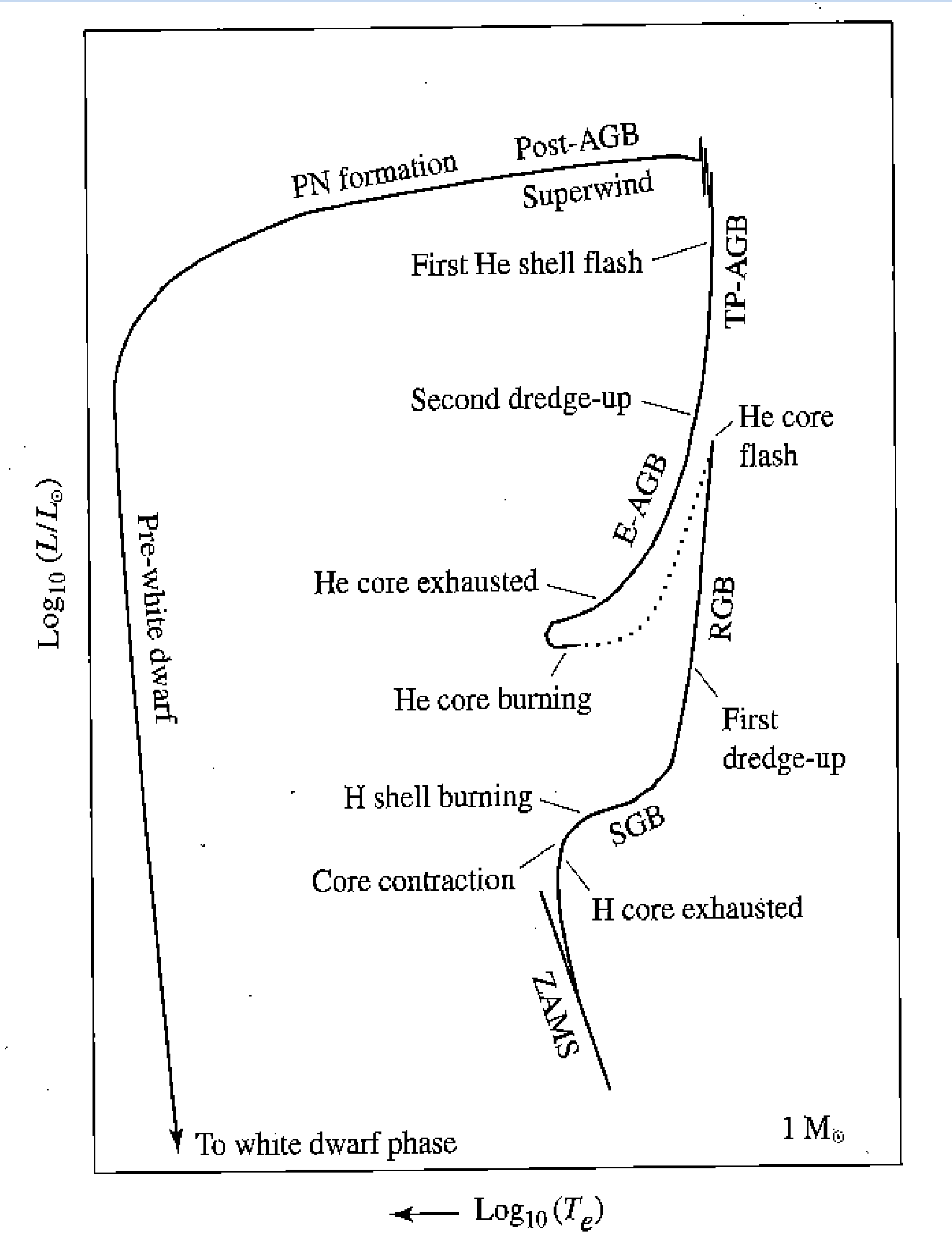
Chapter 9

Post-main-sequence evolution



A schematic diagram of the evolution of 1-solar-mass star from the zero-age main sequence to the formation of a white dwarf star. (Adapted from Bradley, p.458)

Post-main-sequence evolution

9.1 Red giants

9.2 Variable stars

9.3 Star clusters

9.4 Evolution of binary stars

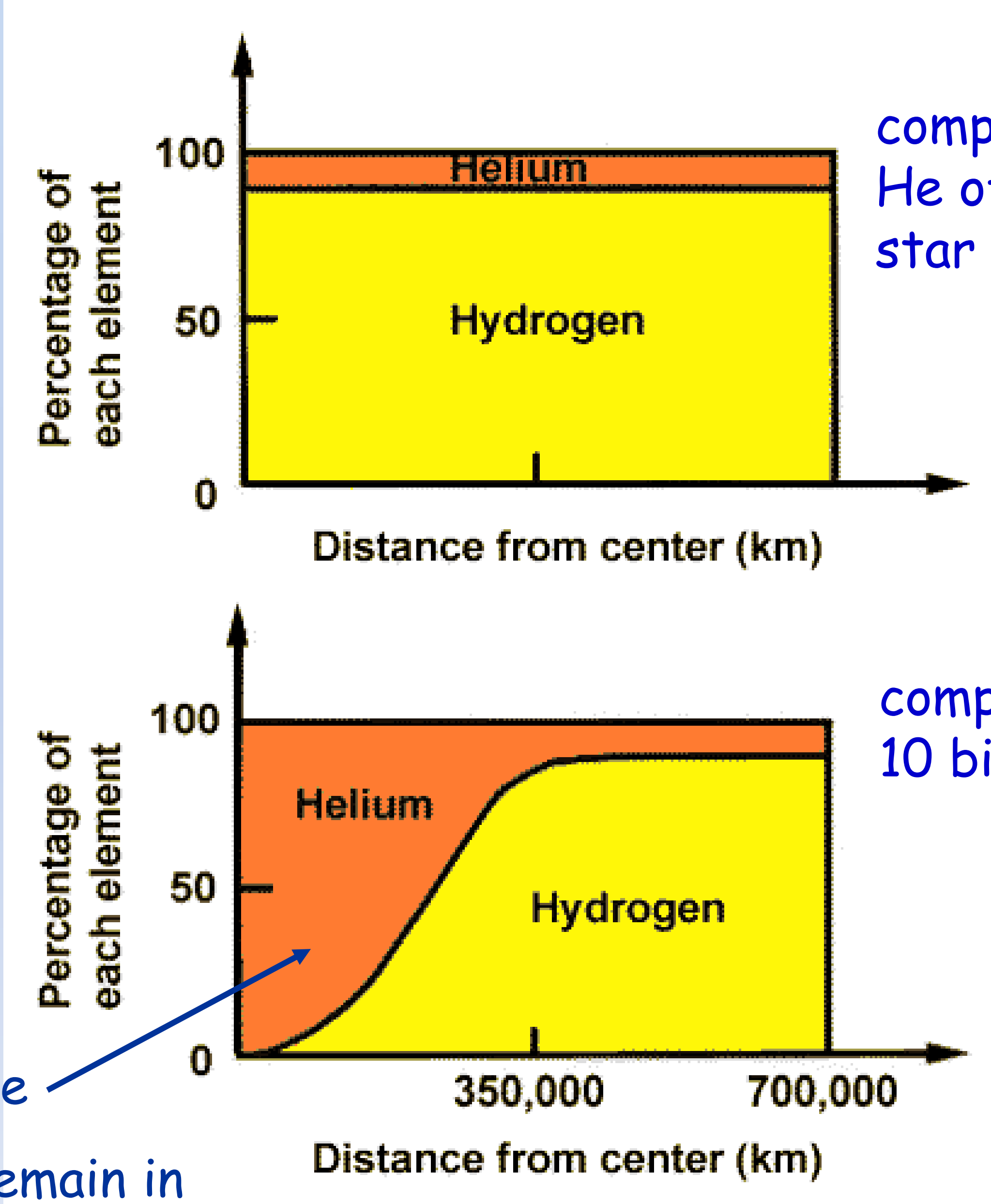
9.1 Red giants

- ✓ Recall: Main-sequence stars are very stable (due to the pressure-temperature thermostat)

