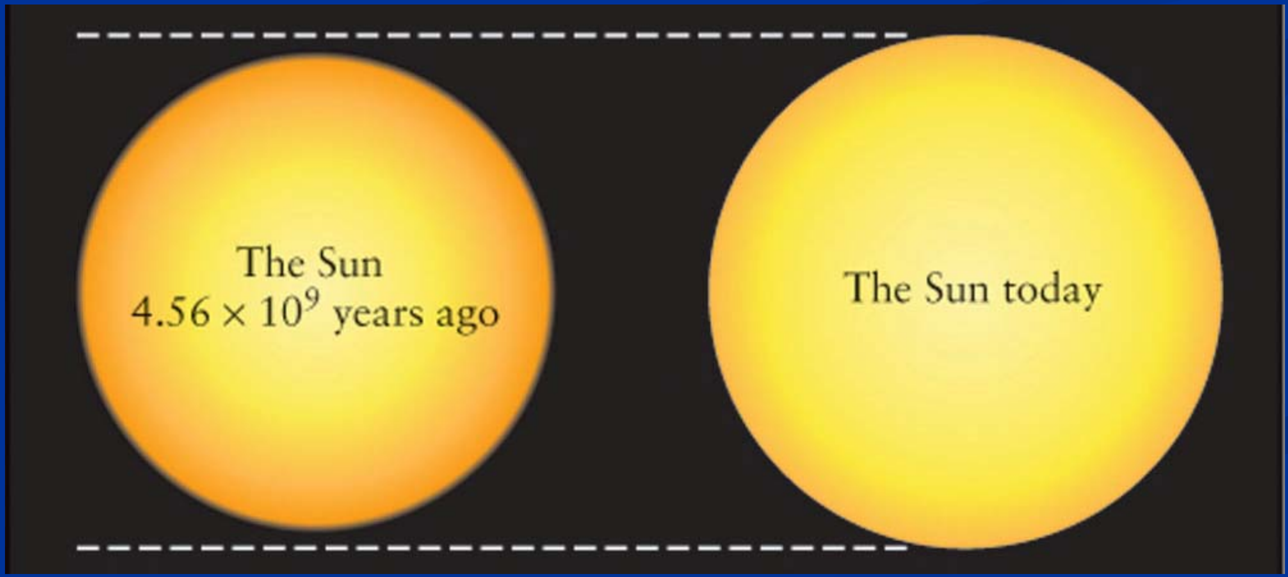
Main Sequence Evolution of the Sun

- Supply of core hydrogen good for ~12 Gyr.
  - Little mixing between core and rest of star.
- Core temperature: 16 million K
- Surface temperature: 5800 K

- Core is contracting very slowly over time as it burns ^{1}H into ^{4}He.

Main Sequence Evolution continued

- Pressure rises → temperature rises → rate of fusion rises → luminosity rises → radius increases.
- Sun is 40% more luminous, 6% larger, and 300 K hotter than at birth.



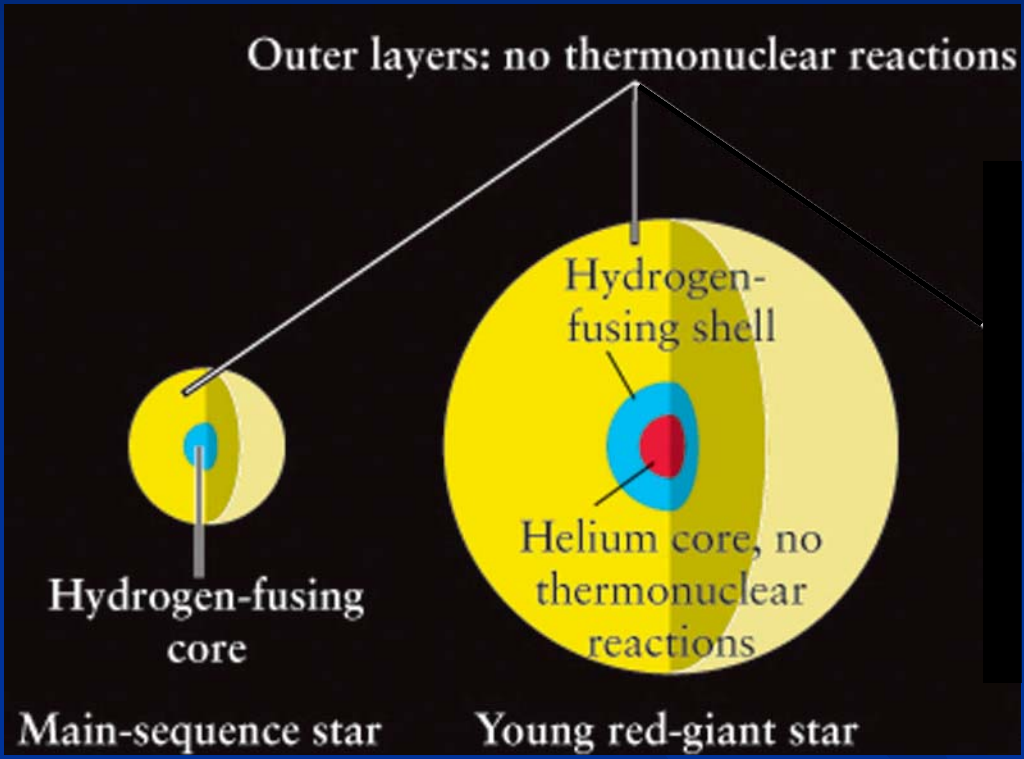
Red Dwarfs

- Stars with masses $\lesssim 0.4\ M_{\odot}$ evolve similarly to Sun until they exhaust their hydrogen.
  - Key difference: convection throughout star mixes core, outer layers thoroughly → ALL hydrogen burns.
  - Final state is a ball of helium!
  - Hydrogen-burning phase is 100's Gyrs.
- Too light to burn helium – these "Red Dwarfs" will gradually cool and dim over time…
- About 85% of all stars fall in this category.

