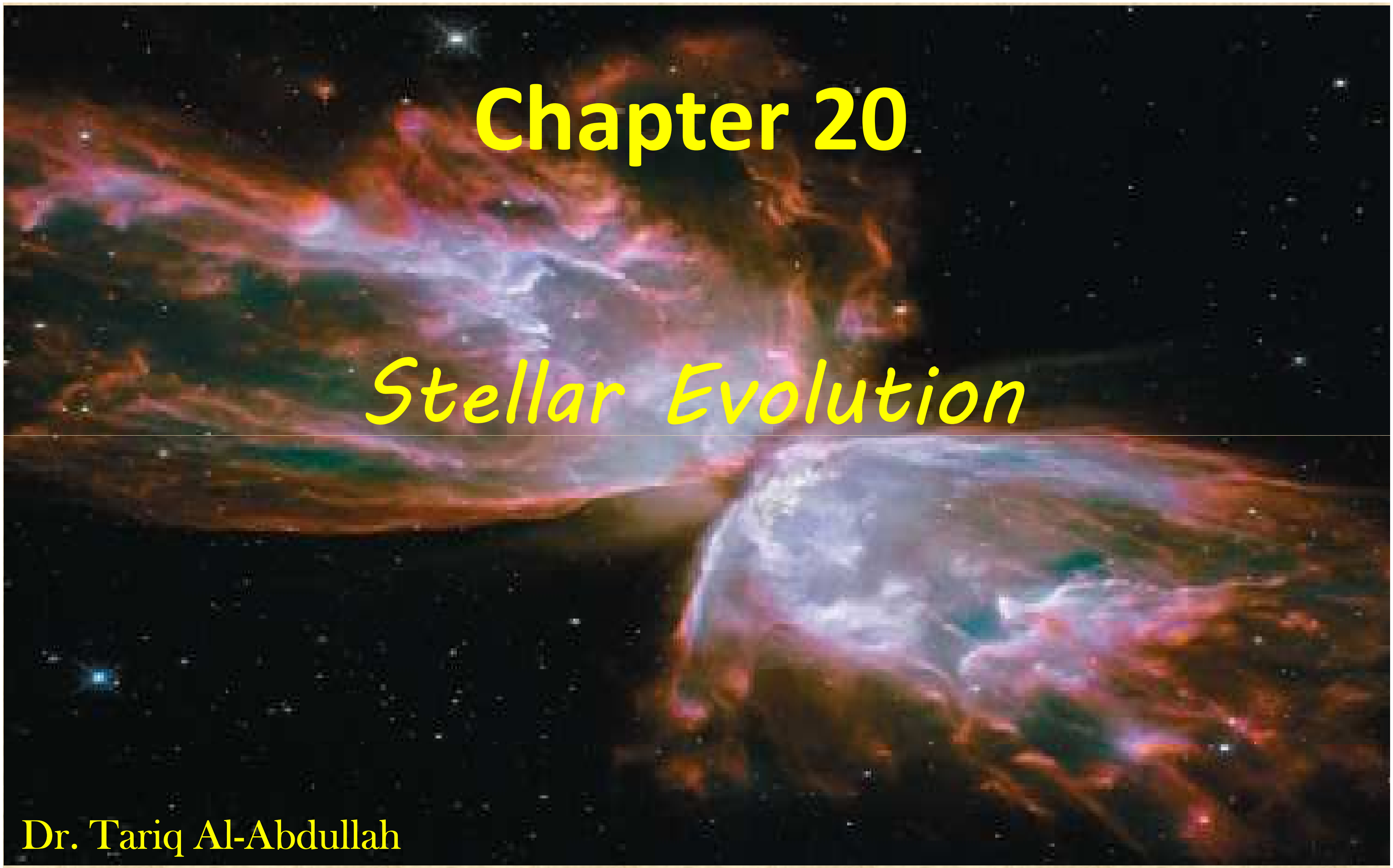


Chapter 20

Stellar Evolution

Dr. Tariq Al-Abdullah

Learning Goals:

20.1 Leaving the Main sequence

20.2 Evolution of a sun-like star

20.3 The death of a low-mass star

20.4 Evolution of Stars more massive the sun

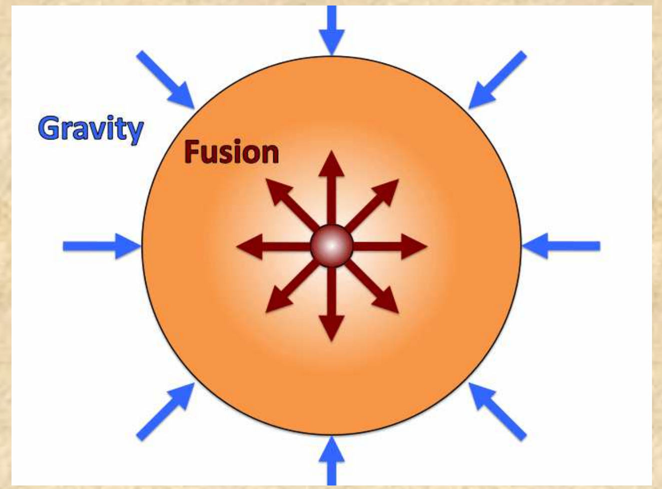
20.5 observing stellar evolution in star clusters

20.6 Stellar evolution in binary systems

20.1 Leaving the Main Sequence

- Most stars spent most of their lives on the main sequence.
- The Sun; took 50 million years to form and 10^{10} years to evolve.
- Low-mass stars still stars, M-type (red dwarf) consume fuel slowly.
- O- & B-star evolve away in few million years. All of them are perished.
- Between the two extremes; many Stars are observed.
- On the main sequence H fuses into He in its core: Core H-Burning.

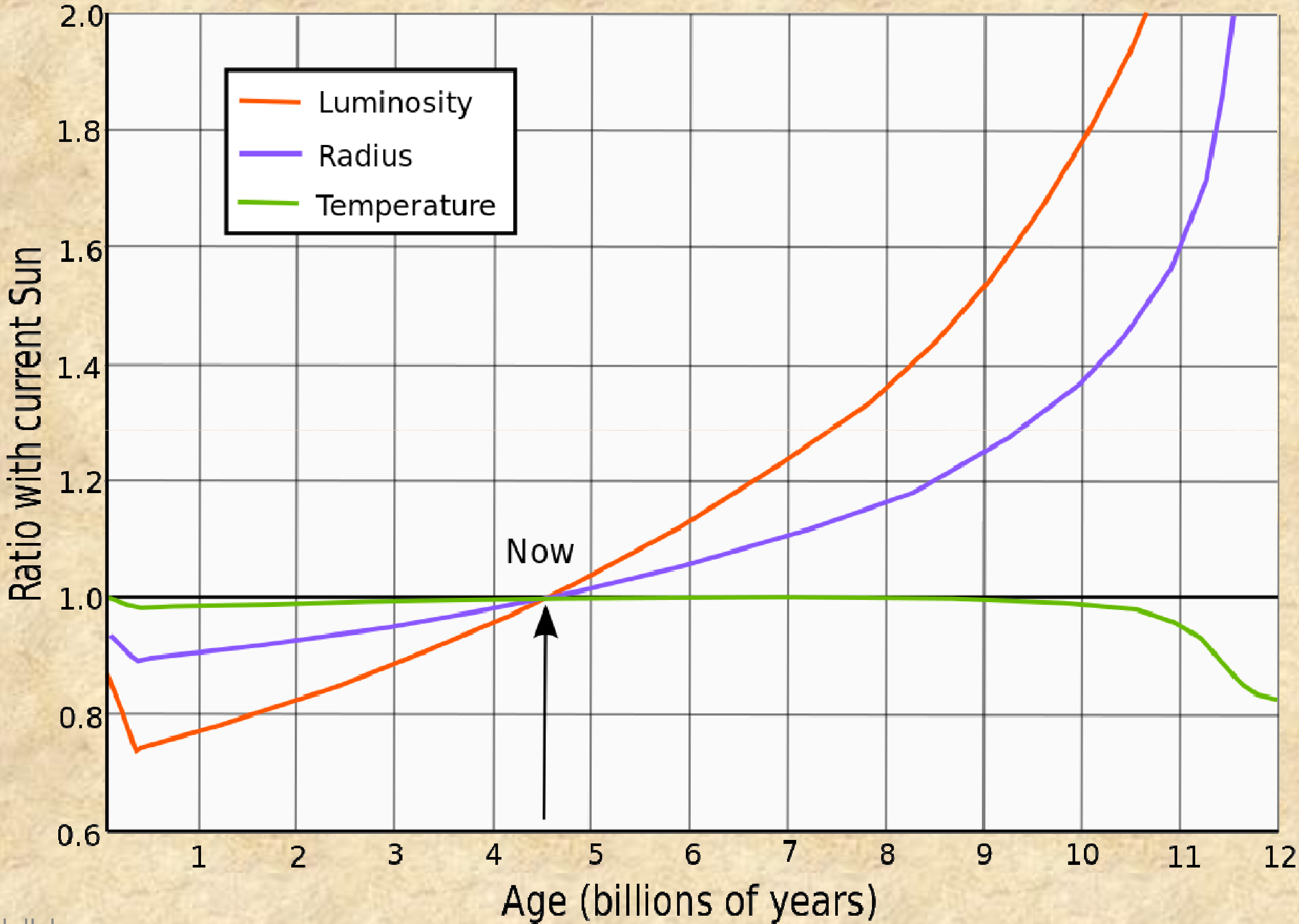
- A main sequence star is in Hydrostatic Equilibrium.
- More pressure: Expansion.
- Decreasing Temperature: Collapse



20.1 Leaving the Main Sequence

- As the M.S. star ages → Its core T increases ➔ L & R increases. **Very Slow**.
- The Star location on the H-R diagram is unchanged.
- As the H in the core is consumed → internal balance will change ➔ internal structure and outward appearance will change: Rapid
- Rapid ➔ the star leaves the main sequence ➔ its days are numbered.
- Depending on its mass: Its post stages → end of a star's life.
- Low mass stars die gently, high mass stars die catastrophically.
- High mass = 8 $M_\odot$, Low mass < 8 $M_\odot$
- We will concentrate on a few representative evolutionary sequence.

20.1 Leaving the Main Sequence

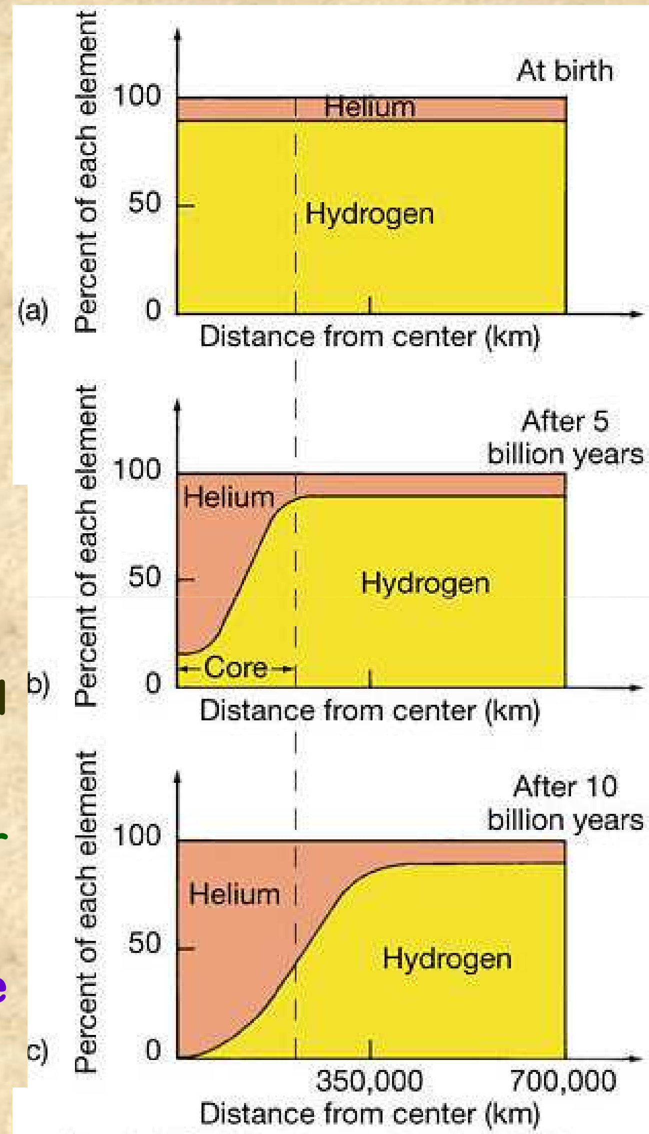


20.2 Evolution of a Sun-Like Star

- No sudden large scale changes in the Star's properties when it is on the main sequence. Same Temp., 30% higher Luminosity, Radius, Density.
- After 10^{10} years a Sun-like star burns its fuel. No refuel.