  → spend ~90% of lifetime on the main sequence
- ✓ **Isothermal core**
  - ➢ H at core almost exhausted, so fusion rate drop;
  - ➢ core mainly He surround by H layer;
  - ➢ temperature gradient around the core becomes small
- ✓ Thermal pressure drops

  → the core contracts due to gravity

  → temperature increases

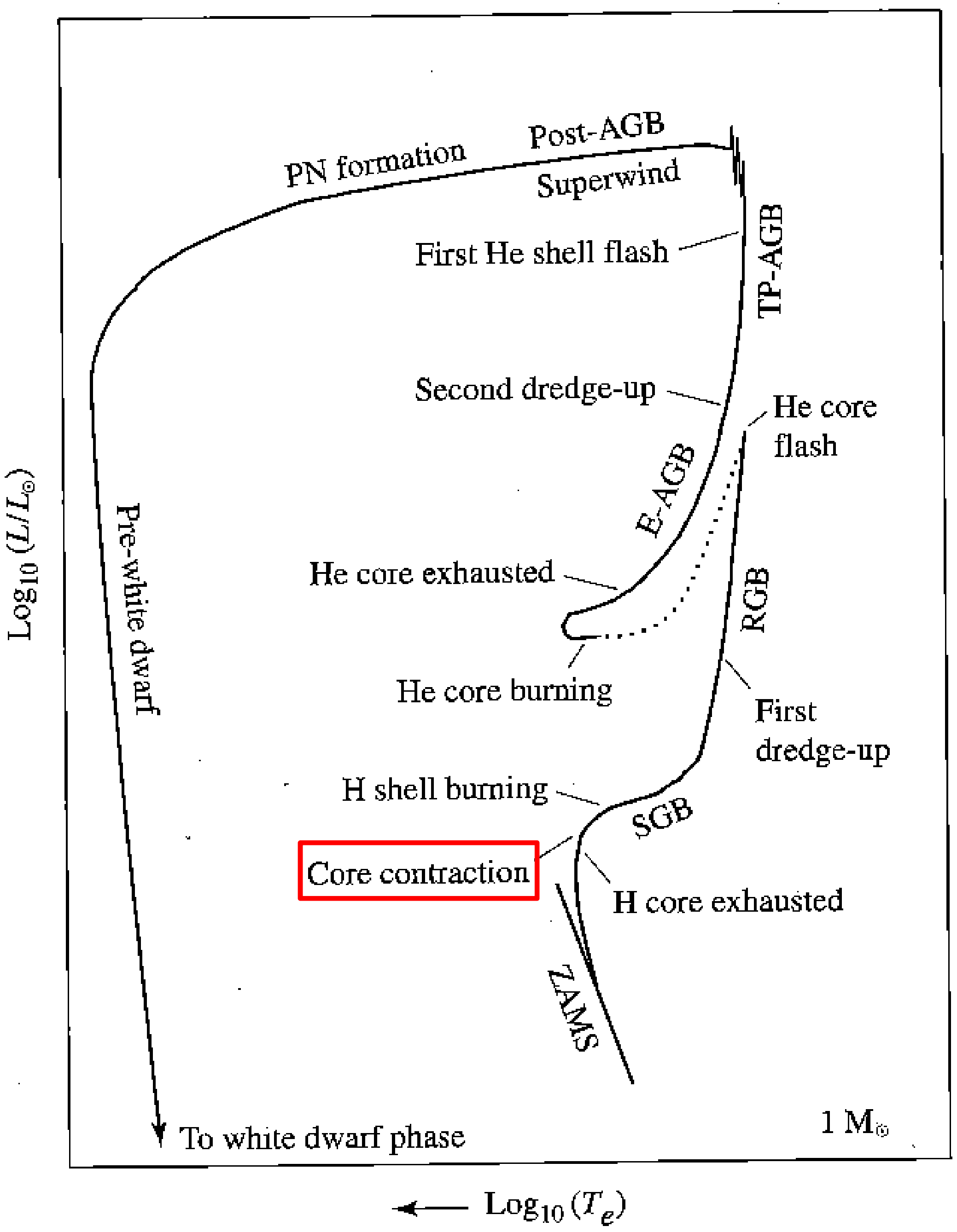


composition of H & He of a Sun-like star at birth

composition after 10 billion yrs

isothermal core

contracts to remain in hydrostatic equilibrium



PN formation
Post-AGB
Superwind
First He shell flash
TP-AGB
Second dredge-up
He core flash
E-AGB
He core exhausted
RGB
He core burning
First dredge-up
H shell burning
SGB
Core contraction
H core exhausted
ZAMS
Pre-white dwarf
To white dwarf phase
1 M⊙
Log10 (L/L⊙)
Log10 (Te)

9.1 Red giants

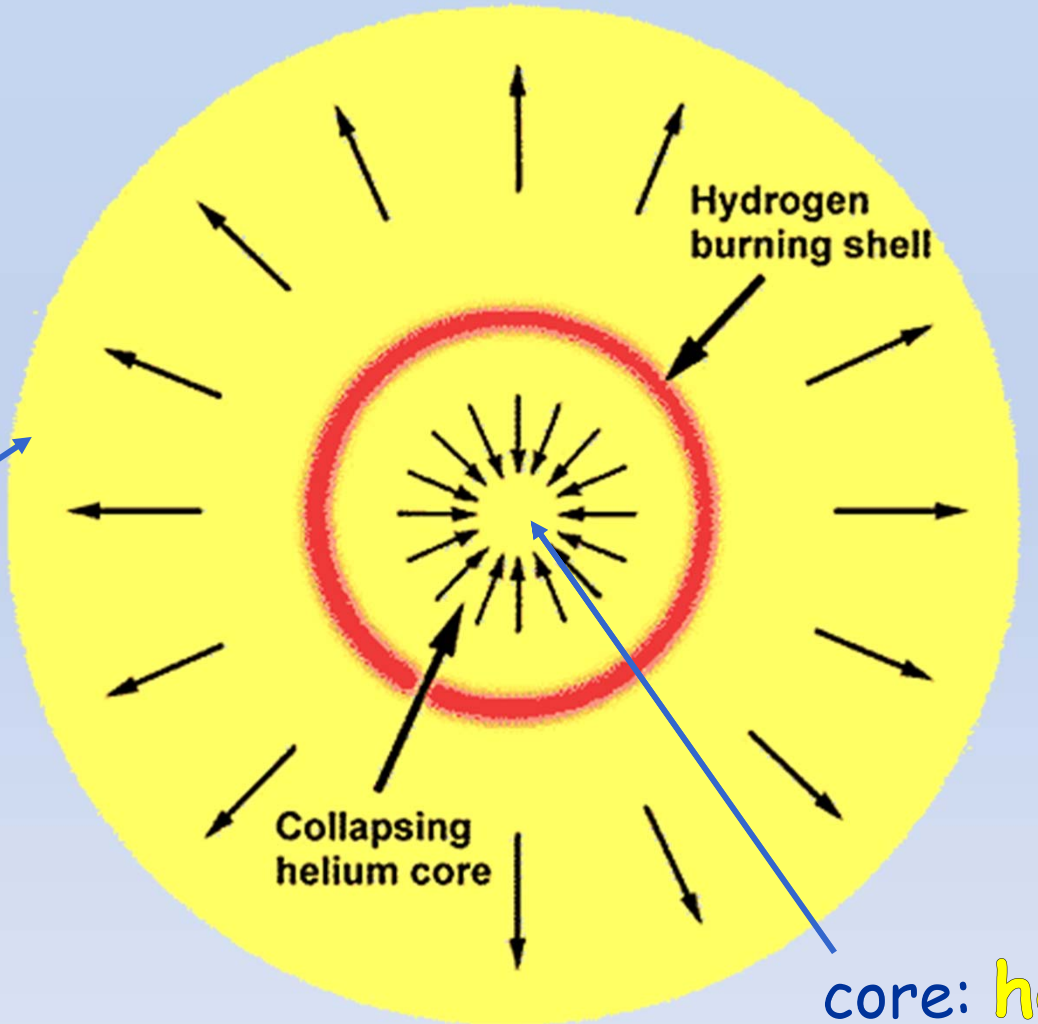
- ✓ Core contracts, T increases

  → the core becomes ***dense*** and ***hot*** (but not enough to burn helium yet)
- ✓ H in a shell just outside the core starts fusion, called *shell hydrogen burning*
- ✓ Radiation pressure from the hydrogen-burning shell pushes the outer layer outward