Evolution After the Main Sequence

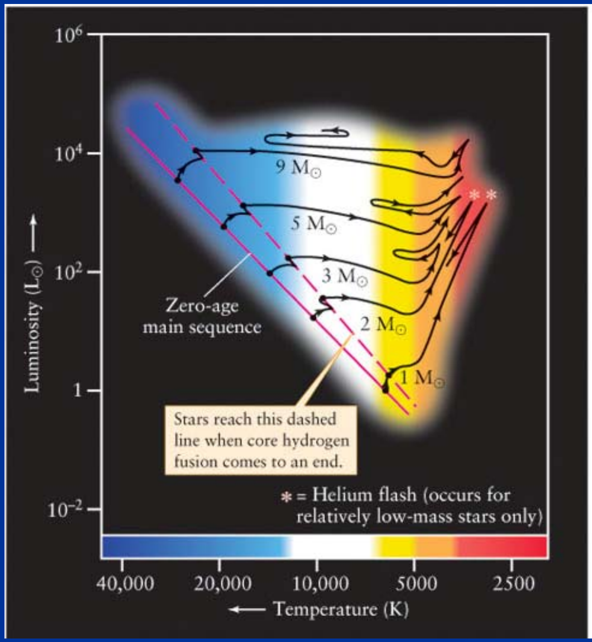
Leaving the Main Sequence

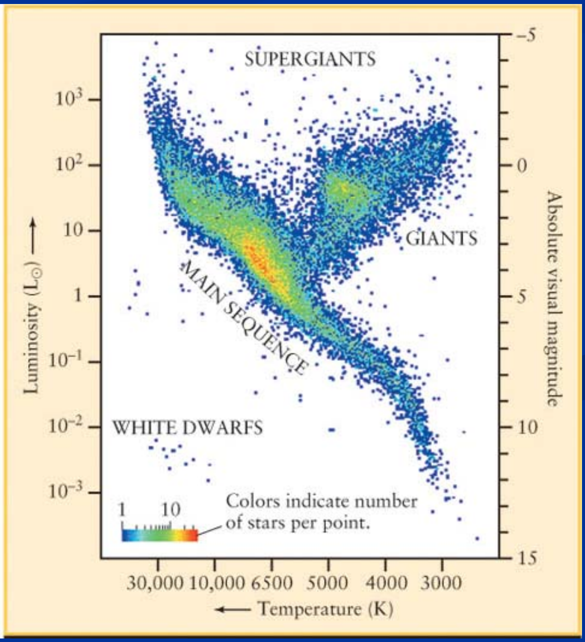
- Core supply of hydrogen runs out after ~12 Gyr
- Core now primarily ^{4}He
  - initially too cool to burn
- Thin shell of ^{1}H just outside core burns
- Core compresses, heats up
- Shell heats due to core, expands…



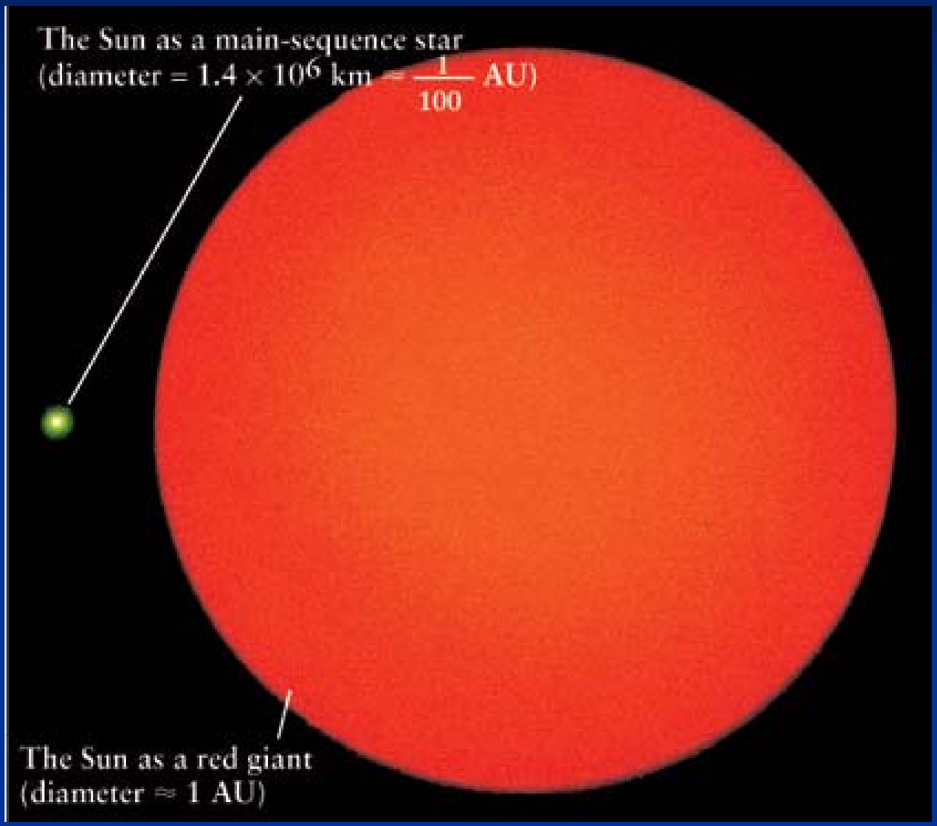
Red Giants

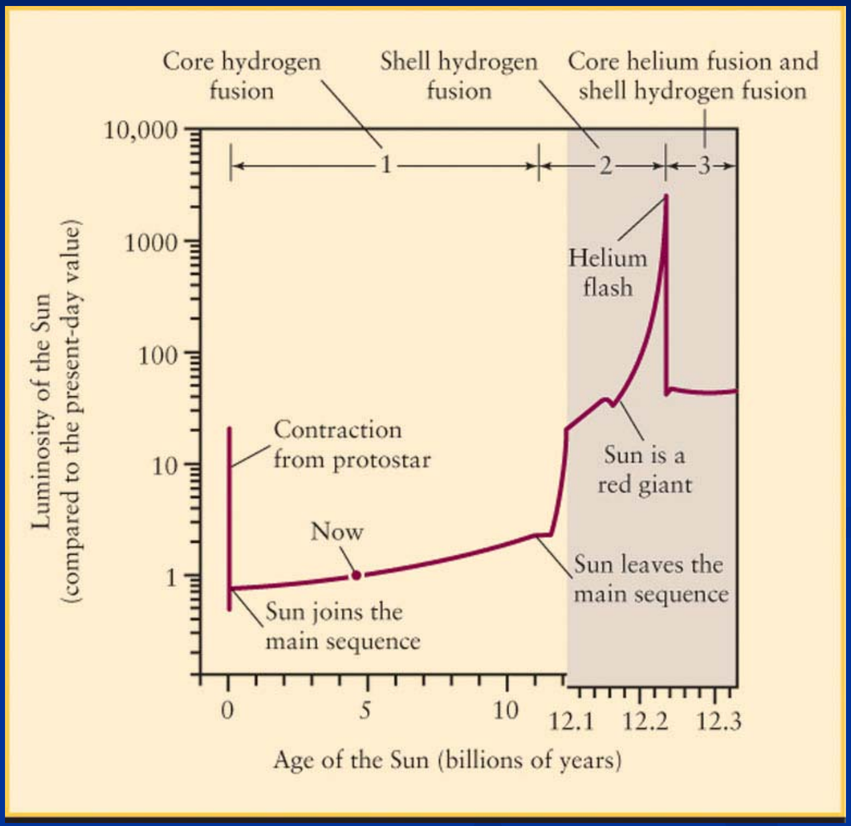
- As shell ^{1}H burning progresses, star enters the Red Giant phase.
  - Luminosity and size increase, surface temperature drops.
  - Star moves off main sequence towards realm of Giants.
  - Shell burning lasts ~250 Myr.