Stage 8: The Subgiant Branch

- Nuclear fusion proceeds. Structure --->
- He increases faster at the center? T is highest and burning is fastest there.
- He increases near the edge of the core, but slower ➔ H is Depleted completely at the center.
- H-burning moves to higher layers in the core. Pure He grow.



20.2 Evolution of a Sun-Like Star

Stage 8: The Subgiant Branch

- No enough pressure to oppose the gravity at the center ➔ core begins to contract ➔ process of burning H accelerates..

- $T < 10^8$ K. No He fusion → no generation of energy through fusion.

- Shrinkage of He core➔ Temp. increases in the center, and heating the overlying burning layers ➔ H-burning fast in the a shell surrounding He-core [Hydrogen-Shell-Burning]

→ energy generation >> original Main Sequence Star

- He-Core continues to shrink, no burning BUT center gets brighter

- Density stage-7 ($7x10^5$) → stage-8 ($2x10^6$) kg/m^3

- Star leaves H-R diagram horizontally to right

- Surface temperature decreases, L increases.

- Radius is tripled, ***subgiant star***

Stage 8: The Subgiant Branch

When Hydrogen is being fused causing the increase the Hydrogen fusion which also causes an increase of the radiation pressure making the outer layers to expand and cool.

Main sequence star vs Subgiant star

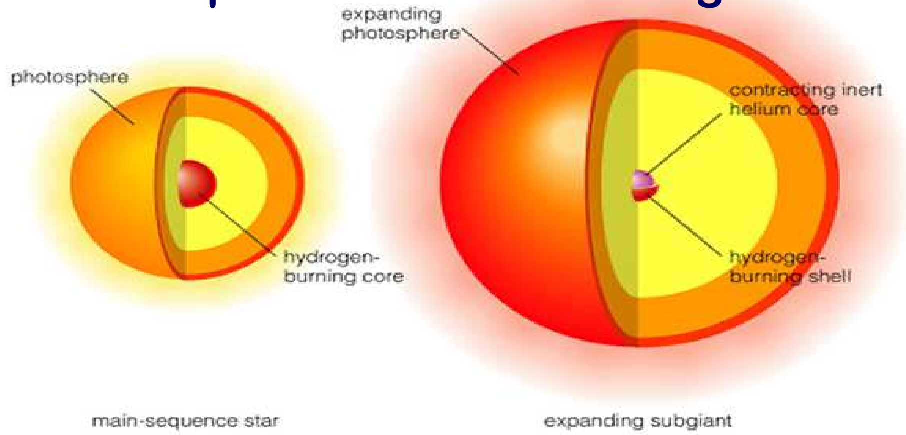


TABLE 20.1 Evolution of a Sun-Like Star

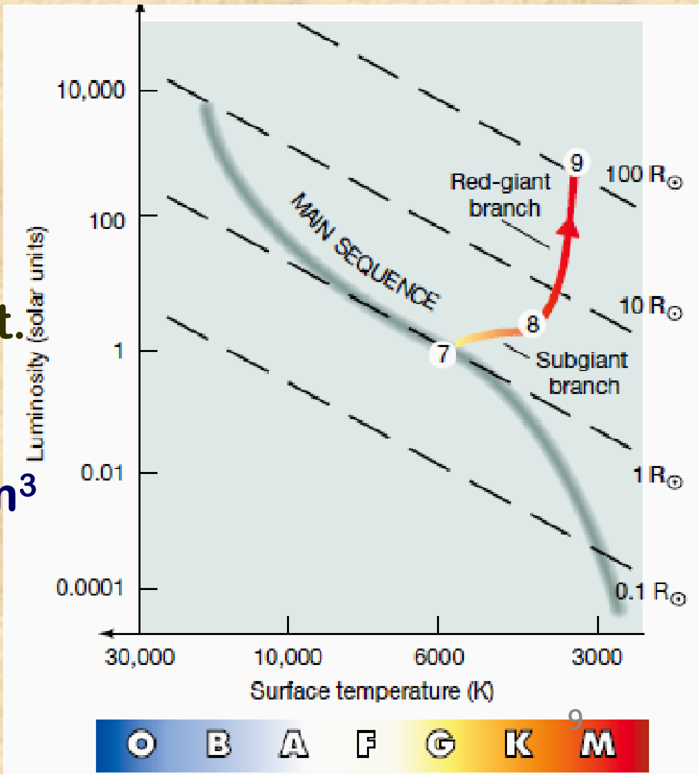
Stage	Approximate Time to Next Stage (yr)	Central Temperature (10^6 K)	Surface Temperature (K)	Central Density (kg/m^3)	Radius (km)	Radius (solar radii)	Object
7	10^{10}	15	6000	10^5	7×10^5	1	Main-sequence star
8	10^8	50	4000	10^7	2×10^6	3	Subgiant branch
9	10^5	100	4000	10^8	7×10^7	100	Helium flash
10	5×10^7	200	5000	10^7	7×10^6	10	Horizontal branch
11	10^4	250	4000	10^8	4×10^8	500	Asymptotic-giant branch
12	10^5	300	100,000	10^{10}	10^4	0.01	Carbon core
		—	3000	10^{-17}	7×10^8	1000	Planetary nebula*
13	—	100	50,000	10^{10}	10^4	0.01	White dwarf
14	—	Close to 0	Close to 0	10^{10}	10^4	0.01	Black dwarf

Stage 9: The Red-Giant Branch

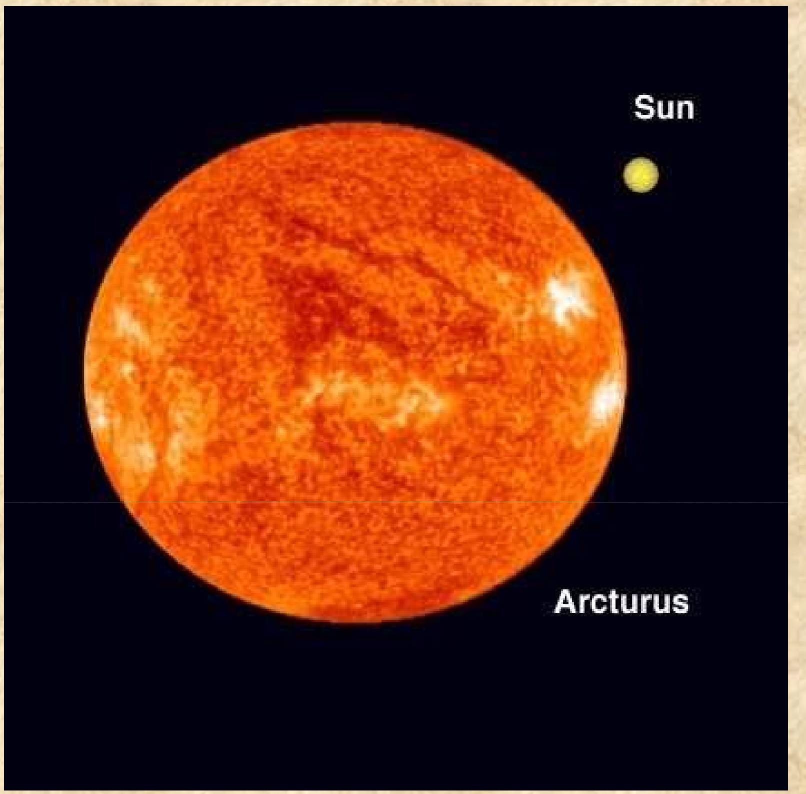
- The Star is far from the main sequence.
- Unbalanced shrinking core vs enhanced H-burning➔ outer layer increased in R
- At stage 8 → the interior is opaque to the radiation.
- Convection carries the core enormous energy to the star's surface.
- in 8 -- 9, $T_{surface}$ is constant, vertical path to 9.
- @ stage 9 ➔ **Red-giant branch**.
- L = hundreds $L_{\odot}$, R = 100 $R_{\odot}$.
- T is lower, L is brighter, R is bigger, Mercury's orbit.
- Core continues shrinking,

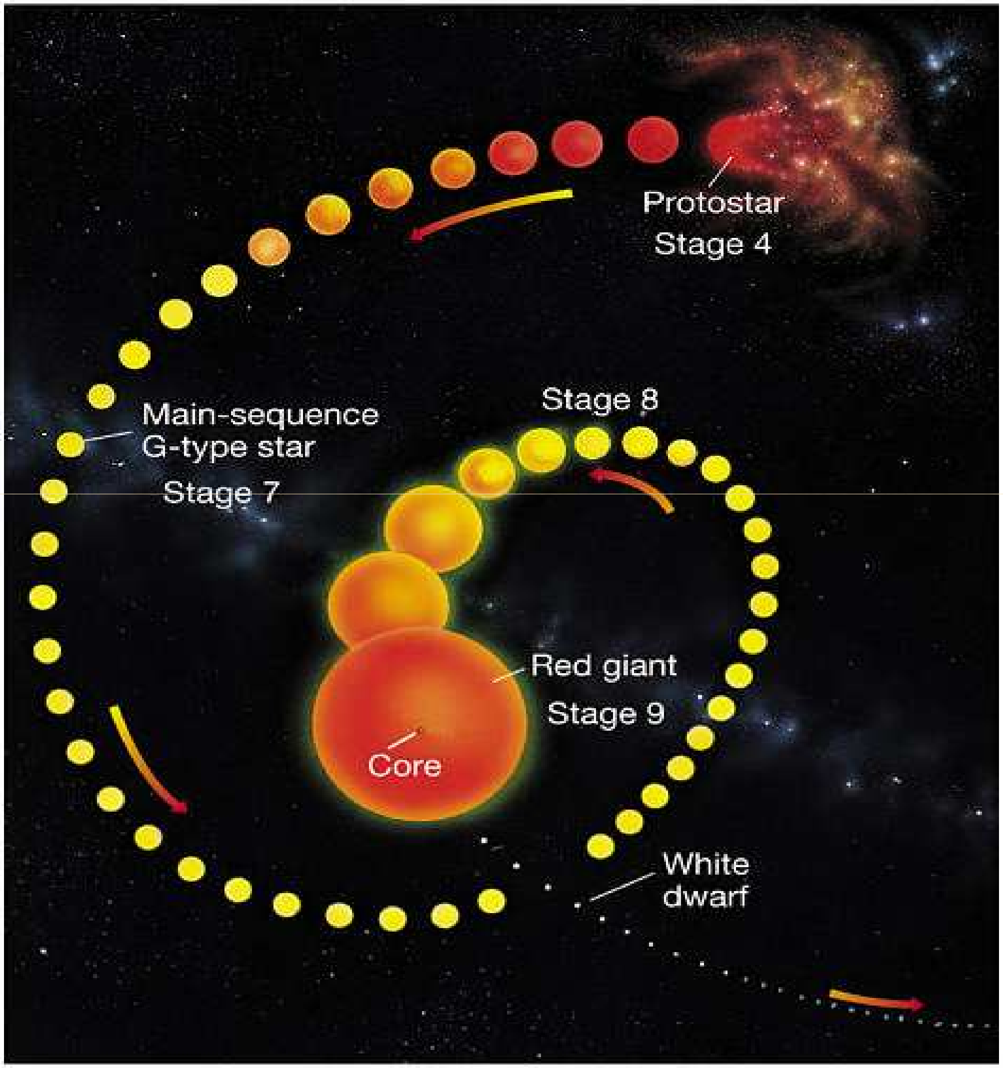
•density $1.5x10^5$ (now) →10^8 kg/m^3, surface 10^{-3} kg/m^3

- About 25 percent of the mass of the entire star is packed into its planet-sized core.