  → the outer layer expands

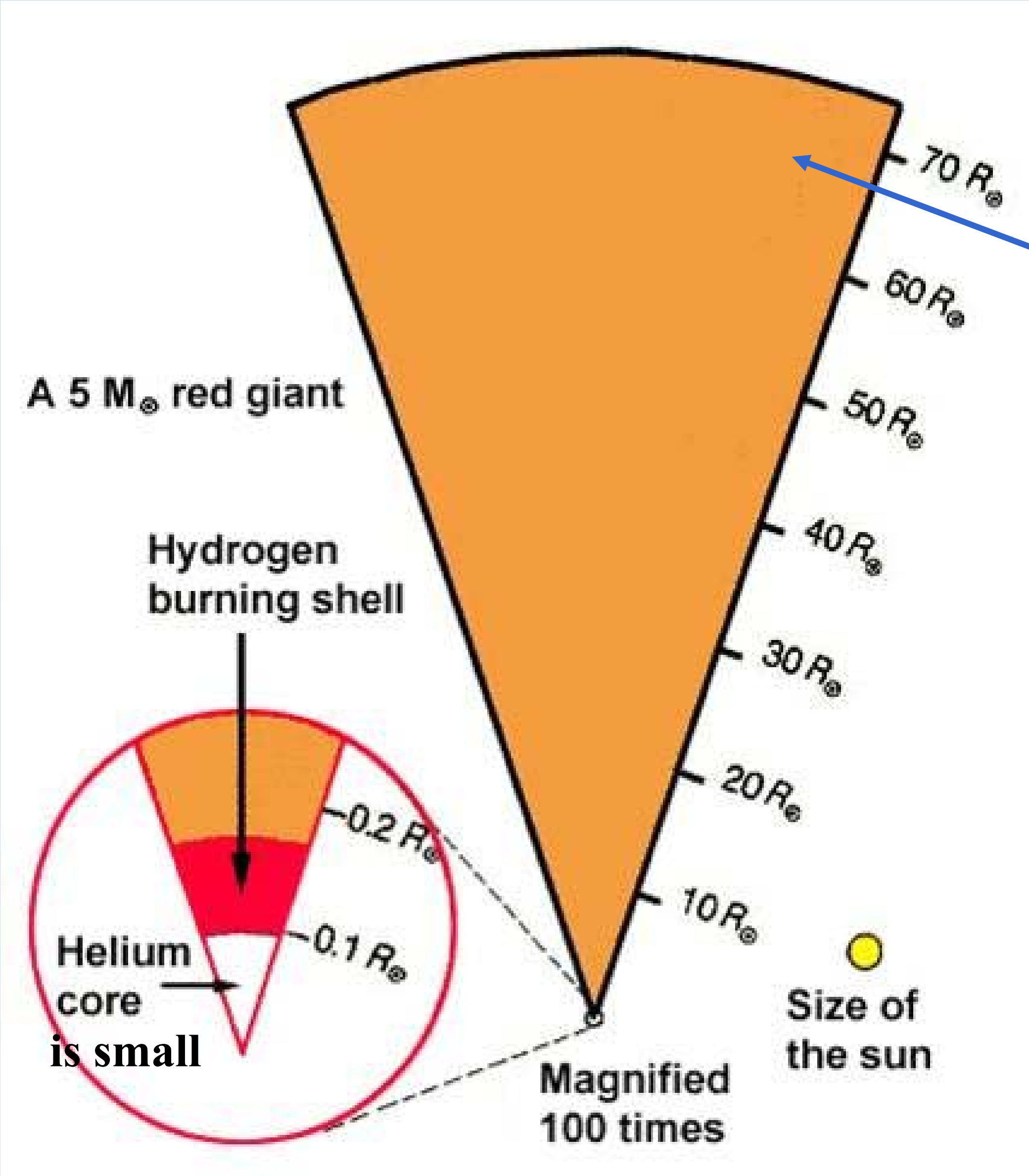
  → the outer layer becomes *less dense* and ***cool***