Red Giants


The Sun as a main-sequence star
(diameter = 1.4 × 10^6 km = 1/100 AU)
The Sun as a red giant
(diameter ≈ 1 AU)


Core hydrogen fusion
Shell hydrogen fusion
Core helium fusion and shell hydrogen fusion
10,000
1000
100
10
1
1
2
3
Helium flash
Contraction from protostar
Now
Sun is a red giant
Sun leaves the main sequence
Sun joins the main sequence
Luminosity of the Sun
(compared to the present-day value)
0
5
10
12.1
12.2
12.3
Age of the Sun (billions of years)

Beginnings of ^{4}He Burning

- Burning of ^{4}He into carbon and oxygen begins when core temperature reaches 100 million K.
- How ^{4}He burning starts depends on mass:
  - $\gtrsim$ 2-3 $M_\odot$: ^{4}He burning begins gradually, smoothly
  - $\lesssim$ 2-3 $M_\odot$: ^{4}He burning begins explosively
- High-mass stars have a core that contracts until hot enough to burn ^{4}He.
- Low-mass stars have a core supported by electron degeneracy…

Electron Degeneracy

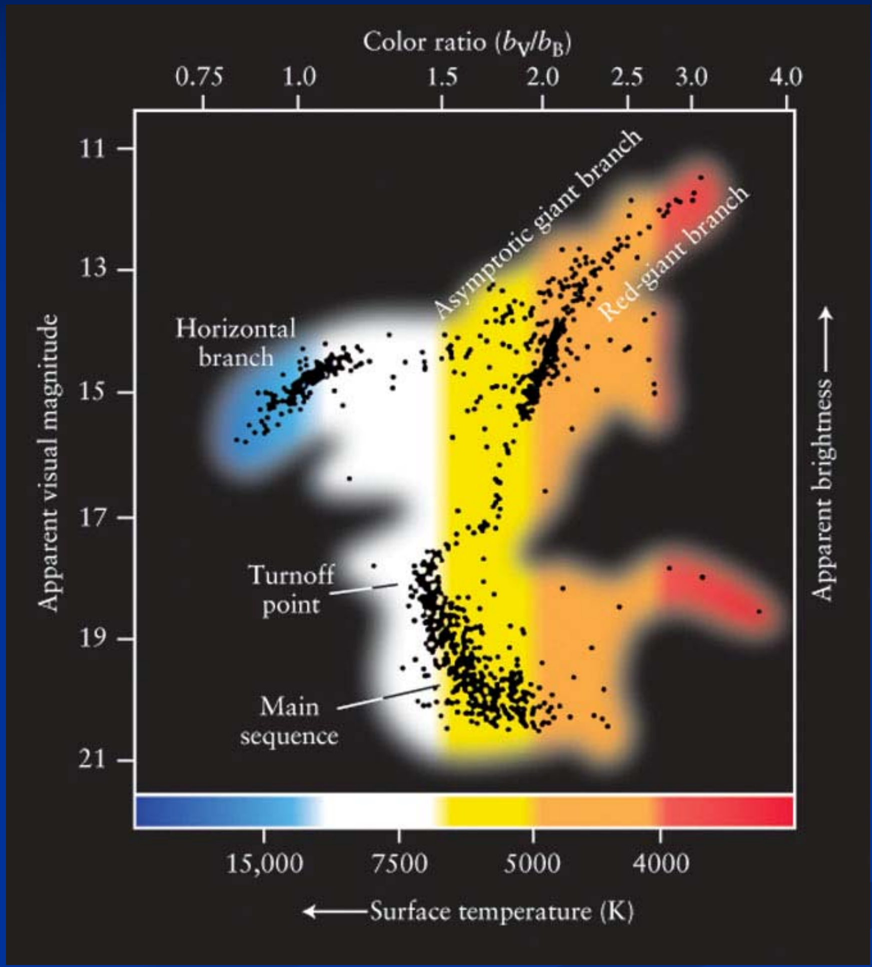
- Quantum mechanics limits how densely free electrons can be packed together.
  - Pauli exclusion principle: two electrons cannot simultaneously occupy the same quantum state
    - (i.e., same position + momentum + spin)
    - Quantum mechanical way of saying you cannot have two objects in the same place at the same time
- When a population of electrons cannot be packed any closer, they provide a powerful pressure against further contraction
  - The electrons are said to be in a state of degeneracy
  - Degenerate-electron pressure is independent of temperature

^{4}He Burning continued

- In low-mass stars, the ^{4}He ions and their electrons are packed so densely that the electrons are degenerate.
- As the temperature rises, the pressure remains the same.
- When the temperature reaches 100 million K, ^{4}He burning begins – rapidly heating the core.
- Hotter → yet faster burning → Helium Flash!
- Eventually hot enough that electrons lose degeneracy and ^{4}He burns as in more massive stars.