20.2 Evolution of a Sun-Like Star





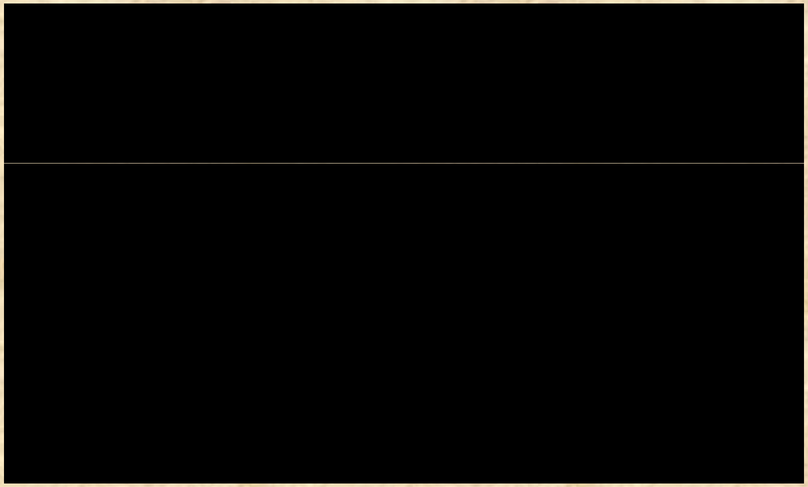
The red-giant is the KIII giant Arcturus

$M=1.5M_{sun}$, $R = 21R_{sun}$, $L = 160L_{sun}$

Hydrogen-shell-burning stage

Stage 10: Helium Fusion

- Unbalanced state of a red-giant star ➔ collapsing core
- Rest of the star is drifting into space ➔ envelope and core are far away
- After few hundred million years: density 10^8 kg/m^3, temperature risen to 10^8 K
- Helium begins to burn in the core to synthesize carbon
- Triple-alpha process:



$$^{4}\mathrm{He} + {}^{4}\mathrm{He} \rightarrow {}^{8}\mathrm{Be} + \text{energy}$$

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

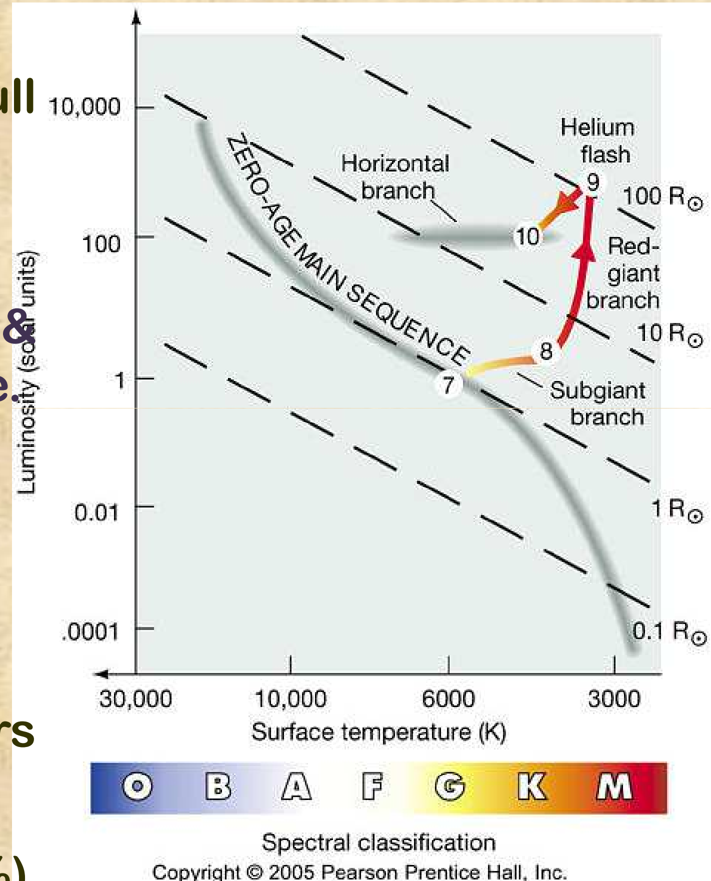
- The ^{8}Be nucleus is highly **unstable**, and will decay in about 10^{-12} s unless an alpha particle fuses with it first.
- This is why high **temperatures** and **densities** are necessary.

Stage 10

- Till now: p, He → nuclear fusions
- Vast sea of electrons stripped from atoms by large heat in stellar's interior.
- Electrons may play an important rule in determining the star's evolution.
- Q. M. rules should be applied.
- Pauli-exclusion principle prohibits the electrons to be very close.
- The principle → **electron degeneracy** ➔ electron degeneracy pressure ➔ do work against further collapsing.
- Burning is unstable → explosive consequences.
- In a star supported by thermal pressure: the gas after He-fusion will expand and cool ➔ reestablishing an equilibrium.
- In electron supported core: Pressure is independent of T, Temperature is higher, no expansion, no rise in pressure.
- The core is unable to respond to the rapidly changing conditions: **: He Flash**

Stage 10: Horizontal branch

- **He FLASH:** flood of energy released → heats the core → thermal pressure dominates.
- density drops and core expands ➔ gravity pull inward → stable core.
- fusing He into C at temp. well above 10^8 K,
- the flash doesn't increase L ➔ reduction in R & energy output, T increases because of steady core.
- A star jumps to stage 10, stable He core.
- @ 10: He-burning core & H-burning shell.
- after 10: <u>Horizontal branch</u>.
- a "helium main sequence" of sorts, where stars remain for a time.
- Mass of red giant < mass of the original star (30%)



ONE IMPORTANT LESSON

The dominant thermonuclear reaction in a star changes with temperature

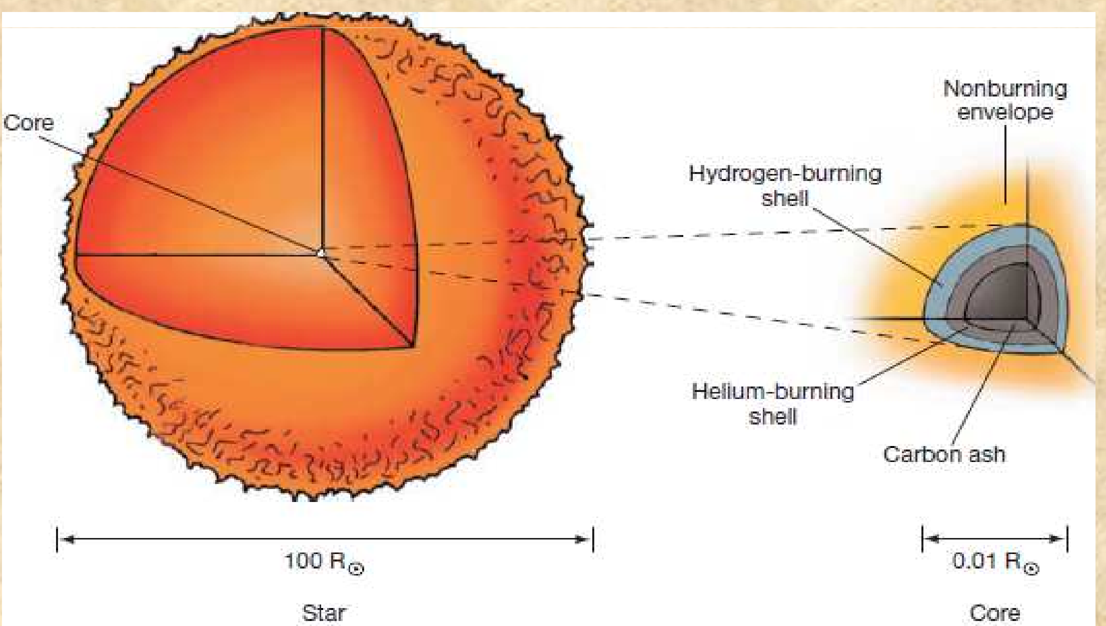
MINIMUM TEMPERATURE	REACTION
8×10^6 K	proton-proton chain
20×10^6 K	CNO cycle
100×10^6 K	triple alpha
600×10^6 K	carbon-helium fusion
10^9 K	carbon burning

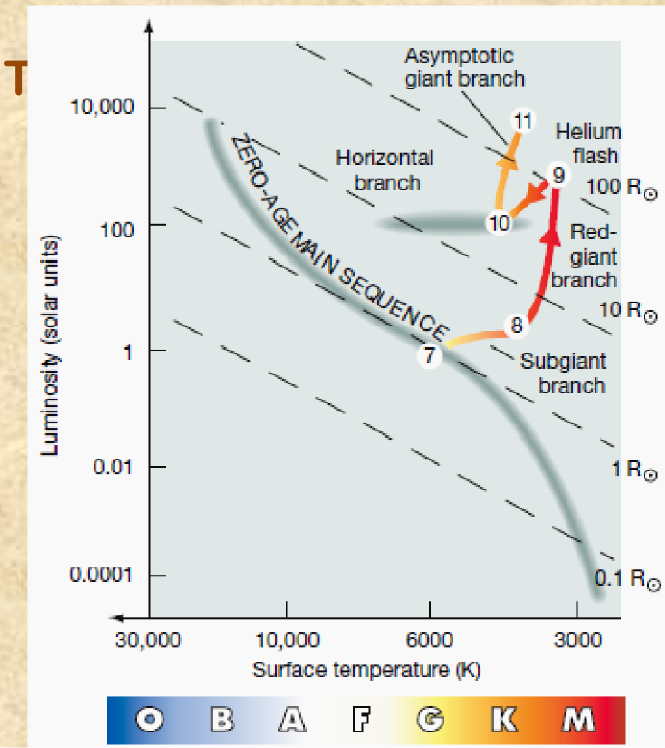
Thermonuclear Reaction

20.2 Evolution of a Sun-Like Star

Stage 11: Back to the Giant Branch

- Consuming He in the core → back to giant branch.
- He consumed in few tens million years → New carbon-rich inner core forms.
- The non burning carbon-core shrinks in size, Temp increases as gravity pulls inward ➔ H & He increase burning in outer layers..
- Asymptotic Giant Branch. larger R, greater L, lower T





Dr.

20.3 The Death of a Low-Mass Star

The Fires go out

- Shrinking core is limited to 10^{10} kg/m^3 ➔ Electron degeneracy ➔ T < 600 million K needed for carbon burning, it is only 300 MK.
- Contraction of the core ceases, no rising in its temperature. Stop fusing.
- The inner edge of the helium burning is: $^{12}C + ^{4}He \rightarrow ^{16}O$ + Gamma.

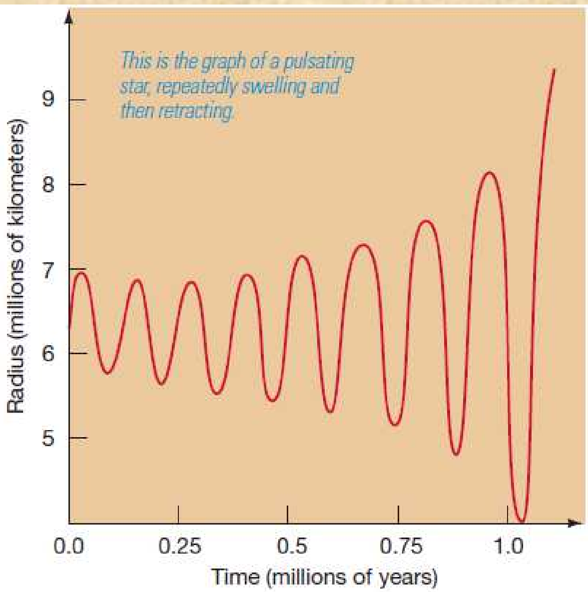
Stage 12: Planetary Nebula

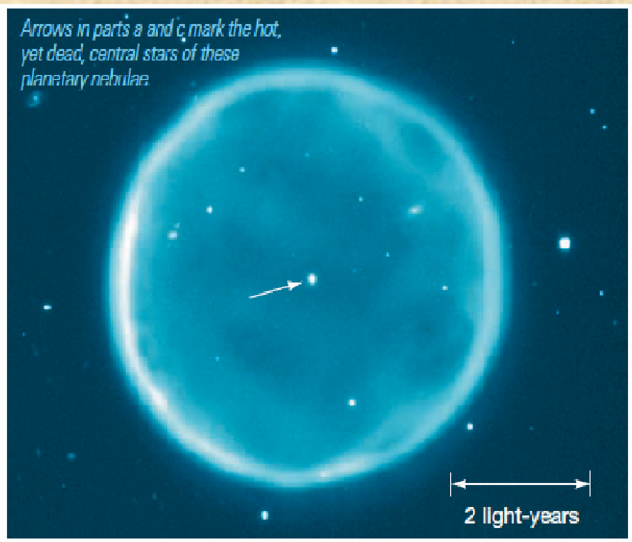
- Carbon core is dead, heavier elements will not be synthesized.
- Outer-core shells burning H & He → more core layers reach their final high-density state ➔ increasing nuclear reaction intensities
- The envelope expand and cool, $R_{max} = 300R_{\odot}$. Up to Mars.
- burning becomes unstable ➔ Helium-shell flashes ➔ large fluctuations in the radiation's intensities ➔ envelope pulsates
- Heated, expands, cooled, contracted ➔ instability of its surface layers.