Not in scale

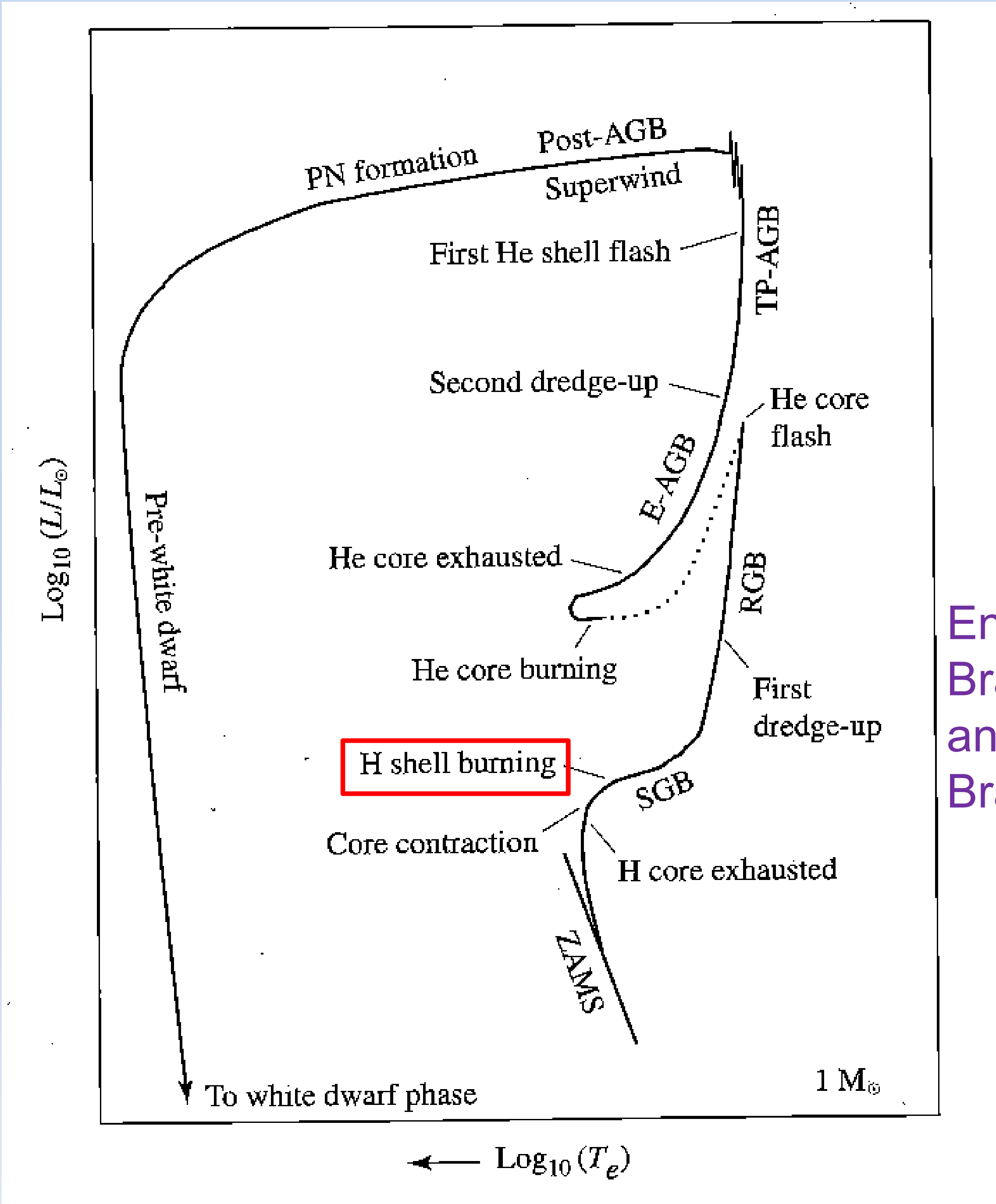


outer layer:
less dense
& cool

core: hot & dense

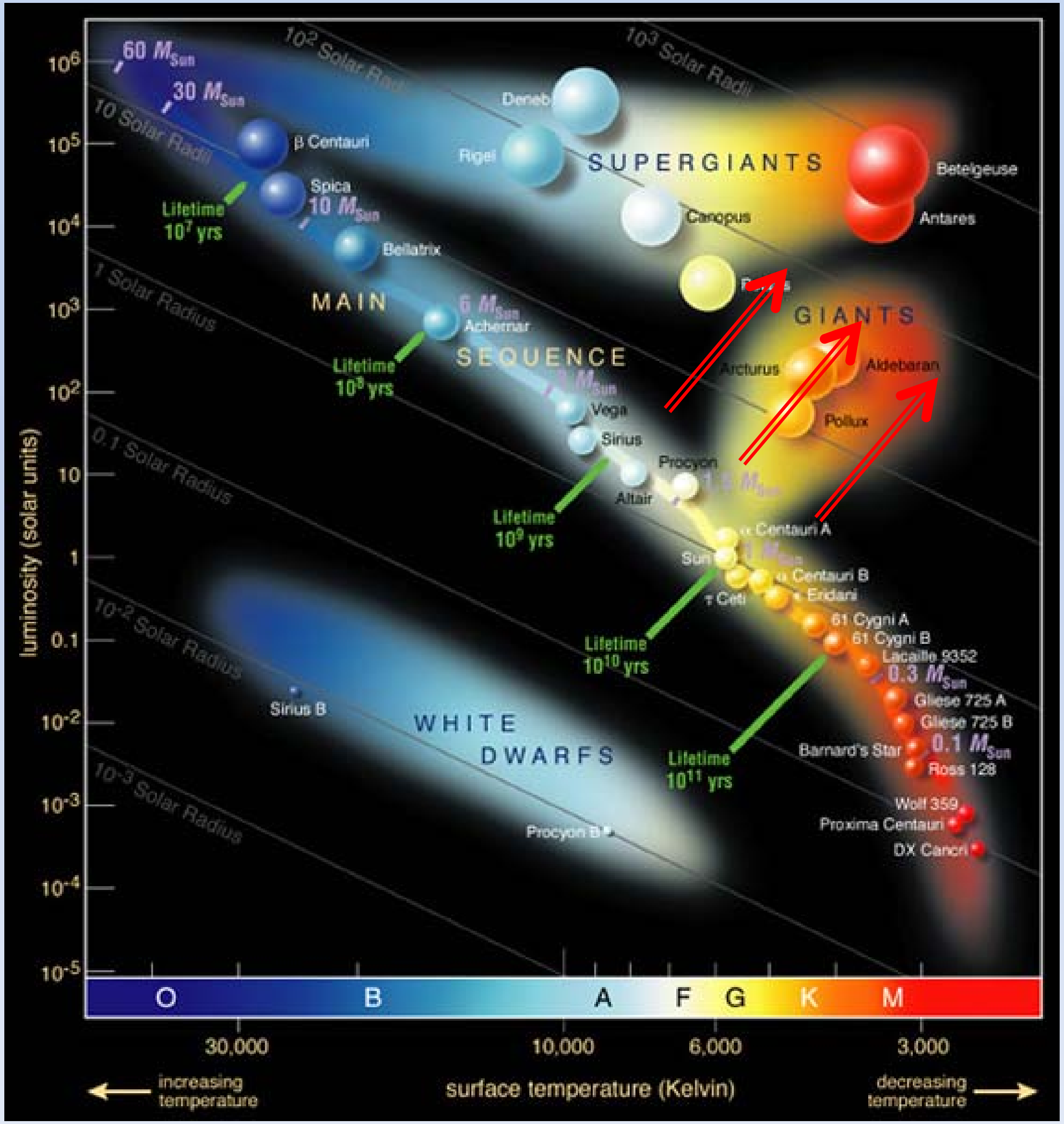


Radiations from hydrogen burning shell push outer layers outwards, hence the layers become larger.



Enter Sub-Giant Branch (SGB) and Red Giant Branch (RGB)

9.1 Red giants



The star moves right and upward.

Red giant (紅巨星): *large*, *luminous* star with *low surface temperature* and *low density at the surface*