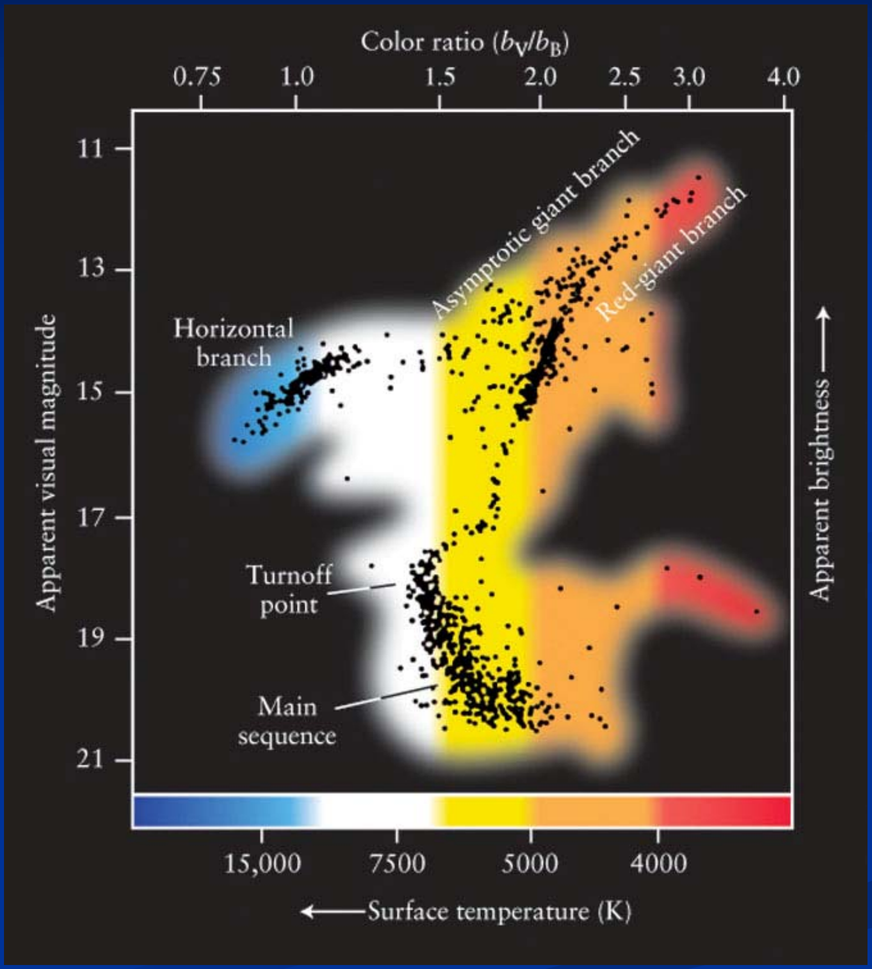
The Horizontal Branch

- With steady ^{4}He burning, the core expands and cools.
- In response, the hydrogen shell cools and stops burning.
- The outer layers contract but heat up – luminosity stays ~ constant as radius drops but temperature rises.
- Welcome to the Horizontal Branch!
- Core ^{4}He burning lasts ~100 Myr.