Stage 12: Planetary Nebula

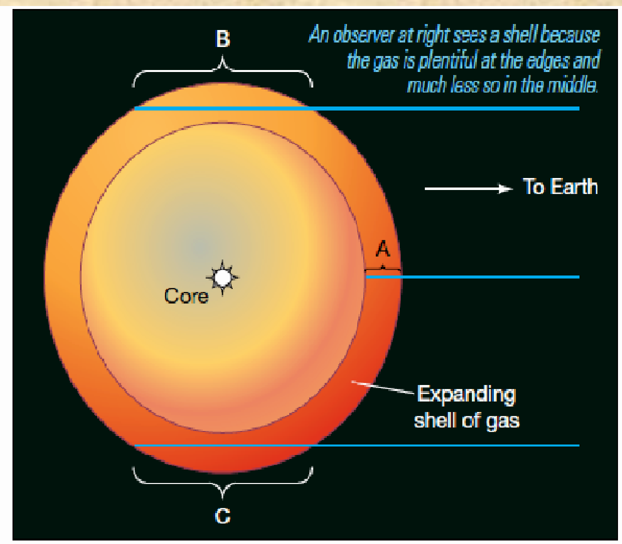
- Instability of the radiation ➔ Pulsating up to the outermost layers
- Around the peak of each pulsating, the temp. drops, atoms recombine ➔ emission of additional photons ➔ Envelope expands and gas escapes.
- The star has two distinct parts:

  1. Well defined carbon core (hot, dense and very luminous)
  2. Expanding cloud of dust and cool gas.





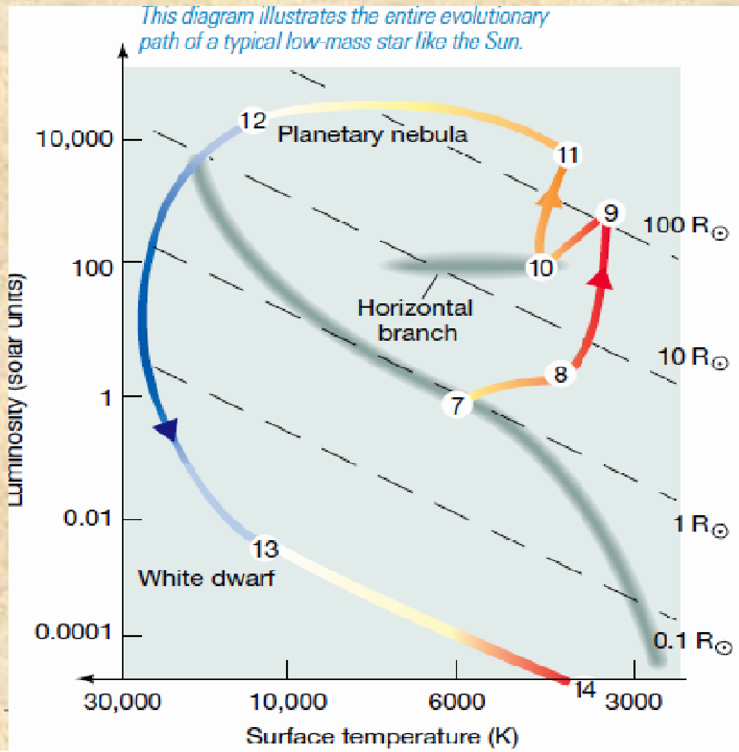
(a)

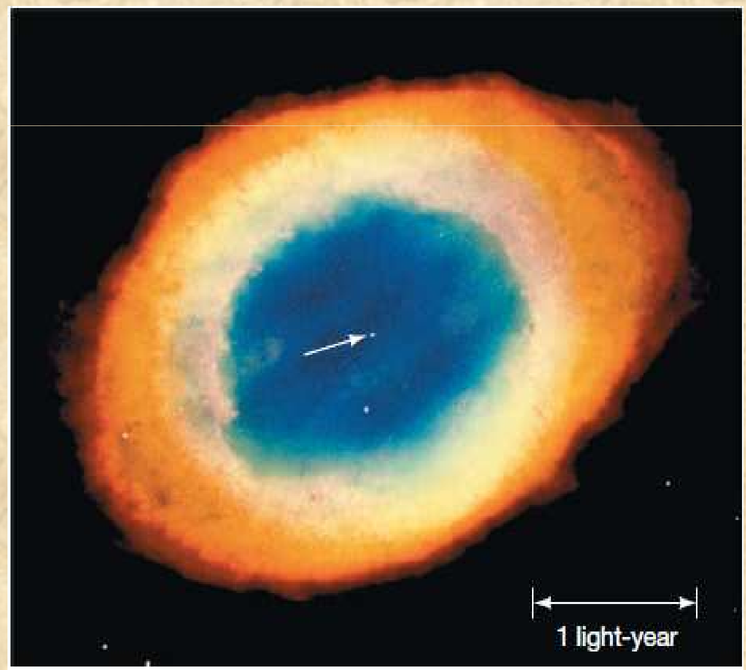


(b)

Stage 12: Planetary Nebula

- Once the core exhausts its fuel → it contracts and heats up → move to left (HR).
- Its UV radiations ionizes the inner part of the surrounding cloud
- Spectacular display: Planetary nebula
- Planetary here is misleading, poor resolution telescope in the 18th century.

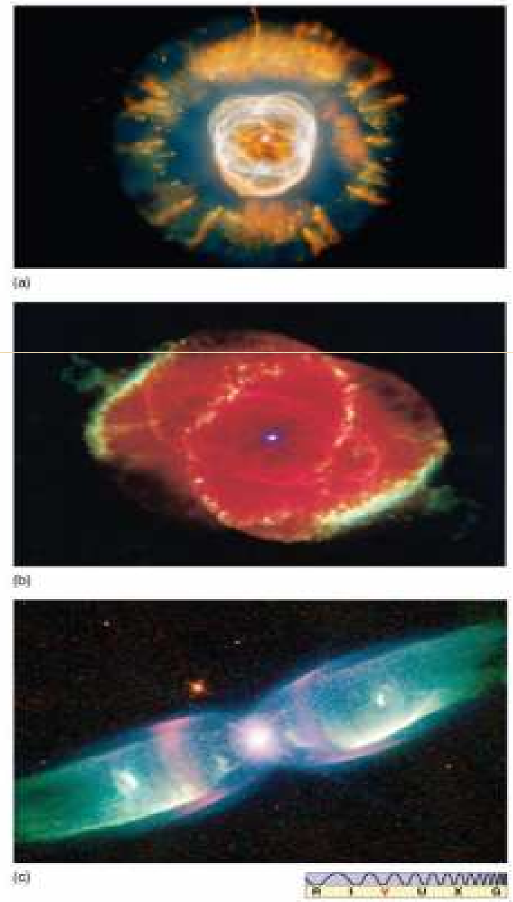




20.3 The Death of a Low-Mass Star

Planetary nebulae can have many shapes:

As the dead core of the star cools, the nebula continues to expand and dissipates into the surroundings.



Eskimo

Cat's eye

M2-9

20.3 The Death of a Low-Mass Star

Stage 13: White Dwarf

• As the envelope recedes, the core becomes visible. Few thousand years.

• The core has the size of the Earth (200,000km → 6400km), M = 0.5M_{sun}.

• Shining by stored heat. White hot surface, appear dim because of it small size. ➔ WHITE DWARF

• Sirius B original star is 4M_{sun}.

• Not all dwarfs have the same chemical compositions.

• Small mass ➔ He dwarf, the Sun → CO dwarf, large stars with M=8M_{sun} → ONe dwarf: $^{16}O+^{4}He \rightarrow ^{20}Ne+\gamma$

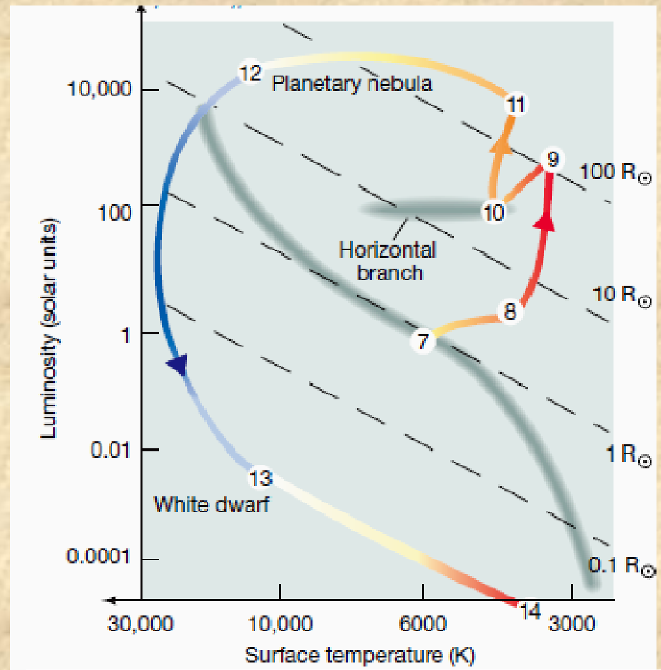
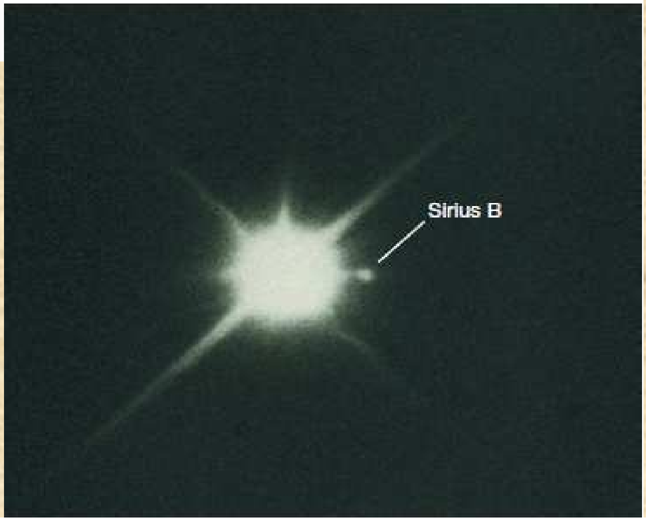
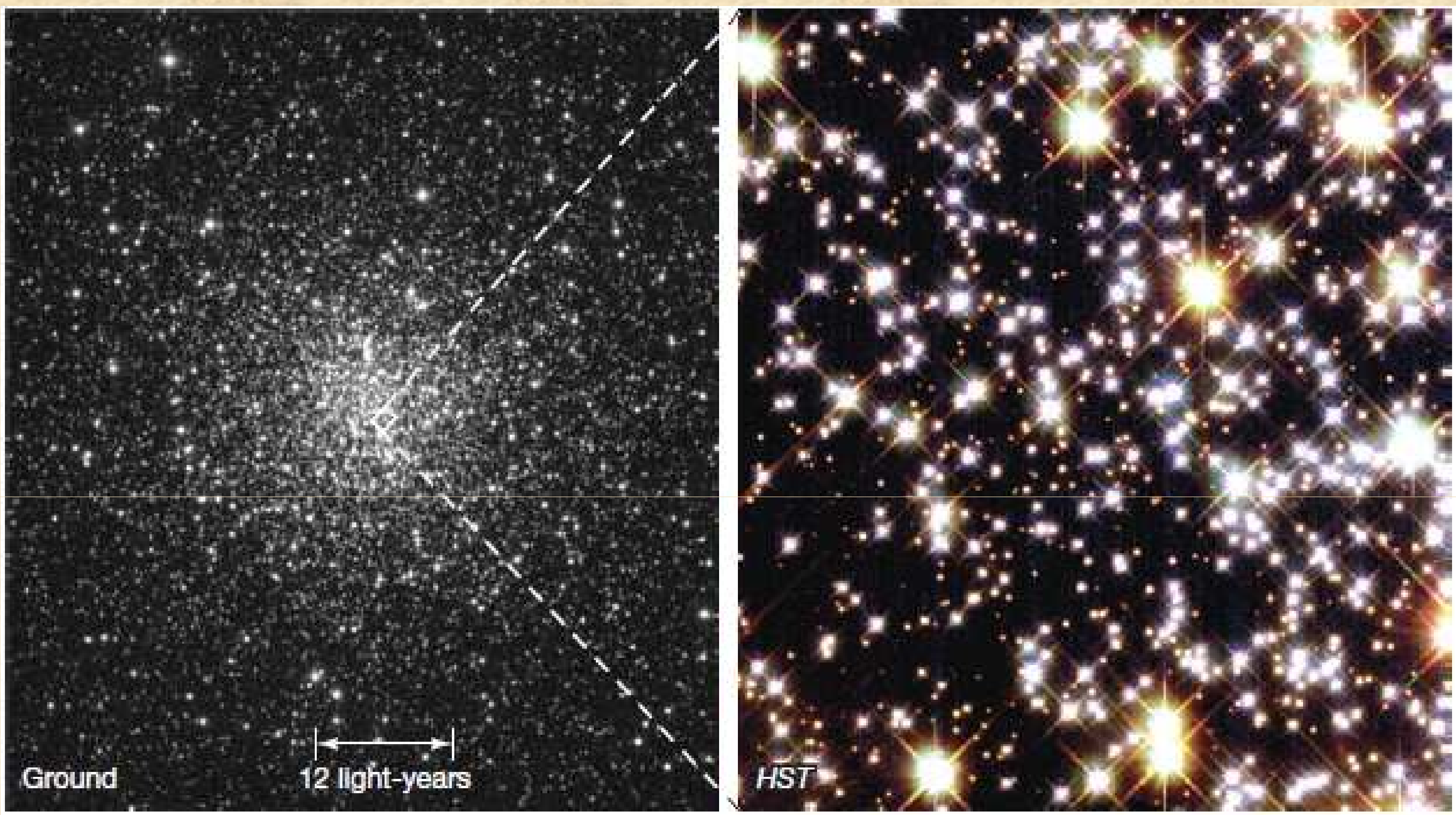