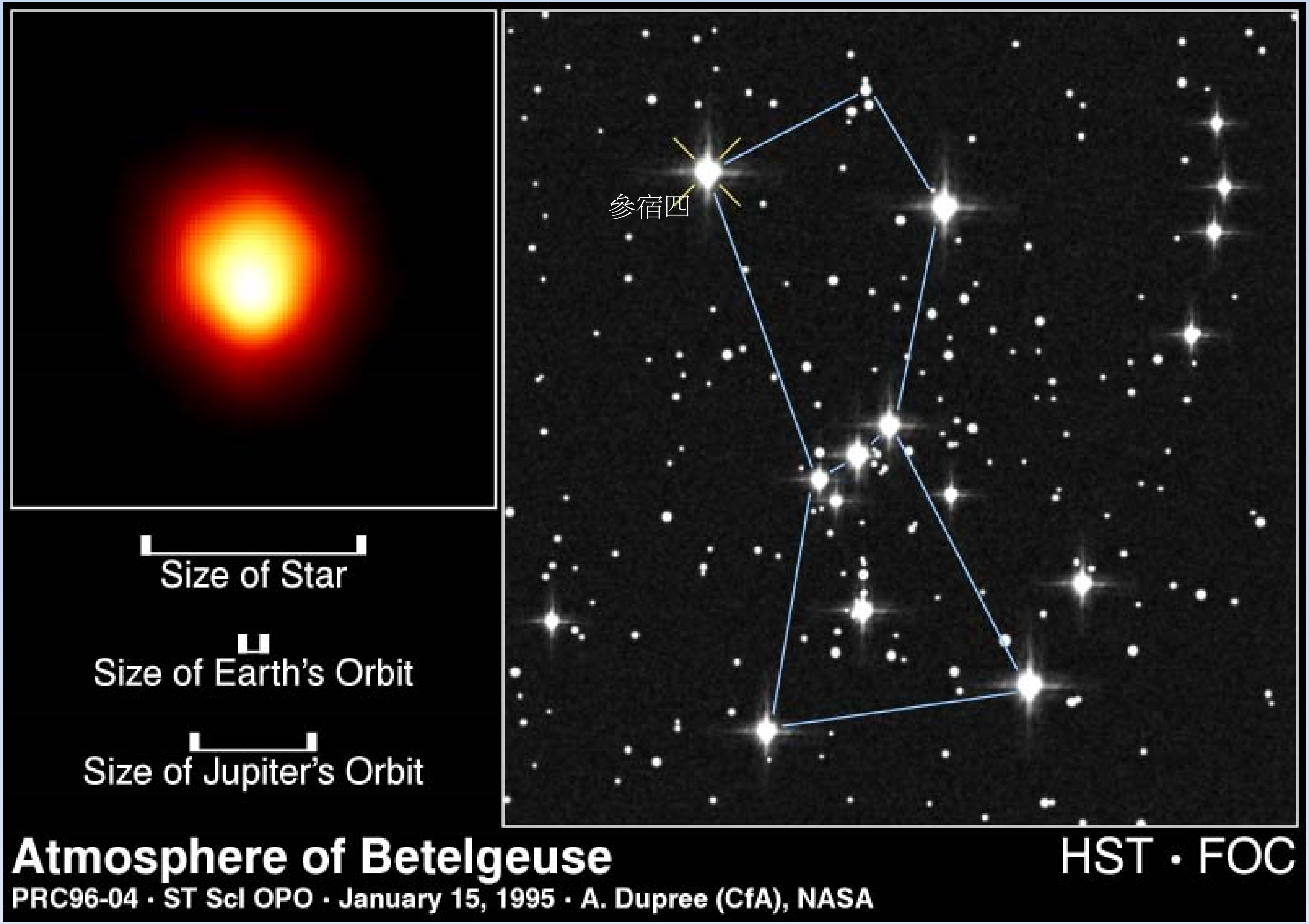
9.1 Red giants

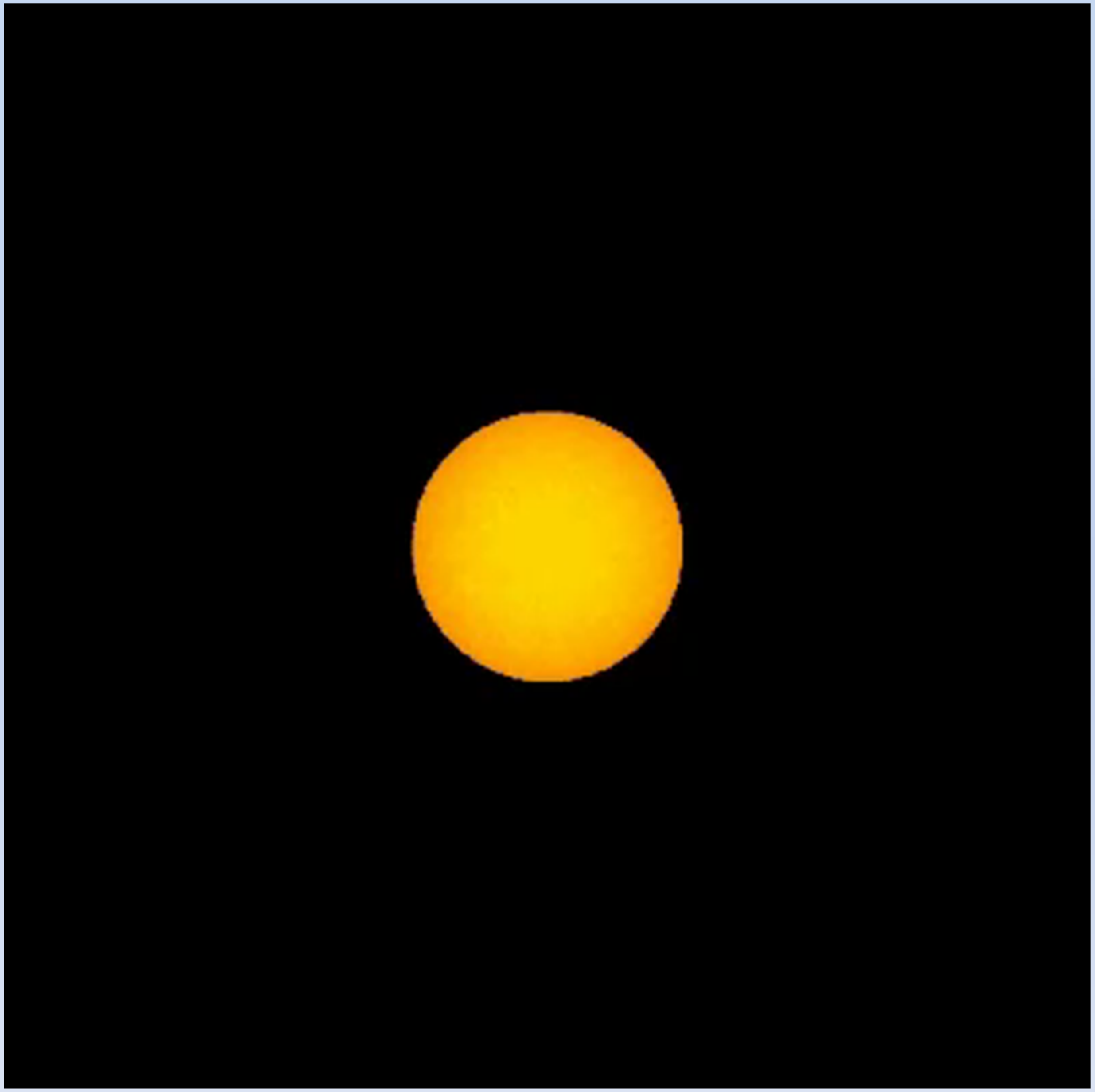
Question: Why is the star more luminous even the temperature of its outer layer's decreases?

By the Stefan-Boltzmann law: $L = 4\pi R^2 \sigma T^4$

Takes the Sun as an example. Its surface temperature will drop to ~ 50%, while its radius will be ~ 250 times the current value.

Hence, a star is more luminous when it becomes a **red giant**.


参宿四
Size of Star
Size of Earth's Orbit
Size of Jupiter's Orbit
Atmosphere of Betelgeuse
HST • FOC
PRC96-04 • ST ScI OPO • January 15, 1995 • A. Dupree (CfA), NASA



RedGiant.mpg


the Sun
becomes a red giant

9.1 Red giants

Mass loss in red giant ✓

- ✓ Red giant: large radius
  - ➢ weak surface gravity
  - ➢ gases escape into space easily
- ✓ Mass loss could be detected by observing the slight blueshift of absorption lines
- ✓ Red giant mass loss ~ 10^{-7} solar mass / year, with speed of ~ 10 km/s (compared: the Sun's current mass loss ~ 10^{-14} solar mass / year)

9.1 Red giants

Mass loss in red giant

- ✓ Because of the mixing of materials between the core and outer layers,
- ✓ heavy elements found in stellar atmosphere from observation of spectral lines

9.1 Red giants

Helium fusion at the core

- ✓ temperature core $T > 10^8$ K, nuclear reactions of helium occurs triple-α process:

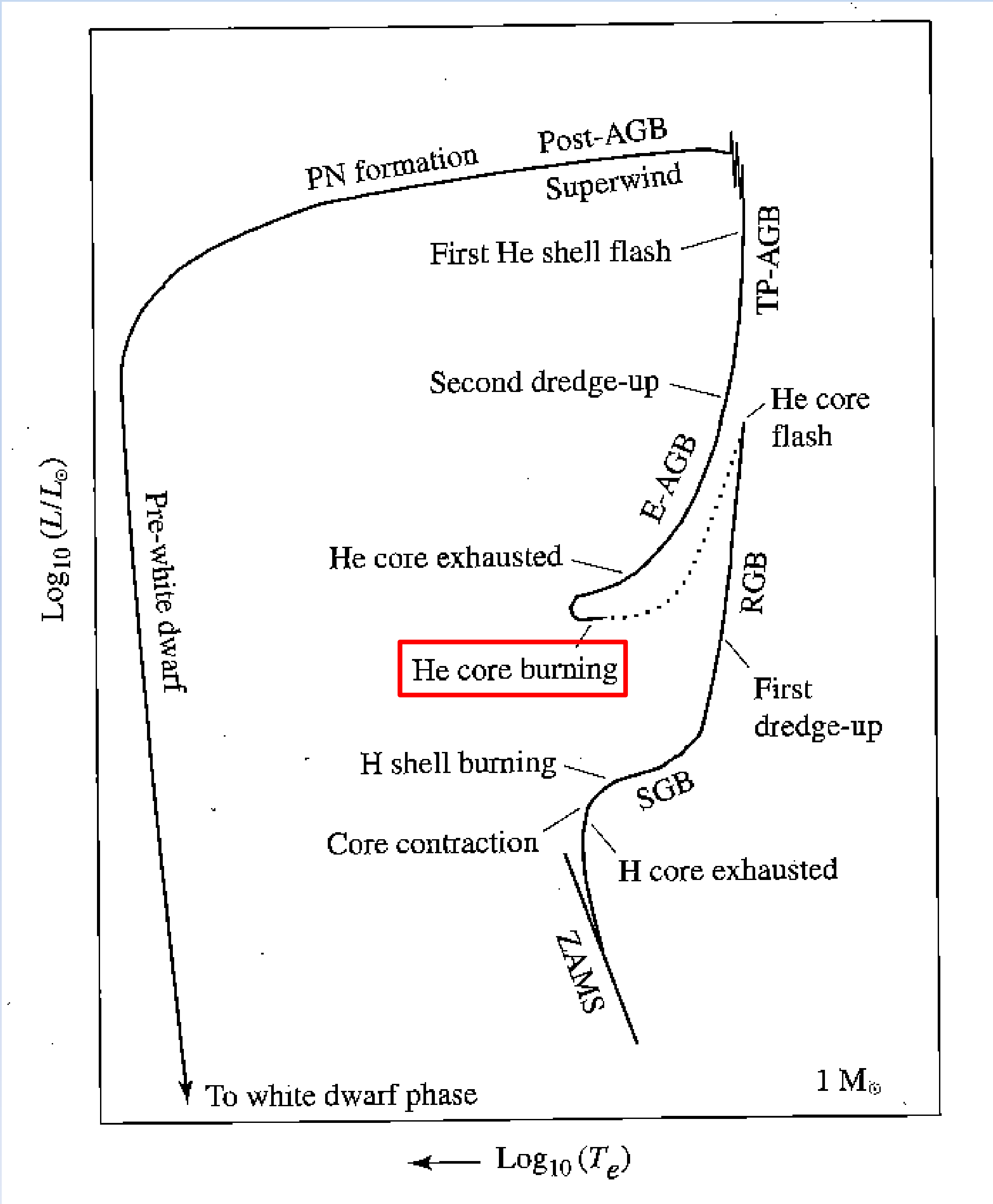
  $3\ {}^4He \rightarrow {}^{12}C$

- ✓ large increase in energy production in core

  → both T_{core} and T_{surface} increase

  → the star moves towards the left on the H-R diagram

- ✓ Pressure-temperature thermostat restored, the star is stable again.

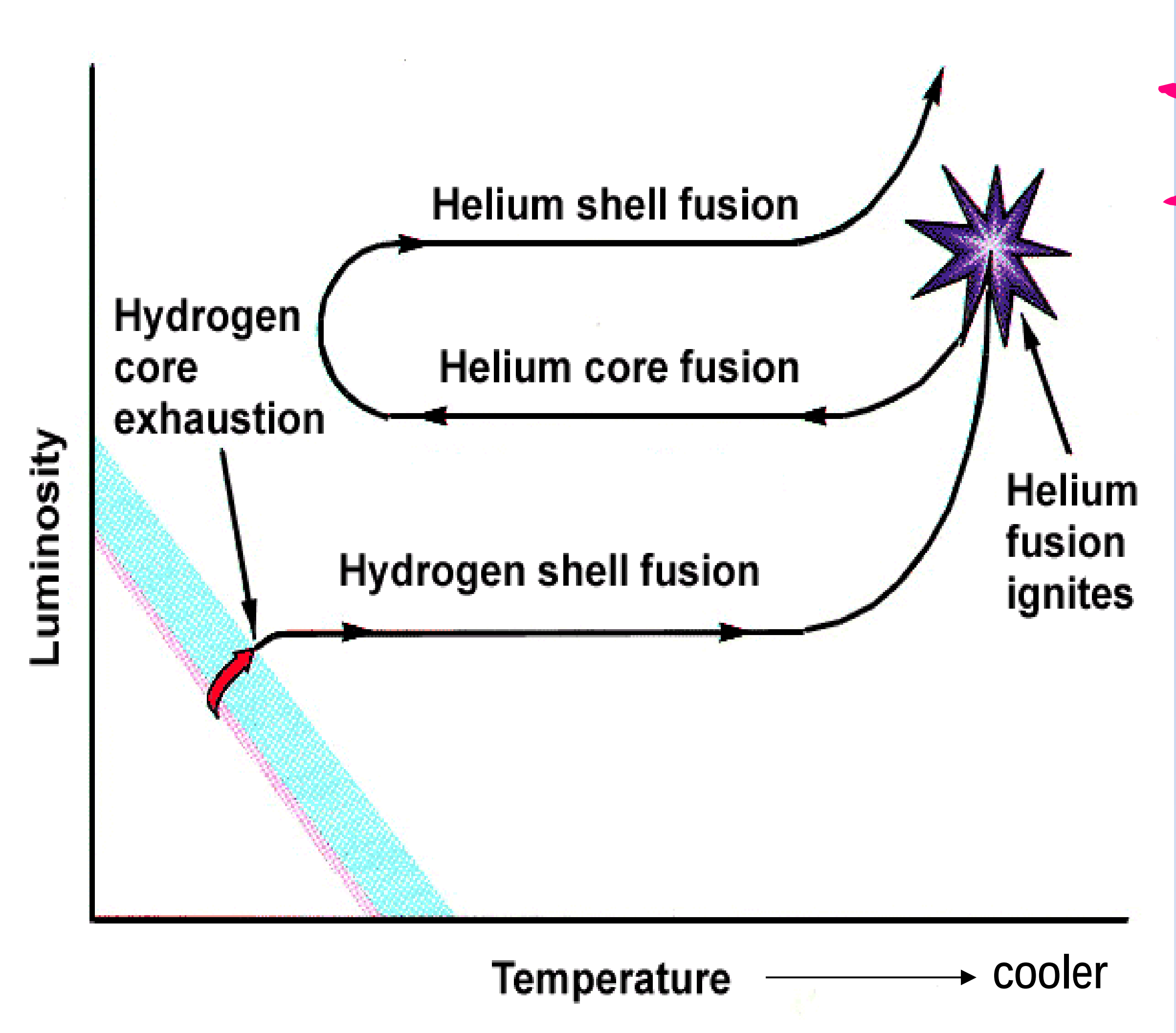


Post-AGB
PN formation
Superwind
First He shell flash
TP-AGB
Second dredge-up
He core flash
E-AGB
He core exhausted
RGB
He core burning
First dredge-up
H shell burning
SGB
Core contraction
H core exhausted
ZAMS
Pre-white dwarf
To white dwarf phase
$1\ M_\odot$
$\mathrm{Log}_{10}(L/L_\odot)$
$\mathrm{Log}_{10}(T_e)$