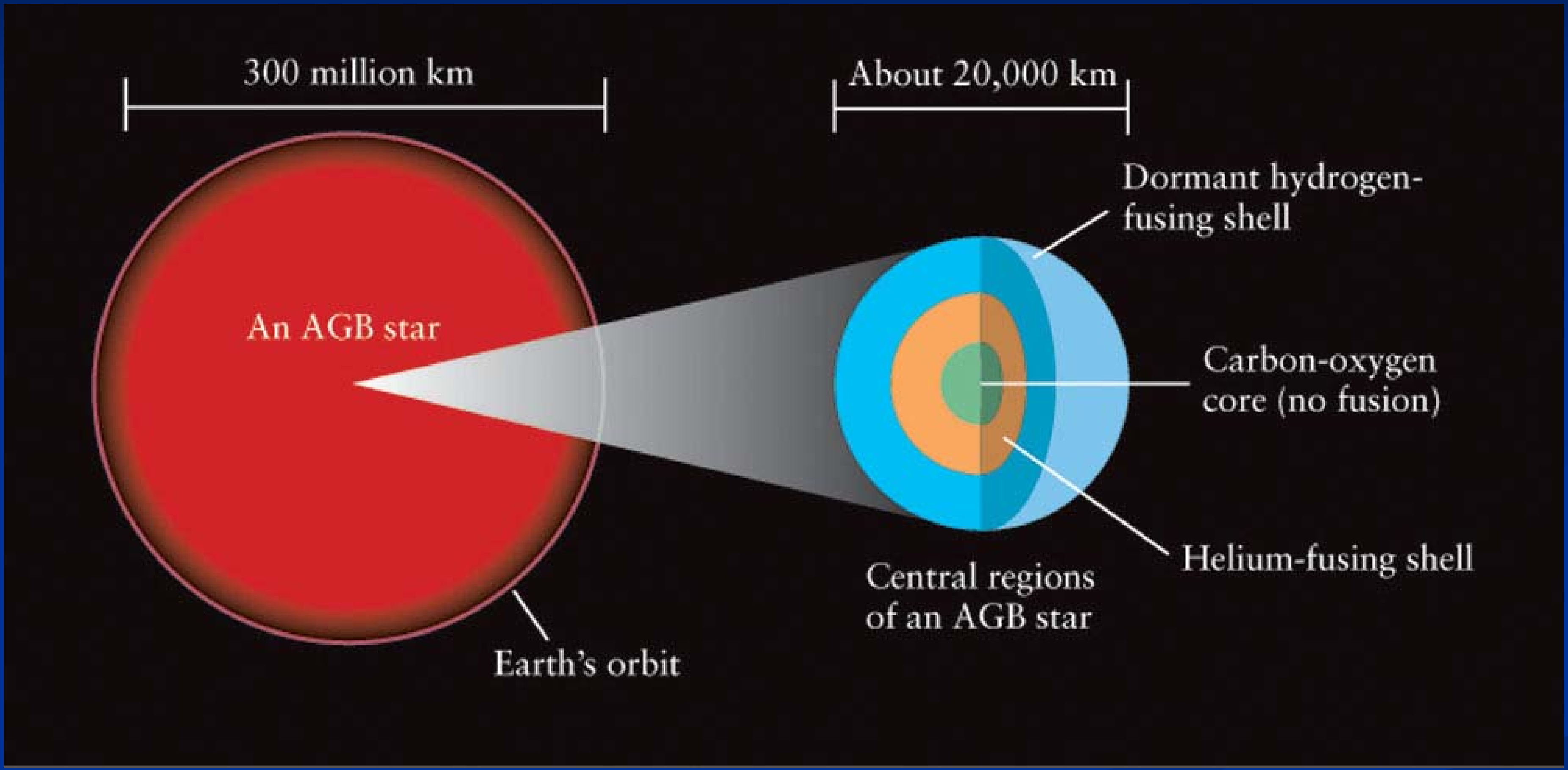


Second Red Giant Stage

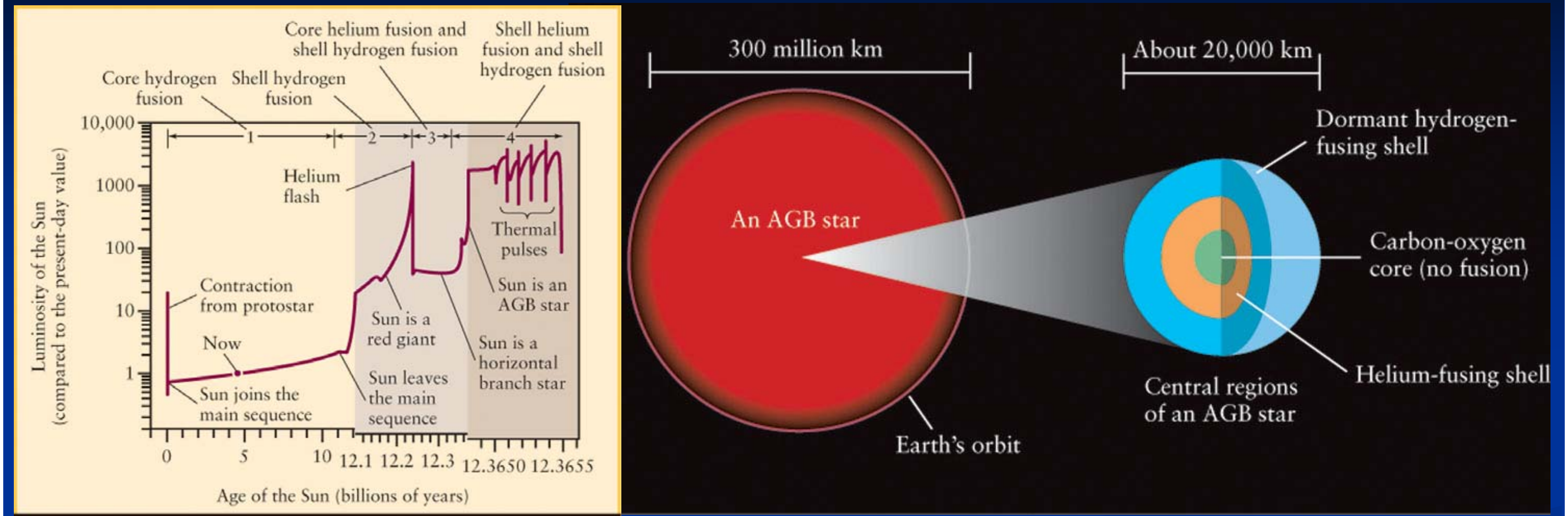
- When core supply of ^4He runs out, history repeats itself:
  - Core contracts until degenerate-electron pressure takes over.
  - Heating of ^4He-rich shell causes shell helium fusion.
  - Star enters a second red-giant phase, along the Asymptotic Giant Branch.



Structure of an Asymptotic Giant Branch Star



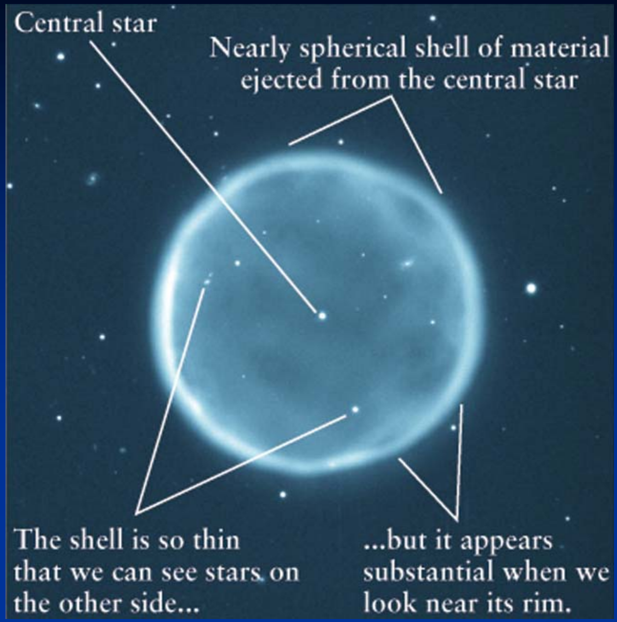
Thermal Pulses

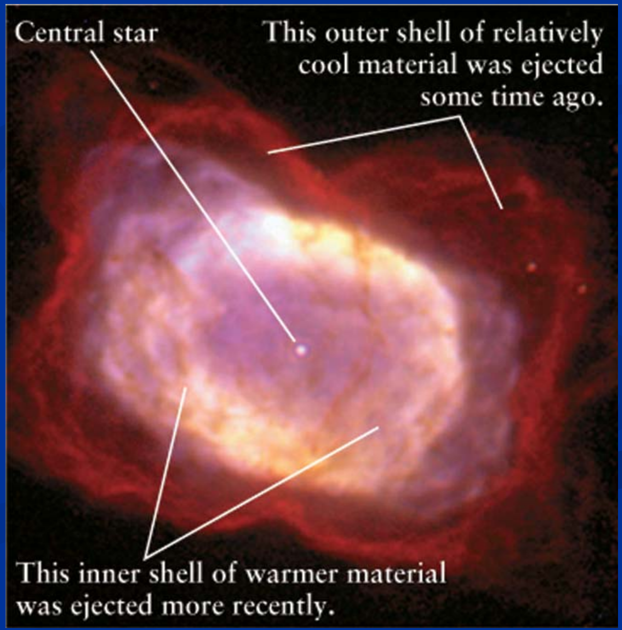


- When burning in the helium shell wraps up, the dormant hydrogen shell contracts, heats, and ignites.
- Eventually helium shell reignites in a helium shell flash.
- Luminosity of AGB star spikes: "thermal pulse"
- Outer layers of star can be ejected by these pulses.
- Pulses can repeat every ~100,000 years.