TABLE 20.2 Sirius B, a Nearby White Dwarf	
Mass	1.1 solar masses
Radius	0.0073 solar radius (5100 km)
Luminosity (total)	0.0025 solar luminosity (10^{24} W)
Surface temperature	27,000 K
Average density	3.9×10^{9} kg/m^{3}



20.3 The Death of a Low-Mass Star

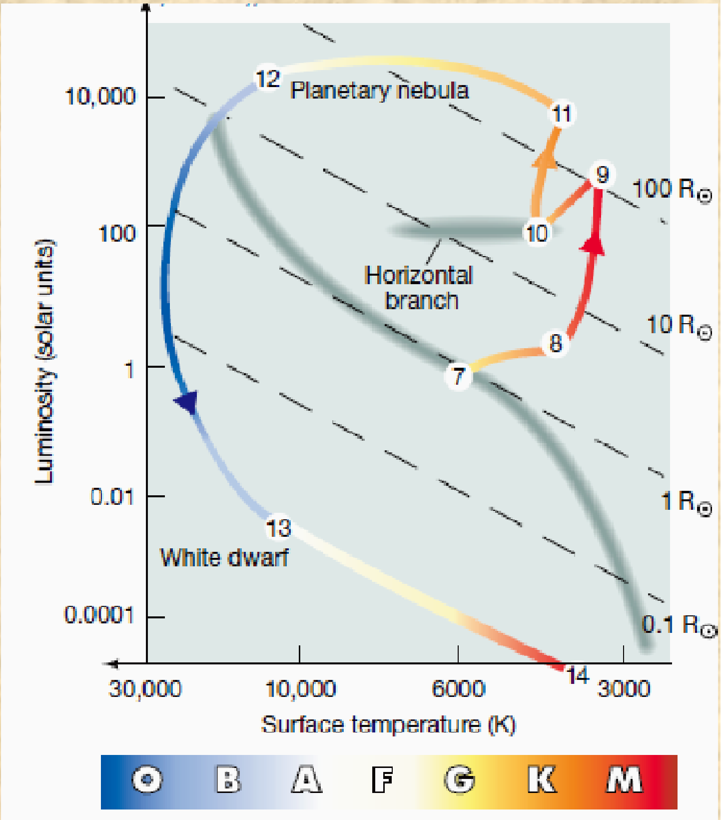


a) The globular cluster M4 as seen through a large ground-based telescope at Kitt Peak National Observatory in Arizona at 5500 light-years away. (b) A peek at M4's "suburbs" by the Hubble Space Telescope shows nearly a hundred white dwarfs within a small 2-square-light-year region.

20.3 The Death of a Low-Mass Star

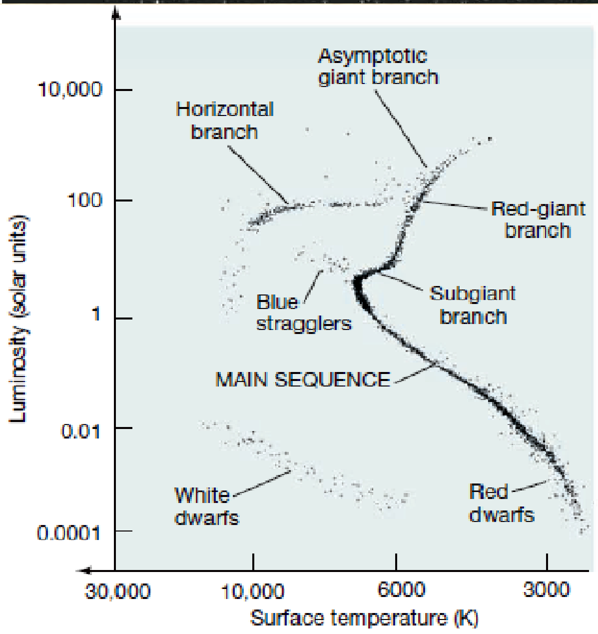
Stage 14: Black Dwarf

- Isolated white dwarf looses heat with time.
- Follows: white – yellow – red track near the bottom of H-R diagram.
- Cooled, dense, burned-out object in space
- No further shrinking, temperature drops almost to absolute zero. Final size is close to the Earth.



Comparing Theory with Reality

- M80 globular cluster, 8000 pc from the Sun.
- H-R diagram shows bright, red giant, AGB, faint red, and white dwarfs.
- Main sequence , giant, and horizontal branches imply age of M80 is 12 billion years.
- Oldest-known objects in the Milky-Way galaxy.
- Stages 7—13 are consistent with theoretical models.
- Main-sequence stars only with mass < $M_{\odot}$
- One solar masses are now AGB.
- More stars > $M_{\odot}$ seem still on the main sequence!
- Blue Stragglers not MS, but should be WD.
- Recent merging of low mass stars.



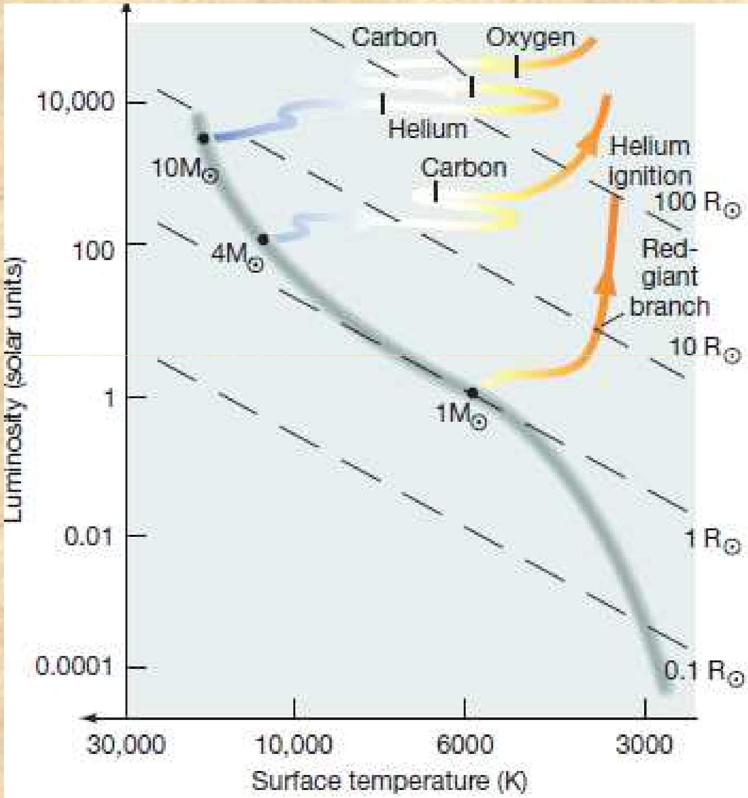
20.4 Evolution of Stars More Massive than the Sun

→ High-mass stars evolve much faster than low-mass stars. Life Time α M^{-3}

→ Large mass and strong gravity generate more heat

→ Red Supergiants:

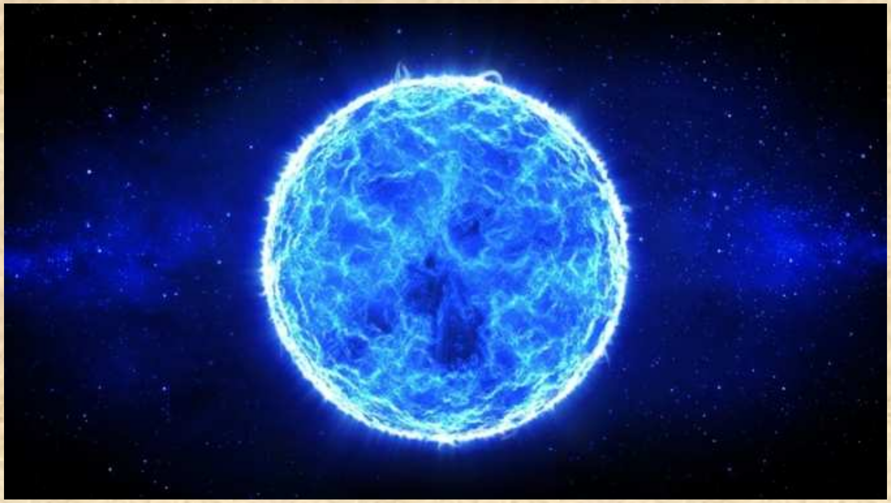
- All stars have same evolving (8 & 9) stages.
- Leaves main sequence horizontally (L,T,R)
- 3-main sequence stars; masses=1,4,10 M_{sun}
- 2.5M_{sun}: He burns smoothly & stably, no He-flashes.
- 4M_{sun}: remains red-giant as He fuses into C. No sudden jump to horizontal branch.
- 8M_{sun}: Achieved 600MK easily, C → O → Ne
- 10M_{sun}: starts to burn He while it is close to main-sequence, its death supernova (Ch21).

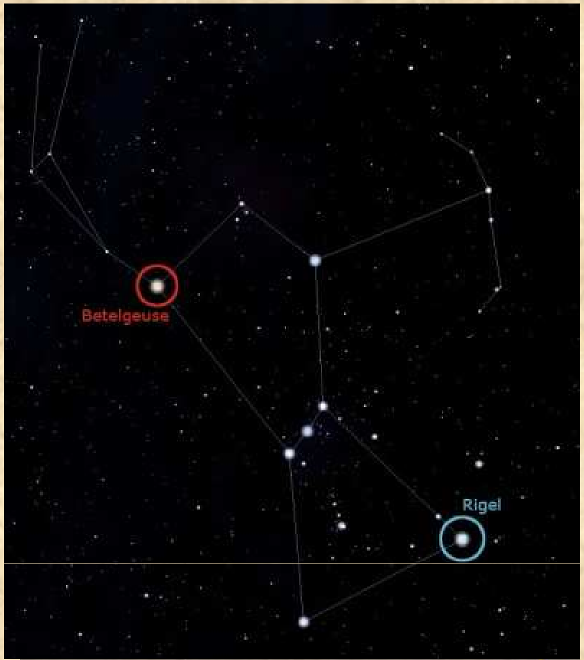


20.4 Evolution of Stars More Massive than the Sun

Example: Rigel [blue supergiant]

- ❑ $R = 70 \times R_{sun}$ and $L = 60{,}000 \times L_{sun}$.
- ❑ it had an original mass = $17 \times M_{sun}$
- ❑ Strong stellar winds drops its mass significantly.
- ❑ Sill near the main-sequence.
- ❑ Flushing He into C in its core.