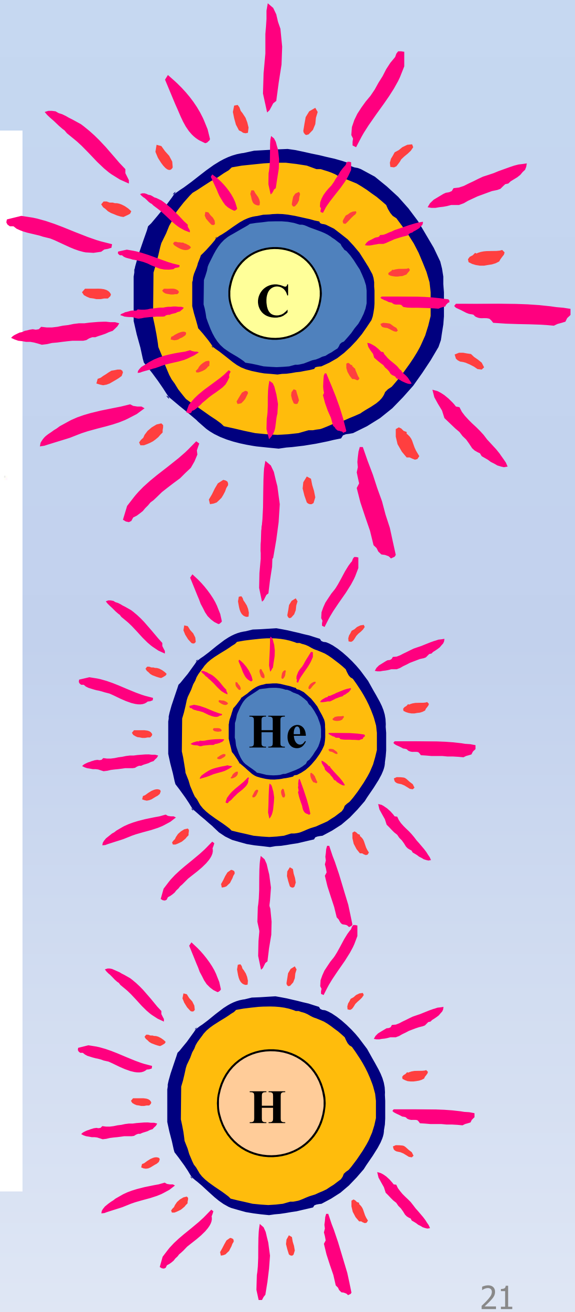
9.1 Red giants

***Nucleosynthesis* (核合成)**

- ✓ For massive stars $(M > 4M_{\odot})$, cycles of nuclear fusion produce heavier and heavier elements until iron. This is called *Nucleosynthesis* (核合成)
- ✓ origin of heavy elements in the universe.
- ✓ The star moves left and right across the HR diagram many times around the giant branch.



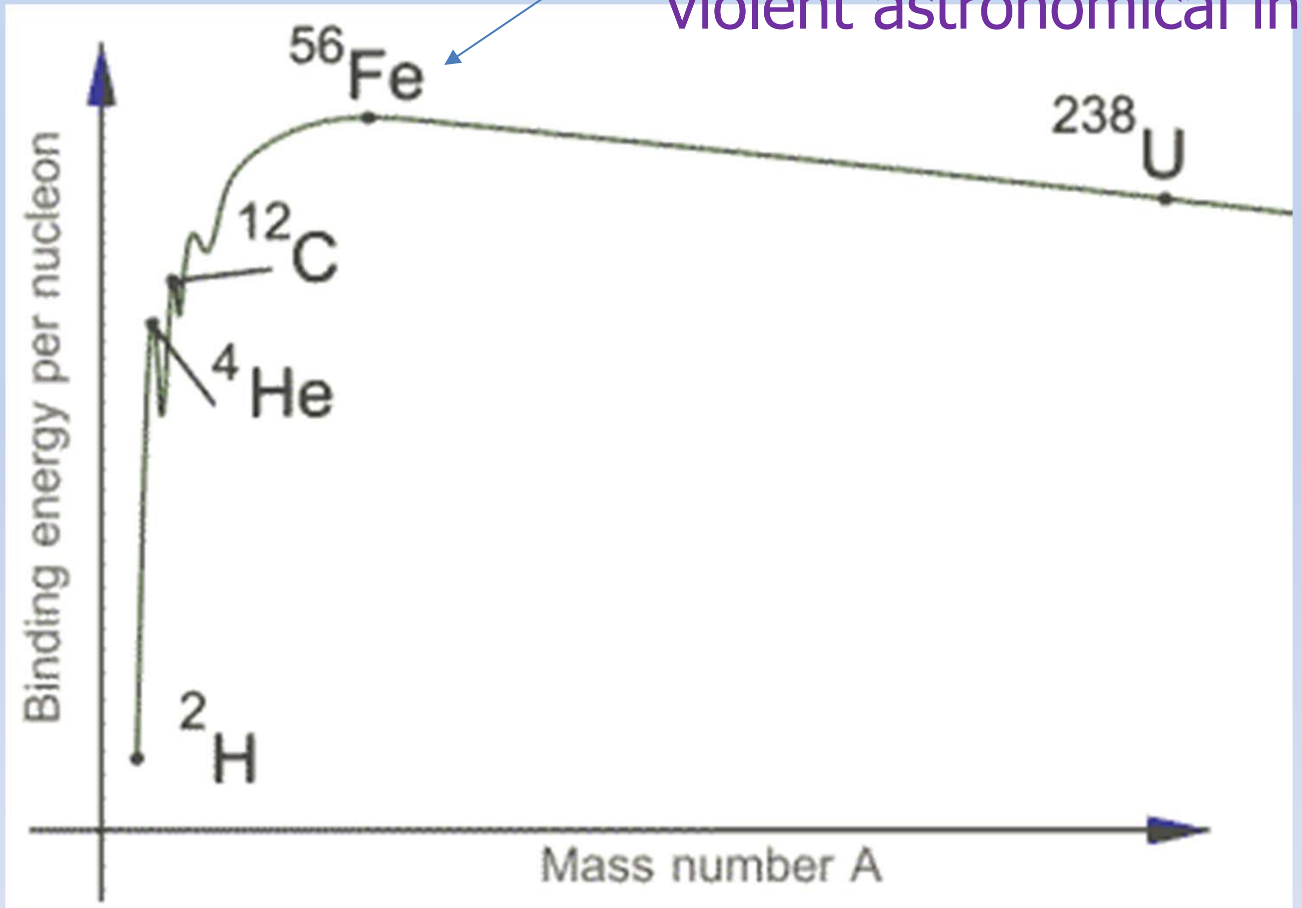
Helium shell fusion
Hydrogen core exhaustion
Helium core fusion
Luminosity
Helium fusion ignites
Hydrogen shell fusion
Temperature
cooler



C
He
H

Nucleosynthesis stops at Fe. Heavier elements need a more violent astronomical incident