Planetary Nebulae

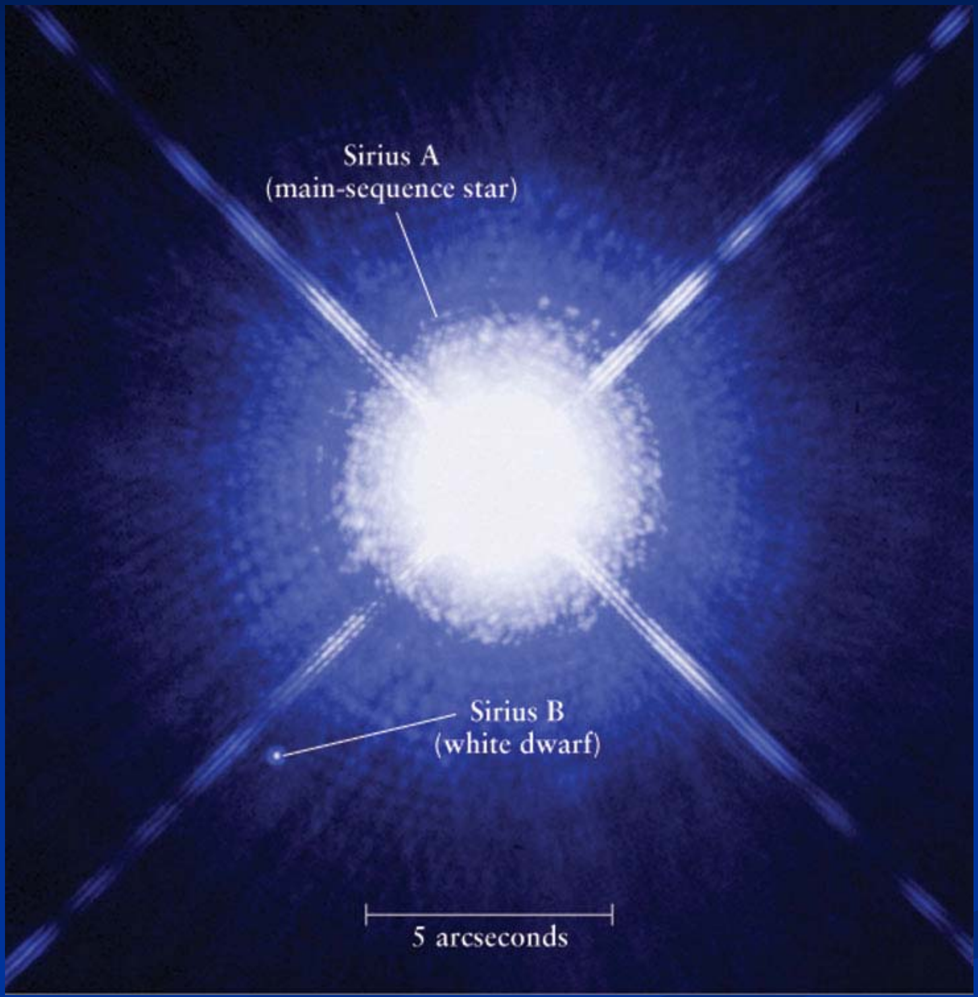
- The ejected outer layers of stellar material form a "planetary nebula"
  - (no relation to planets!)
- The bare, hot stellar core illuminates the nebula with UV light; we see them in fluorescence.
- The nebulae expand slowly (~10 – 30 km/s) and after ~50 kyr fade from view.
- The gases mix with the ISM, enriching it in helium, carbon, nitrogen, and oxygen.





White Dwarf Stars

- The hot core left behind by the thermal pulses is primarily carbon and oxygen in a degenerate-electron sea.
- Stars with masses $\lesssim 4\ M_\odot$ cannot generate the temperate and pressure needed for fusion beyond helium.
- These are White Dwarf stars, and in most cases this is nearly the end of their evolution.



Summary of Solar-Mass Stellar Evolution

- Core hydrogen fusion for 12 billion years (main sequence)
- Shell hydrogen fusion for 250 million years (red giant)
- Core helium and shell hydrogen fusion for 100 million years (horizontal branch)
- Shell helium and hydrogen fusion (asymptotic giant phase)
- White dwarf phase, fusion completed

- This series of stages is similar for all stars with initial masses in the range 0.4 – 4.0 $M_{\odot}$.
- More massive stars are able to start fusion reactions involving carbon and oxygen → next week.