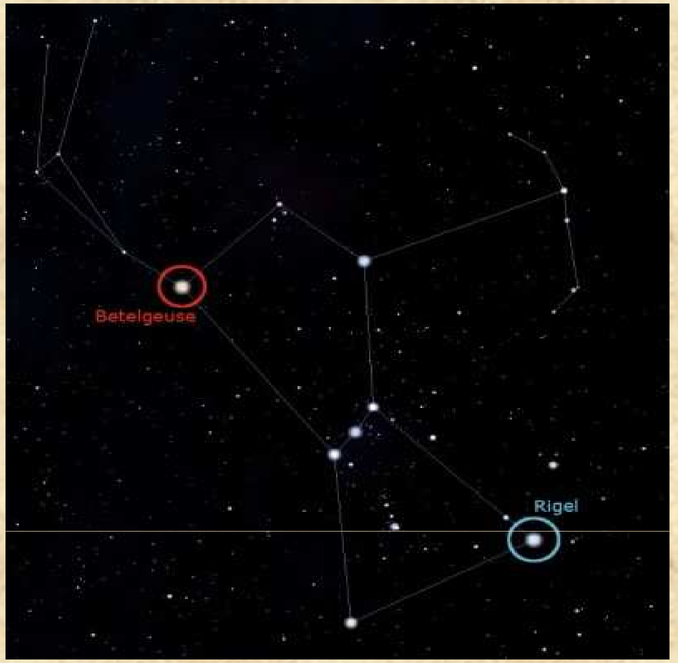




20.4 Evolution of Stars More Massive than the Sun

➔Betelgeuse [red supergiant]

- R = 70 R_{sun} and L = 10,000 L_{sun}.
- it had an original mass = 12 – 17 M_{sun}
- Strong stellar winds drops its mass significantly, surrounded by a huge shell of dust.
- Flushing He into C & O in its core.
- Pulsating, varying radius by almost 60%.
- Lost a lot of mass, uncertain what is left!!.



Dr. T. Al-Abdullah

20.4 Evolution of Stars More Massive than the Sun

➔The end of the road!

- Star's evolution: Collapsing → heating → electron degeneracy → fusion reaction → non-burning core → core builds up. Process Repeating.
- Stars up to $12M_{sun}$ avoid going supernova.
- More than $12M_{sun}$, threshold of becoming supernova.
- Rigel and Betelgeuse lost a lot of mass ➔ million years (close) to explode.

TABLE 20.3 End Points of Evolution for Stars of Different Masses

Initial Mass (Solar Masses)	Final State
Less than 0.08	(Hydrogen) brown dwarf
0.08–0.25	Helium white dwarf
0.25–8	Carbon–oxygen white dwarf
8–12 (approx.)*	Neon–oxygen white dwarf
Greater than 12*	Supernova (Chapter 21)

20.5 Observing Stellar Evolution in Star Cluster

➔ Star cluster excellent source: theory of evolution

➔ Evolving cluster H-R diagram

(a) Time = 0, Zero-Age Main-Sequence:

-- Cluster dominated by its most massive stars.

-- Blue supergiants.

(b) Time = 10^7 yr,

-- O-type stars left the main-sequence, exploded and vanished, few visible as red supergiants.

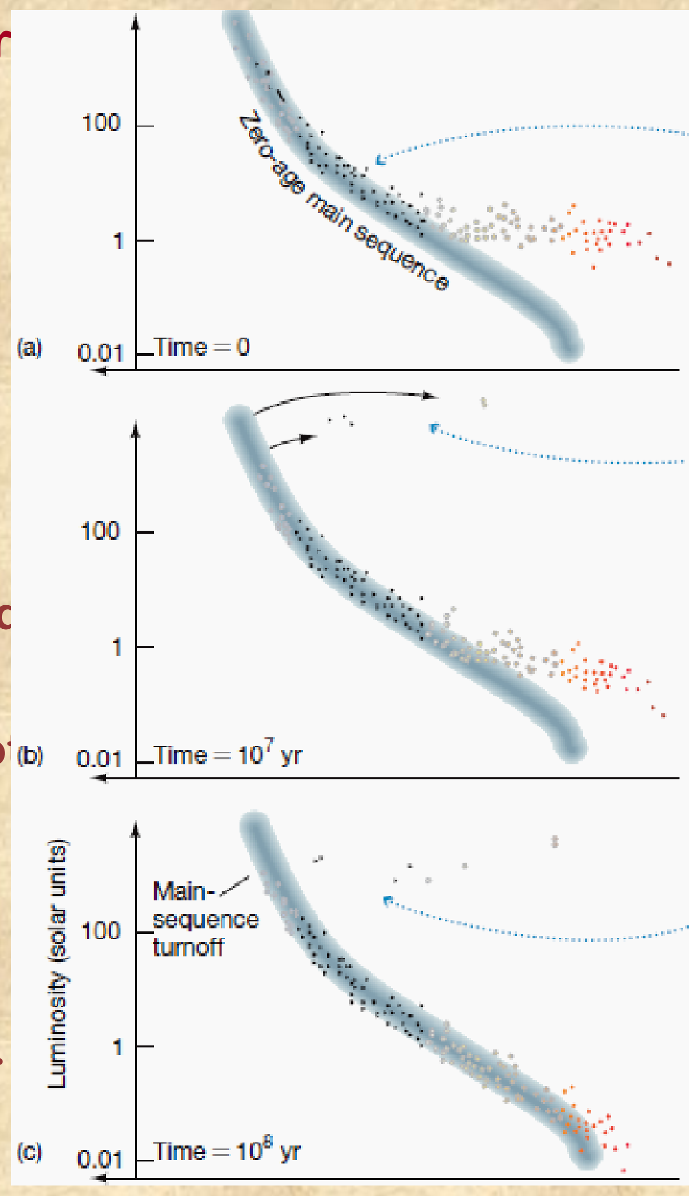
-- Other stars are unchanged, lower main-sequence not arrived yet!

(c) Time = 10^8 yr,

-- B5-stars left, few more red supergiants are visible.

-- M-stars have finally arrived. Few in contracted phase.

-- B-type and red-supergiant stars are dominating.



(c) Time = 10^8 yr,

➔**Main-sequence turnoff**: high luminosity end of the observed main-sequence.

➔ **turnoff mass**: the mass of the star that is just evolving off the main-sequence.

(d) Time = I billion yr,

-- main-sequence turnoff = $2M_{sun}$ or spectral type A2.

-- Subgiant and giant branches with low M are visible.

-- Formation of M-type stars is complete,

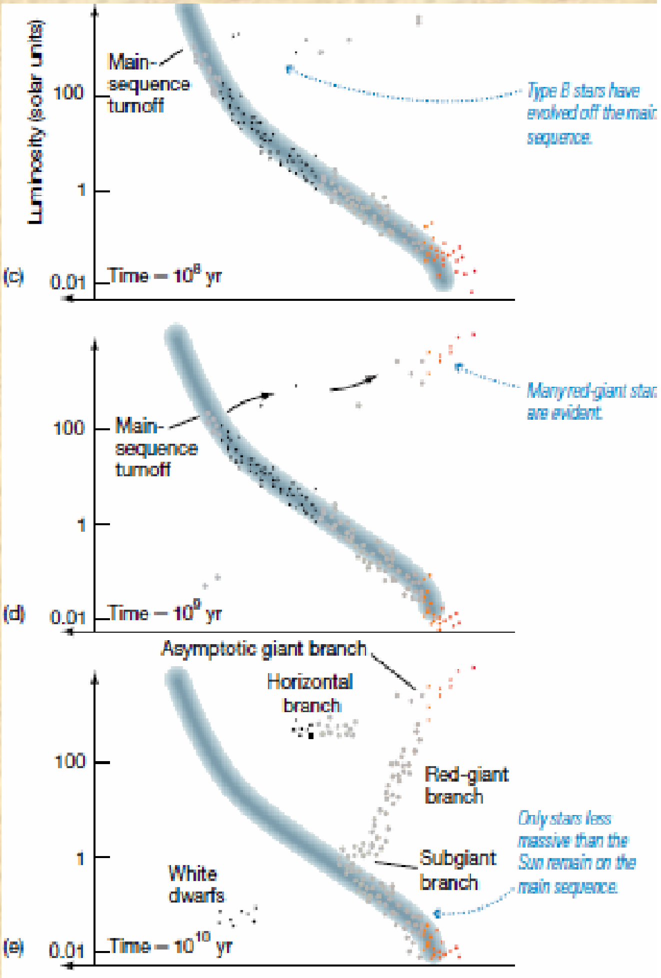
-- First white-dwarf is visible.

(e) Time = 10^{10} yr,

-- Main-sequence turnoff = $1M_{sun}$ ➔ Type-G2.

-- Subgiant and giant stars, horizontal and AGB appear as a distinct regions in the H-R diagram.

-- More white-dwarfs are visible. Only low-mass stars left on the main sequence.



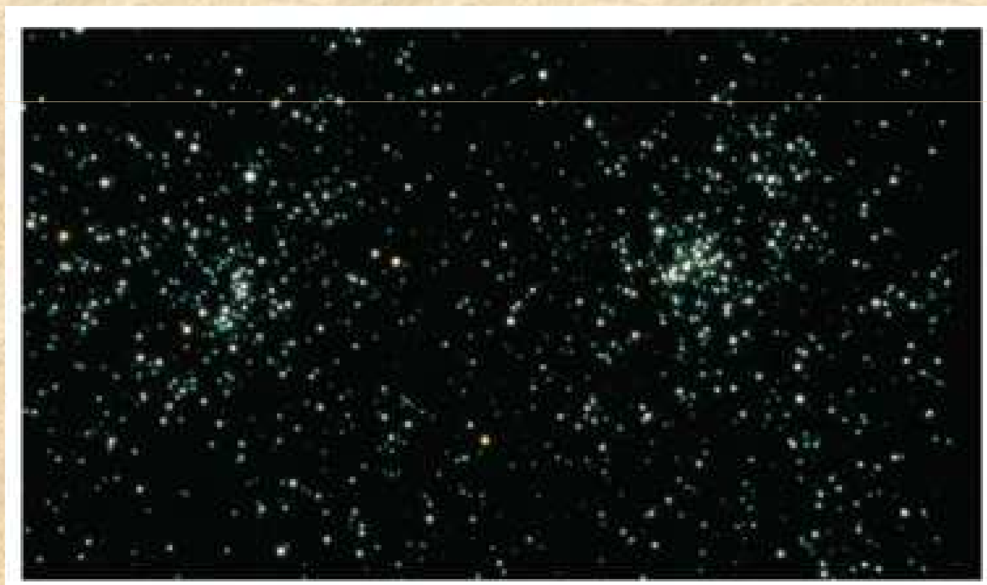
20.5 Observing Stellar Evolution in Star Clusters