White Dwarfs, Novae, and Type Ia SNe

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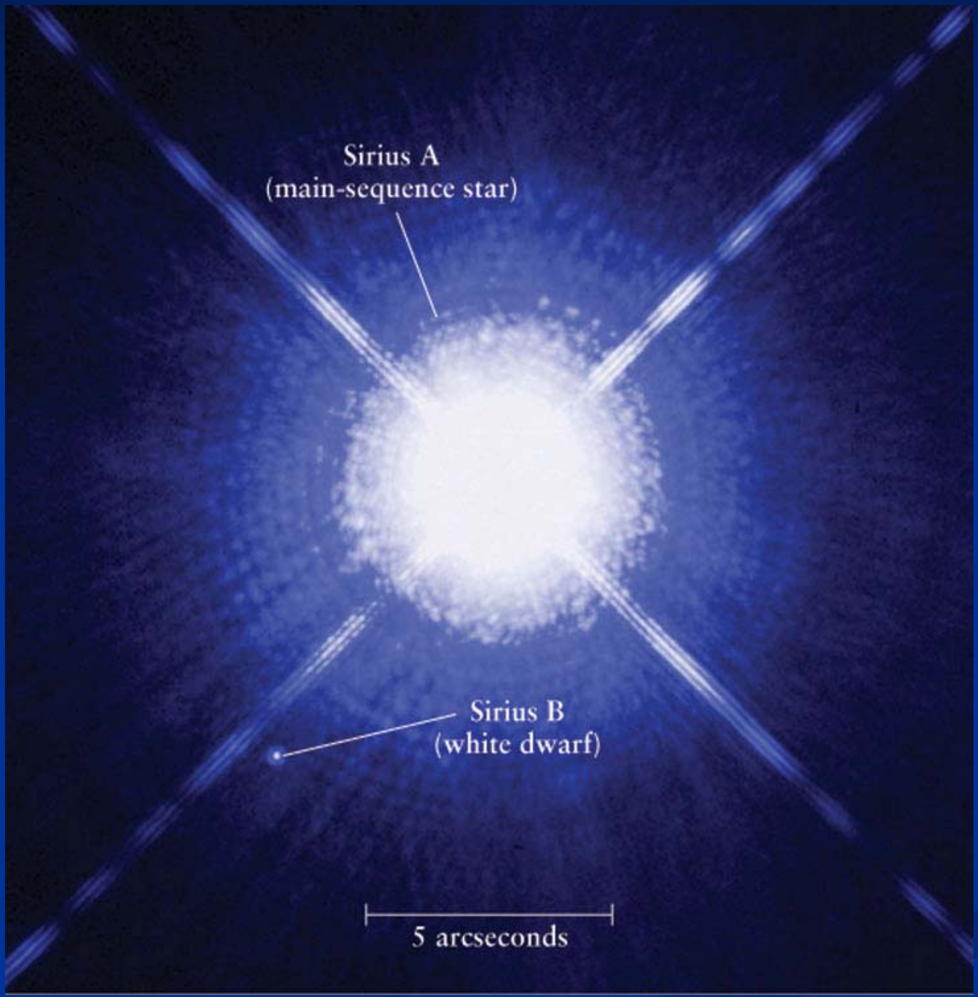
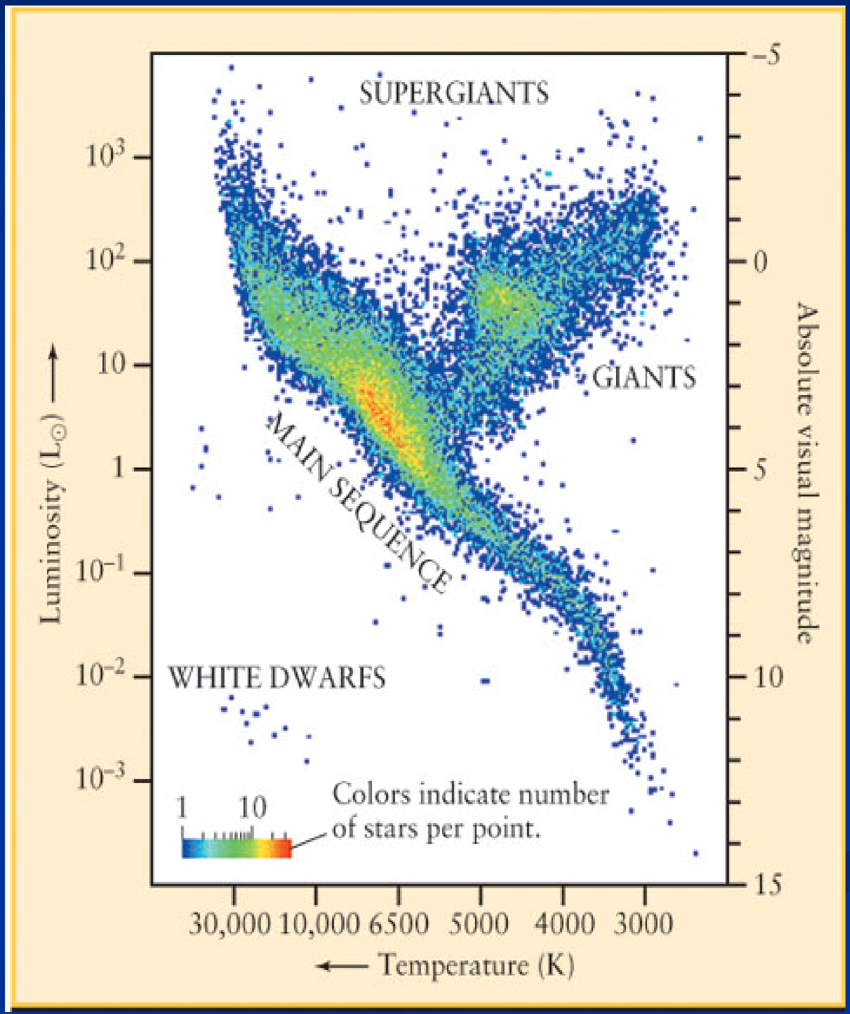


White Dwarfs Again – Isolated Evolution

- White dwarfs slowly radiate away their heat.
- The Sun will eventually form a white dwarf with ~10% its current luminosity, or 0.1 $L_{\odot}$.
- After 5 Gyr as a white dwarf, the Sun's luminosity will be ~10^{-4} $L_{\odot}$ and dropping…



White Dwarfs in Binary Systems

- The less massive star evolves along the main sequence, but if the two stars are close enough…

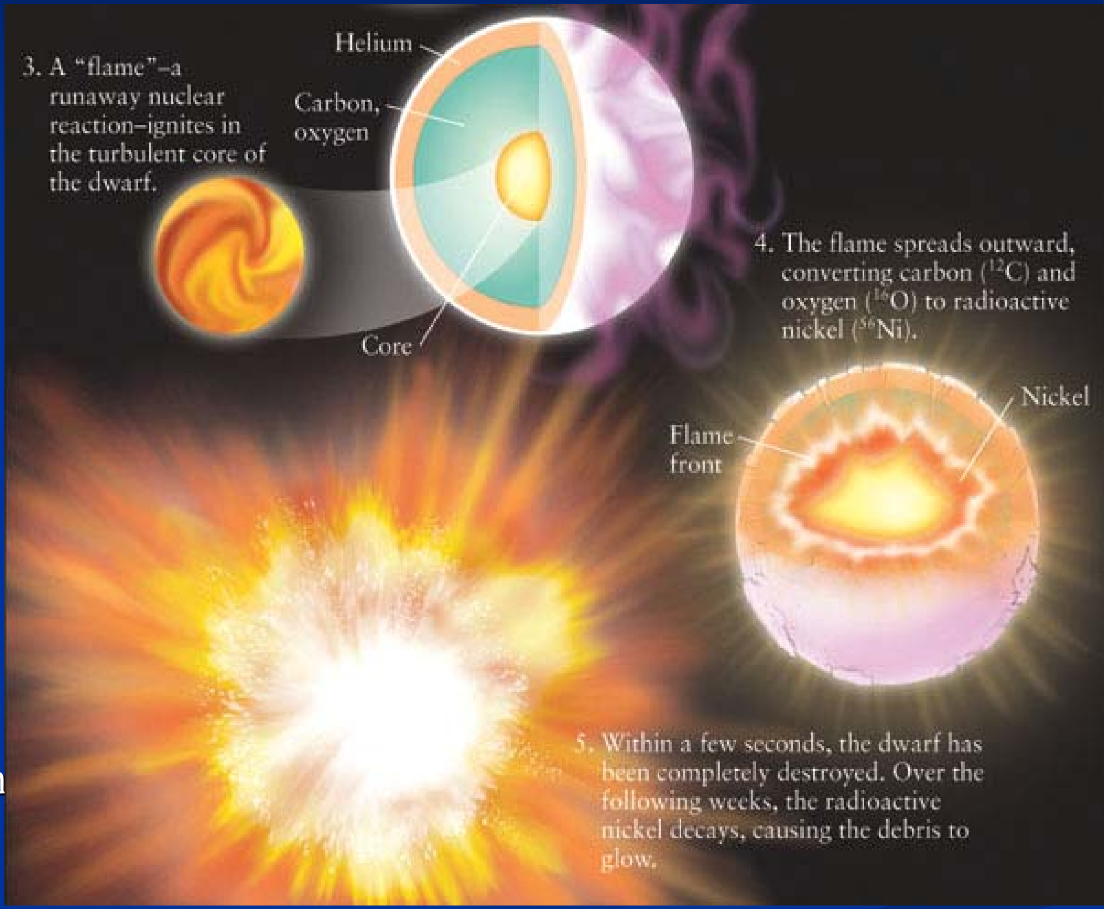
White Dwarfs in Binary Systems

Classical Novae

- Novae occur when a white dwarf accretes hydrogen very slowly from a neighbor.
- When the hydrogen surface is hot enough to ignite, the entire surface burns at once.
- Novae release as much energy as the Sun does in 1000 years.
- White dwarf and companion survive; repeat performances are possible!

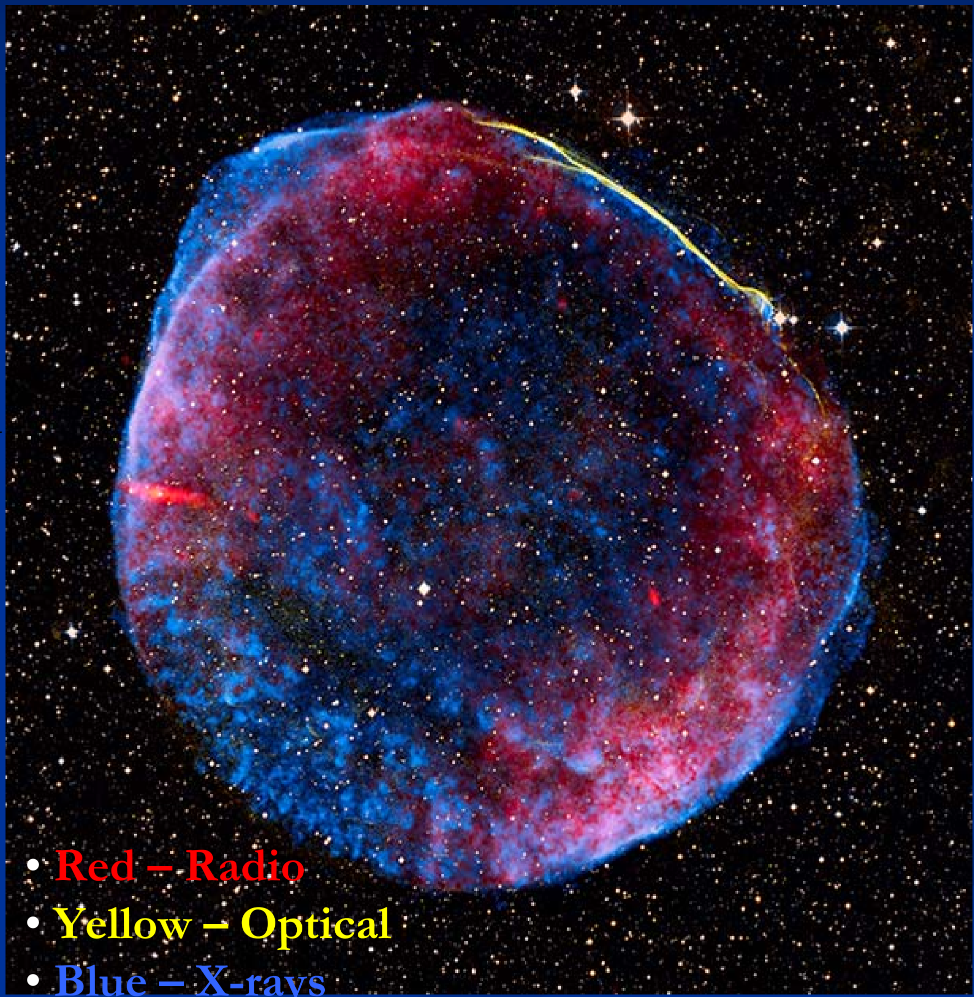
Type Ia Supernovae

- Similar mechanism to Novae, details still unclear.
- Runaway fusion in carbon/oxygen core (similar to helium flash)
- Perhaps initiated by
  - Mass accretion increases core pressure till carbon ignites?
  - Explosive burning of ^{4}He surface layer → shock wave compresses core?
- 10 million times more energetic than a nova.
  - Equal to lifetime output of Sun
  - White dwarf is completely destroyed



Remember SN 1006?

- Young – only 1002 years
- Type Ia
  - no compact remnant detected
  - no companion star detected either
- Nearly uniform low-density environment
  - nearly symmetrical development (except NW)
  - no nearby star formation



Common features of SNe

- High-speed outflow of majority of star's mass
  - speeds of 10 – 20 million m/s, few % speed of light
- Availability of copious quantities of neutrons and far-from-equilibrium conditions allows synthesis of large quantities of heavy elements
- Radioactive isotopes of heavy elements (especially ^{56}Ni and ^{56}Co) power the emission we see
  - SNe are nonthermal emitters!

Type Ia Supernovae as Standard Candles

- Some SN Ia occur in nearby galaxies where we can measure distance accurately by other means – calibrating distance/brightness scale
- Then can use SN Ia to measure distance to farther galaxies.
- Independently measure redshift using spectral lines.
- Comparison measures expansion history of the universe – provided first indication that expansion of universe is accelerating!
  - confirmed by measurements of CMB, large-scale structure
  - but identity of the "dark energy" driving this acceleration remains a mystery

Summary

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  - composition plays a secondary role
- Fusion is the primary energy source
- Stars spend most of their time on the main sequence, burning hydrogen
- Stellar evolution driven by search for hydrostatic equilibrium
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  - Massive stars go through core collapse → neutron stars or black holes
  - White dwarfs in close binary systems suffer thermonuclear explosion → total disruption
- Next week: Evolution of massive stars and Core-collapse SNe