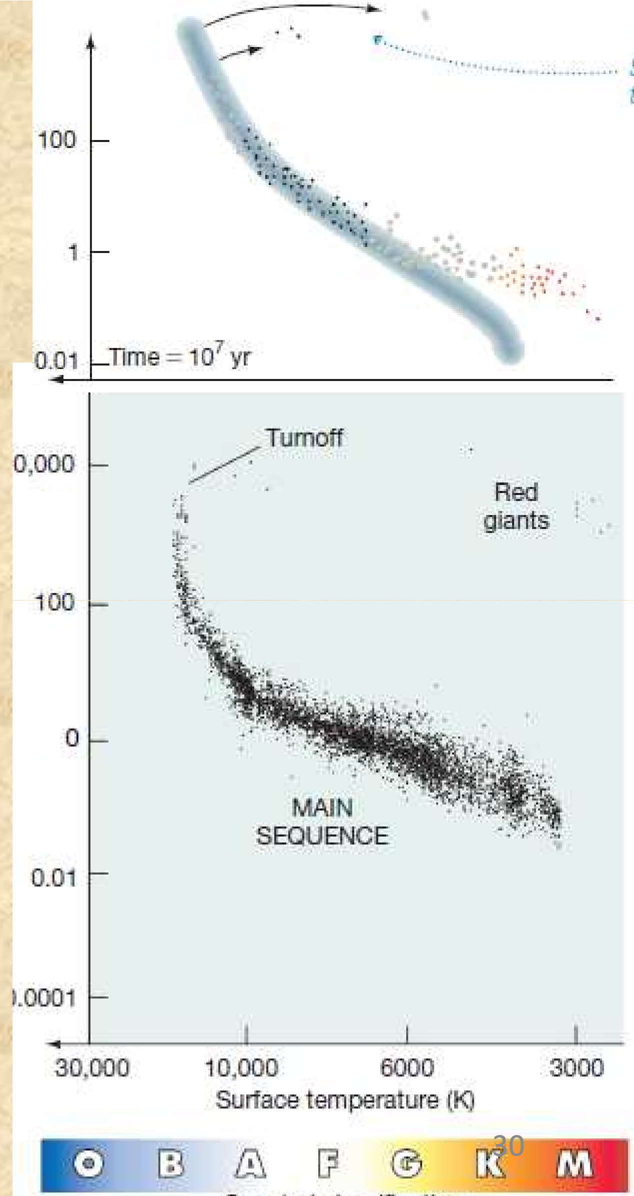
➔ **Example of 10-million years**

➔ **Twin-open clusters: h and χ Persei clusters**

Comparison between observations and theory:

➔ **The twin-clusters are 10^7 yr old.**





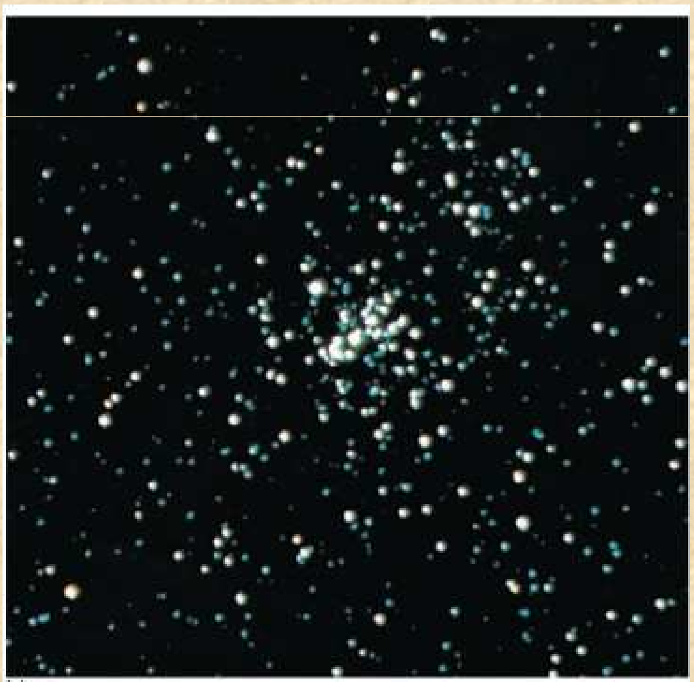
20.5 Observing Stellar Evolution in Star Clusters

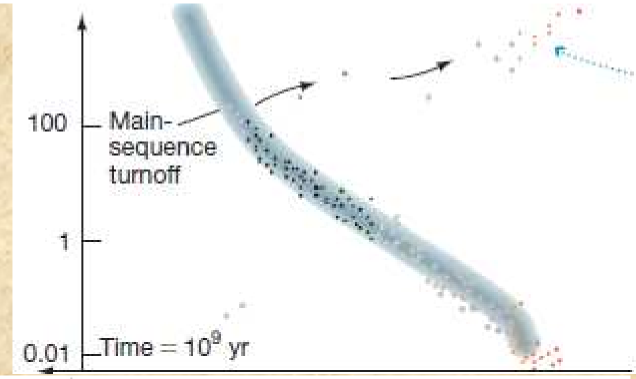
➔ Example of $10^8 – 10^9$ years

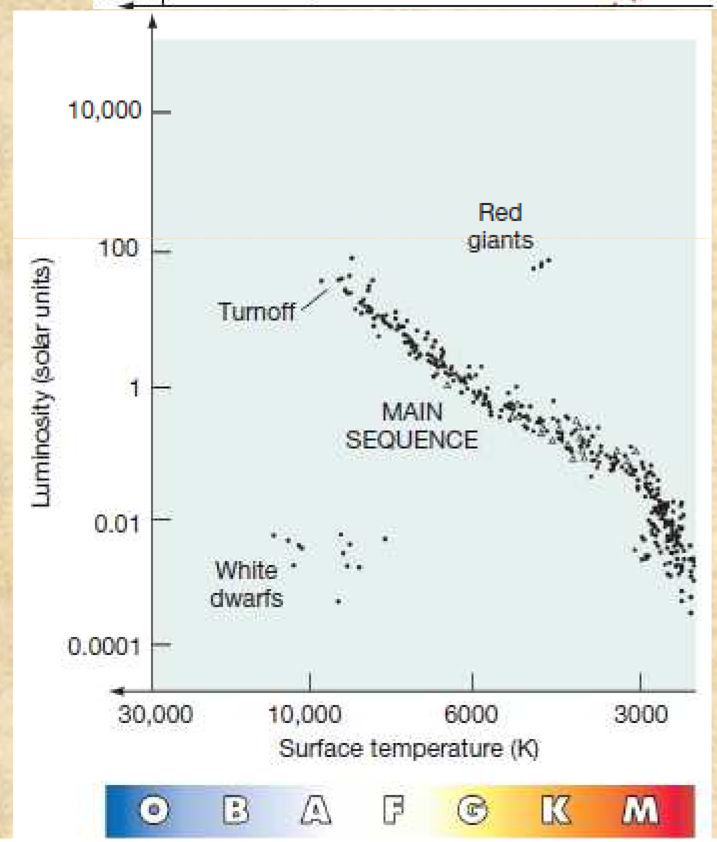
➔ Hyades open cluster.

Comparison between observations and theory:

➔ The cluster age is 600 million years.







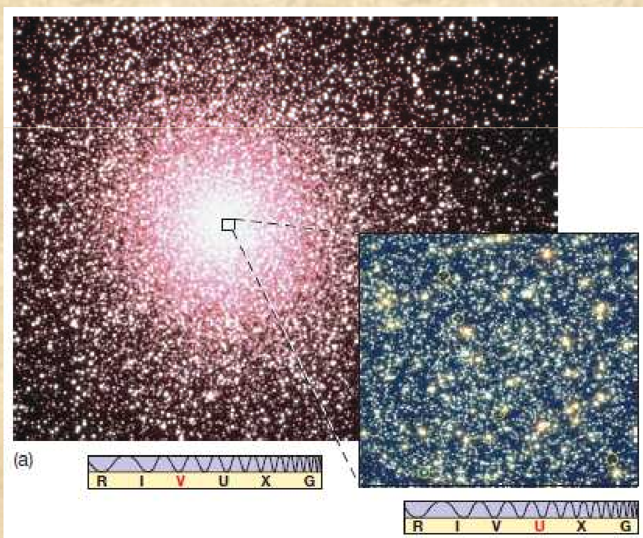
20.5 Observing Stellar Evolution in Star Clusters

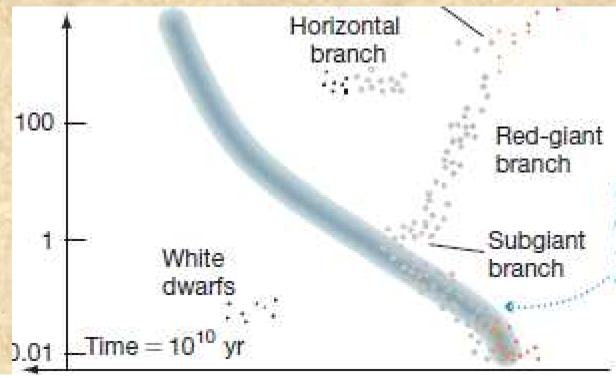
➔ **Example of very old stars**

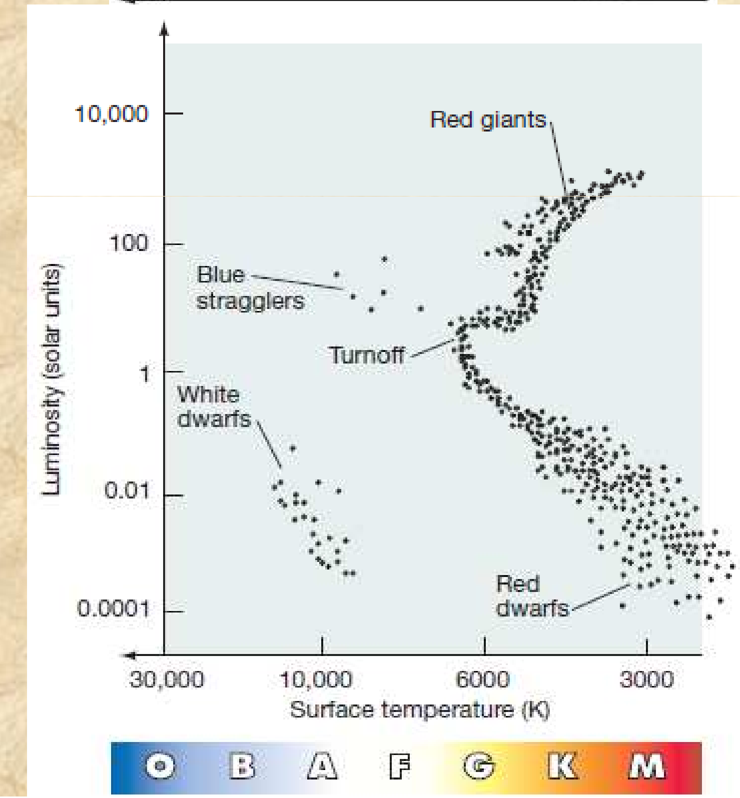
➔ **Globular cluster: 47 Tucanae**

Includes: main-sequence, subgiant, red-giant, horizontal branches, white dwarfs.

➔ **The cluster age is 10 –12 billion years.**







Stellar evolution is one of the great success stories of astrophysics.

20.6 The evolution in Binary Systems

- Our discussion of stellar evolution has so far focused exclusively on isolated stars .
- How membership in a binary star system change the evolutionary tracks ?
  - * The answer depends on the distance between the two stars .
- In binary system whose component stars are very widely separated, Distance ≈ few thousand stellar R_{sun} The. → independent evolution.
- If the two stars are closer, then the gravitational pull of one may strongly influence the envelope of the other.

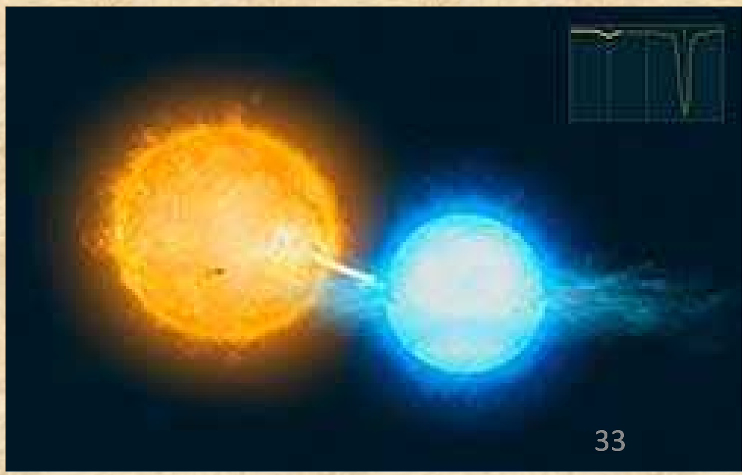
→ Star Algol

→ Variation in its light intensity

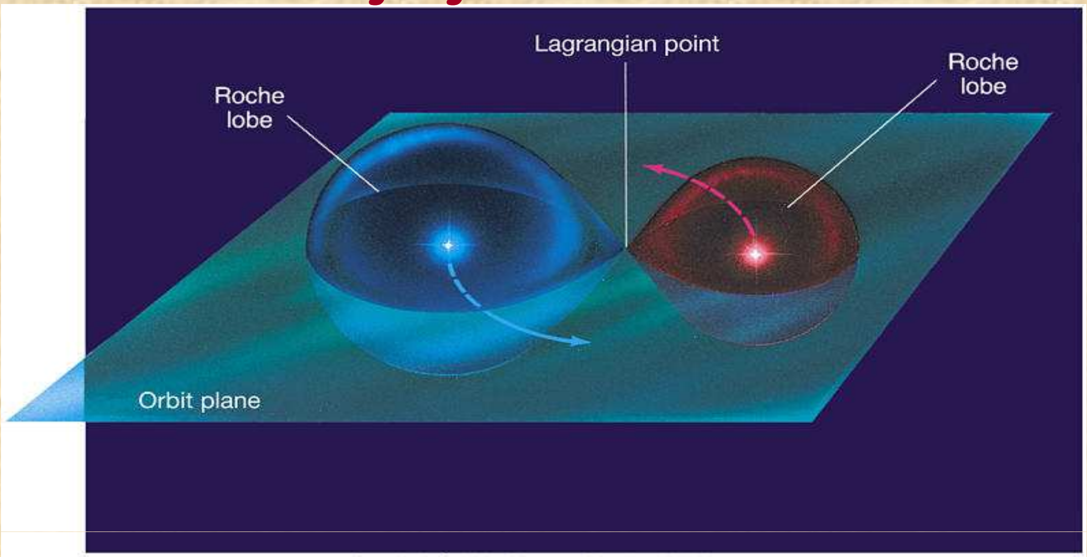
→ Binary: 3.7M_{sun}, B8-star & 0.8M_{sun}, red subgiant

→ Distance 4 million km, orbital period = 3 days

→ B8-star should have evolved faster than its component, if both formed at the same time.



20.6 The evolution in Binary Systems



- **Each star is surrounded by its own teardrop shaped (Zone of influence).**
- **Any matter within that region belongs to the star.**
- **The two teardrop-shaped regions are called Roche Lobes .**
- **The Roche Lobes of the two stars meet at the Lagrangian point.**
- **Lagrangian point is a place where the gravitational pull of the two stars exactly balance the rotation of the binary system.**
- **The greater the mass of one component ➔ the larger is its Roche Lobe ➔ the farther from its center ➔ the closer to the other star is the Lagrangian point.**

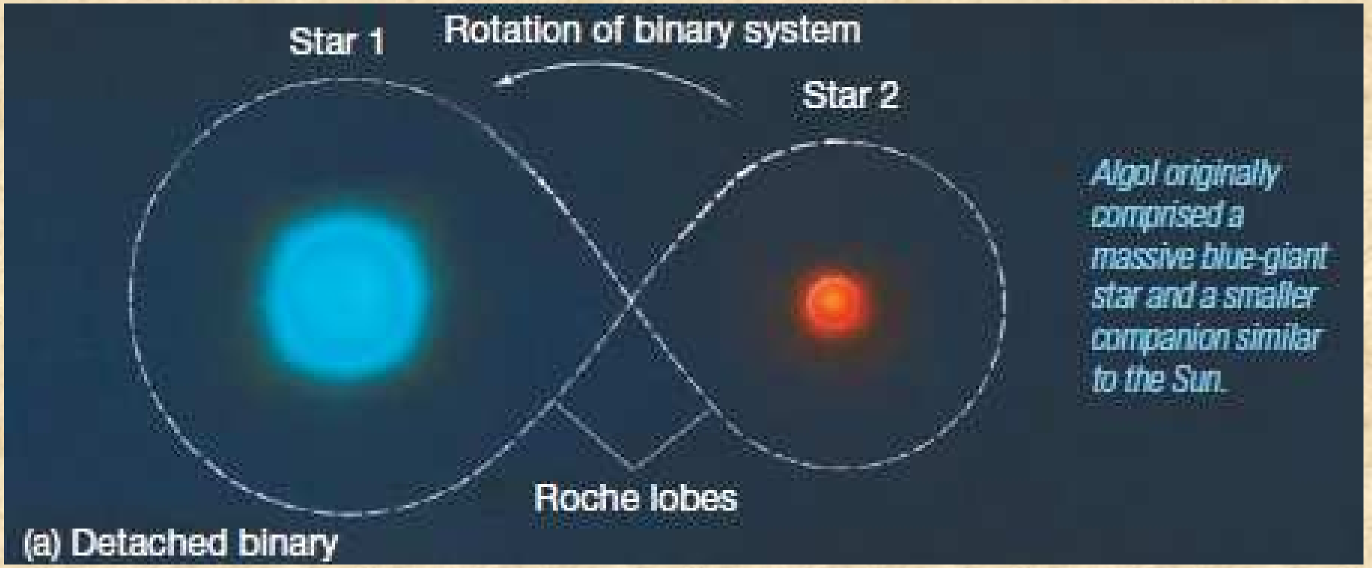
Binary evolution

• Return to the question of how the binary star Algol may have reached its present state ?

• The component is now the 0.8 solar mass subgiant (star1) . And the 3.7 solar mass main sequence star (star 2) .

• Star 1 was more massive of the 2 , having perhaps three times the mass of the sun . Star 2 mass was comparable to the Sun.

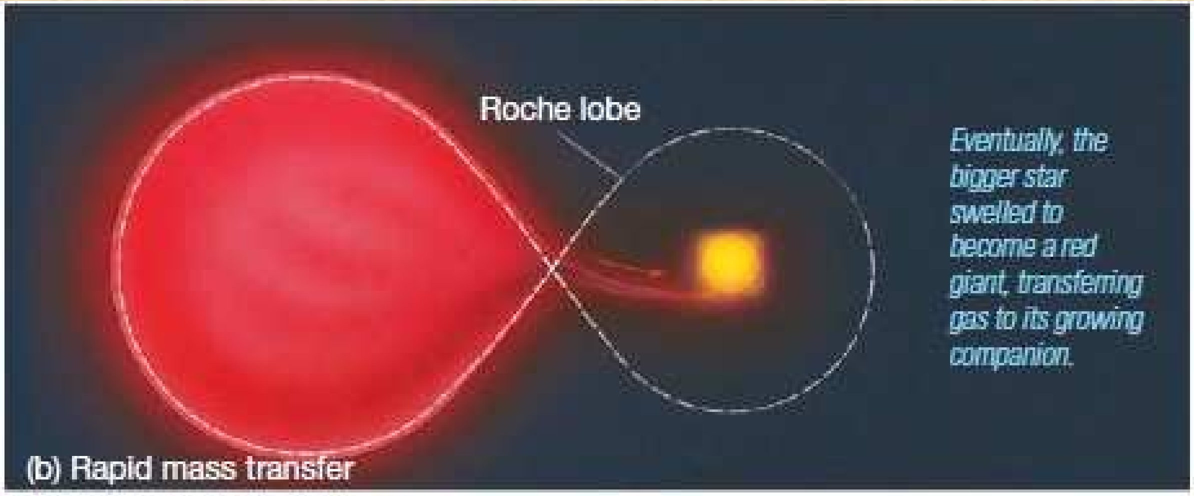
• Both stars lie well within their respective Roche Lobes: ***detached binary***



Binary evolution

*** First: star 1 evolves off the main sequence and moves toward the giant branch.**

- **Its radius to become so large that it overflows its Roche Lobe.**
- **Its gas begins to flow onto the companion through the Lagrangian point.**
- **They are known as semidetached binary or mass–transfer binaries.**
- **Due to Rapid-Mass-Transfer, the mass of Star 2 grows → Its Roche lobe increased**



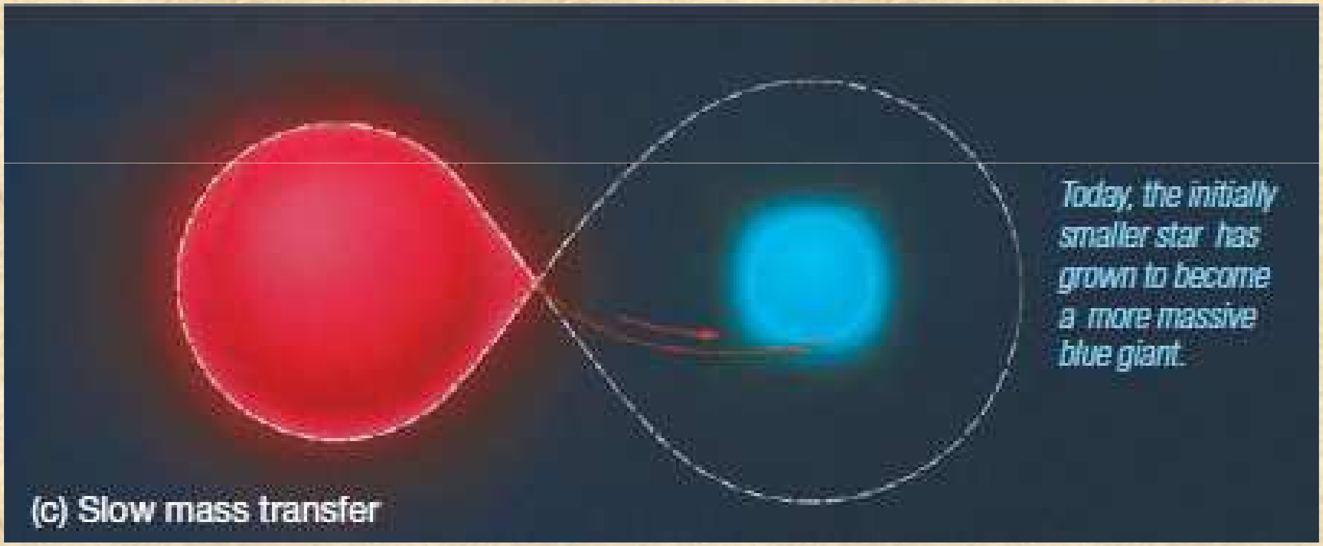
Binary evolution

* Star 2 becomes more massive, but it is on the main sequence.

• Star 1 is still in the subgiant phase and fills its Roche Lobe

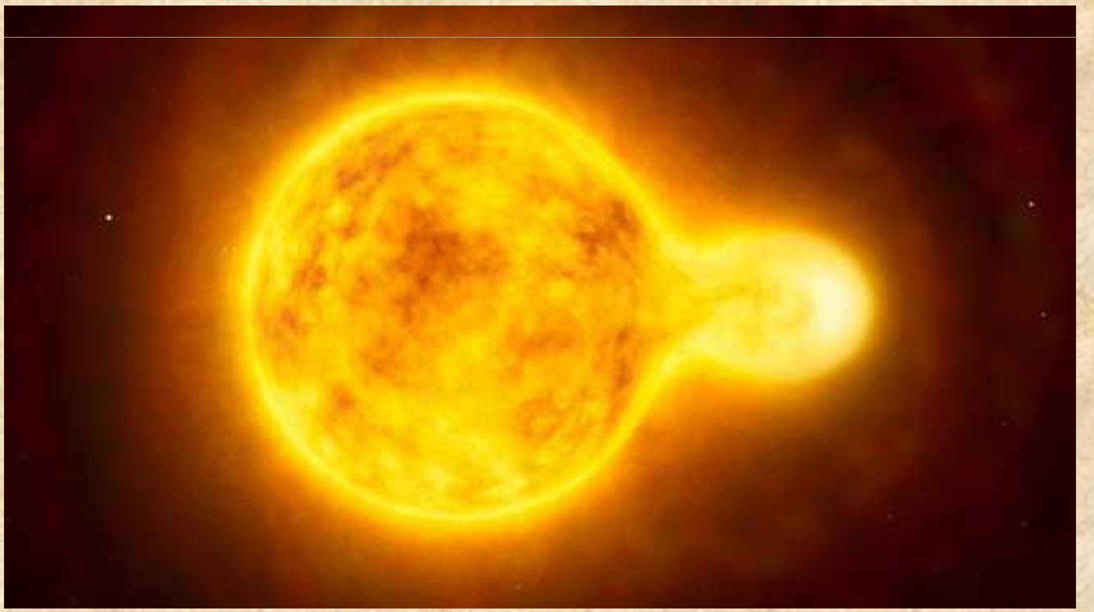
• A steady stream of matter transferred from 1 onto 2 dropped sharply.

• The stars enter a relatively stable state.



➔ Binary evolution

- Removing mass from star 1 ➔ doesn't reach He flash. ➔ He-core white dwarf.
- In tens of million years, star 2 begins to evolve.
- If Star 1 is a giant or subgiant ➔ Contact binary system will occur.
- If star 1 is a white dwarf → very violent future (CH21)




END OF CHAPTER 20