比结合能

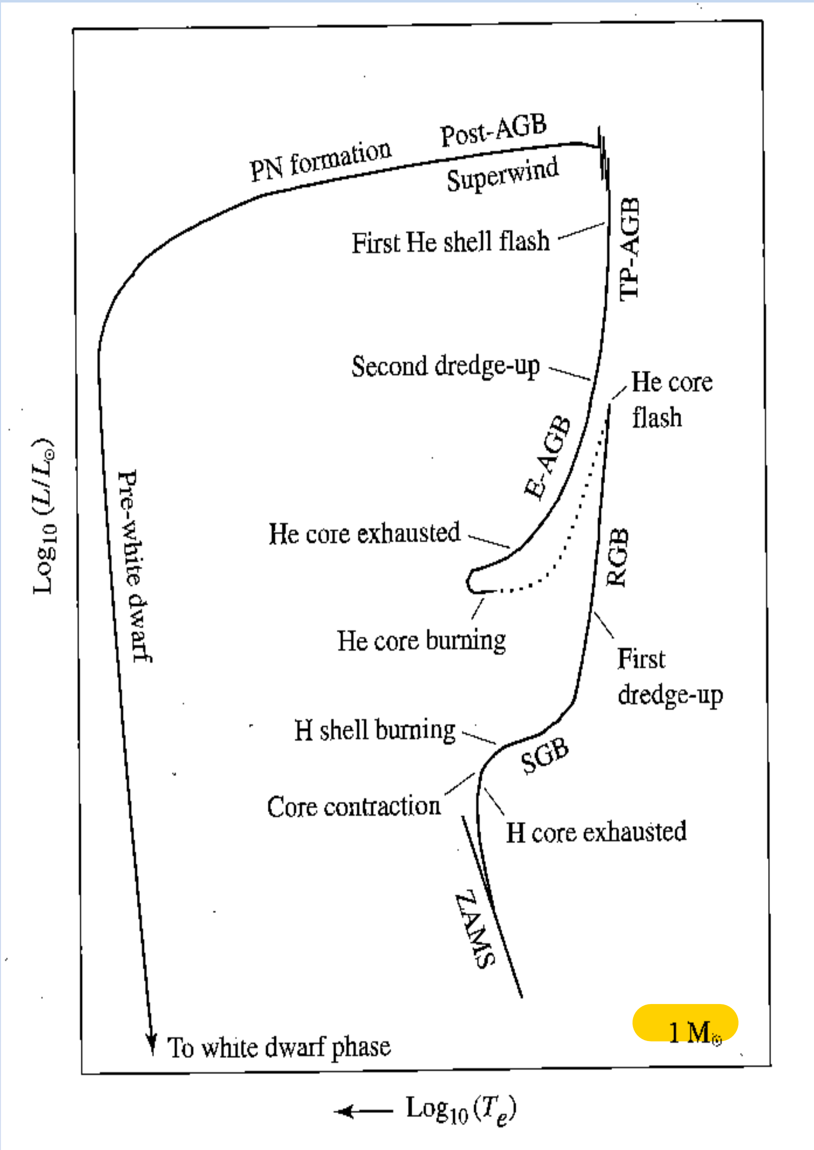


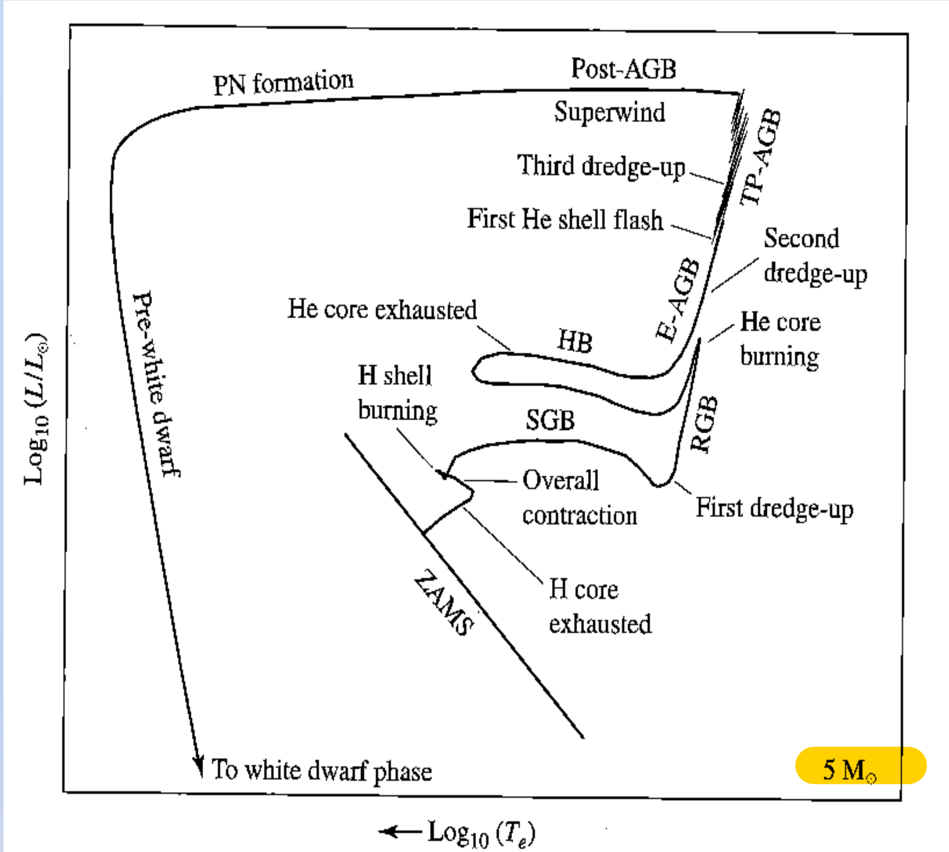
不断地制造这个元素；恒星的中心是制造元素的工厂

9.1 Red giants

Nucleosynthesis (核合成)

For massive stars $(M < 4M_{\odot})$, nucleosynthesis stops when oxygen-rich core is produced. The star is not heavy enough to ignite oxygen fusion





A schematic diagram of the evolution of 5-solar-mass star.

这个恒星都会发生这样的变化，但具体变化内容会不同

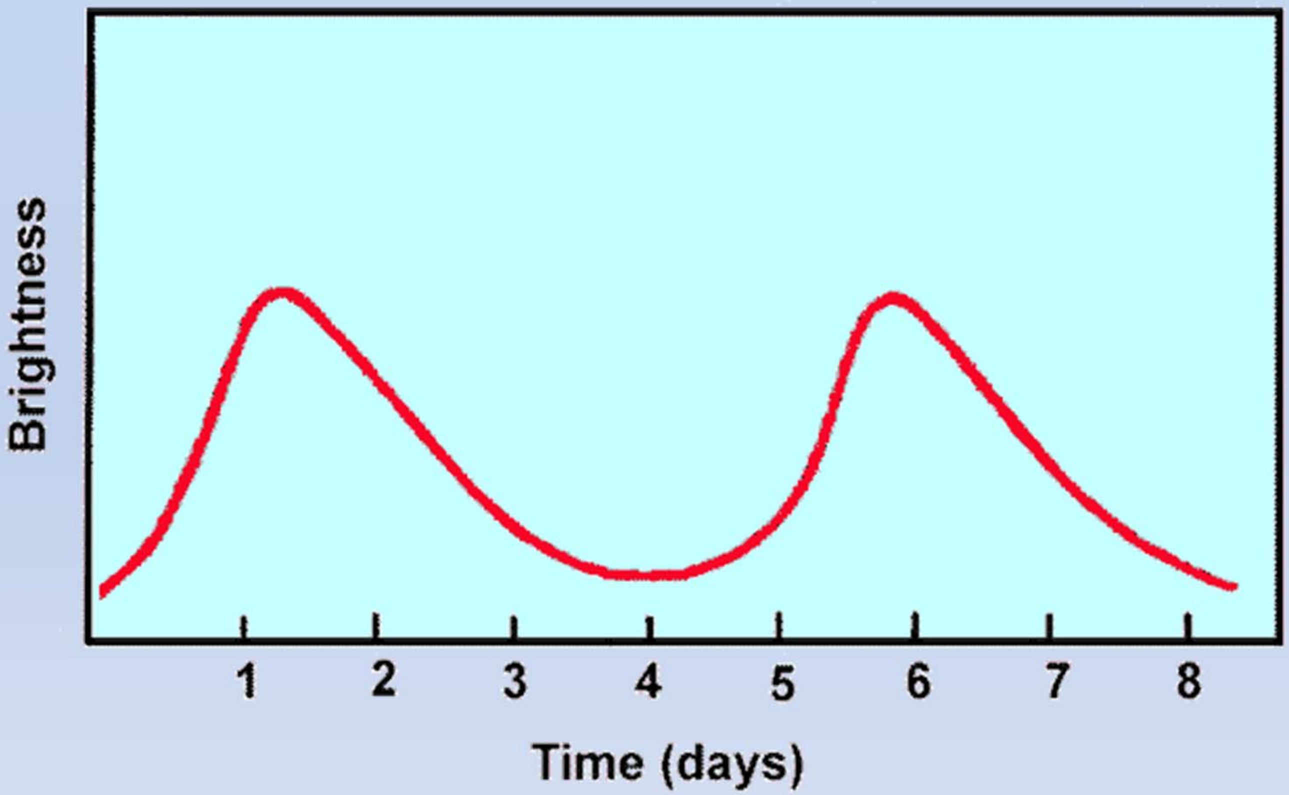
The dotted phase of evolution represents rapid evolution following the helium core flash, which happened in low-mass stars only. Details are skipped.

9.1 Red giants

How's our living place in the next five billion years?

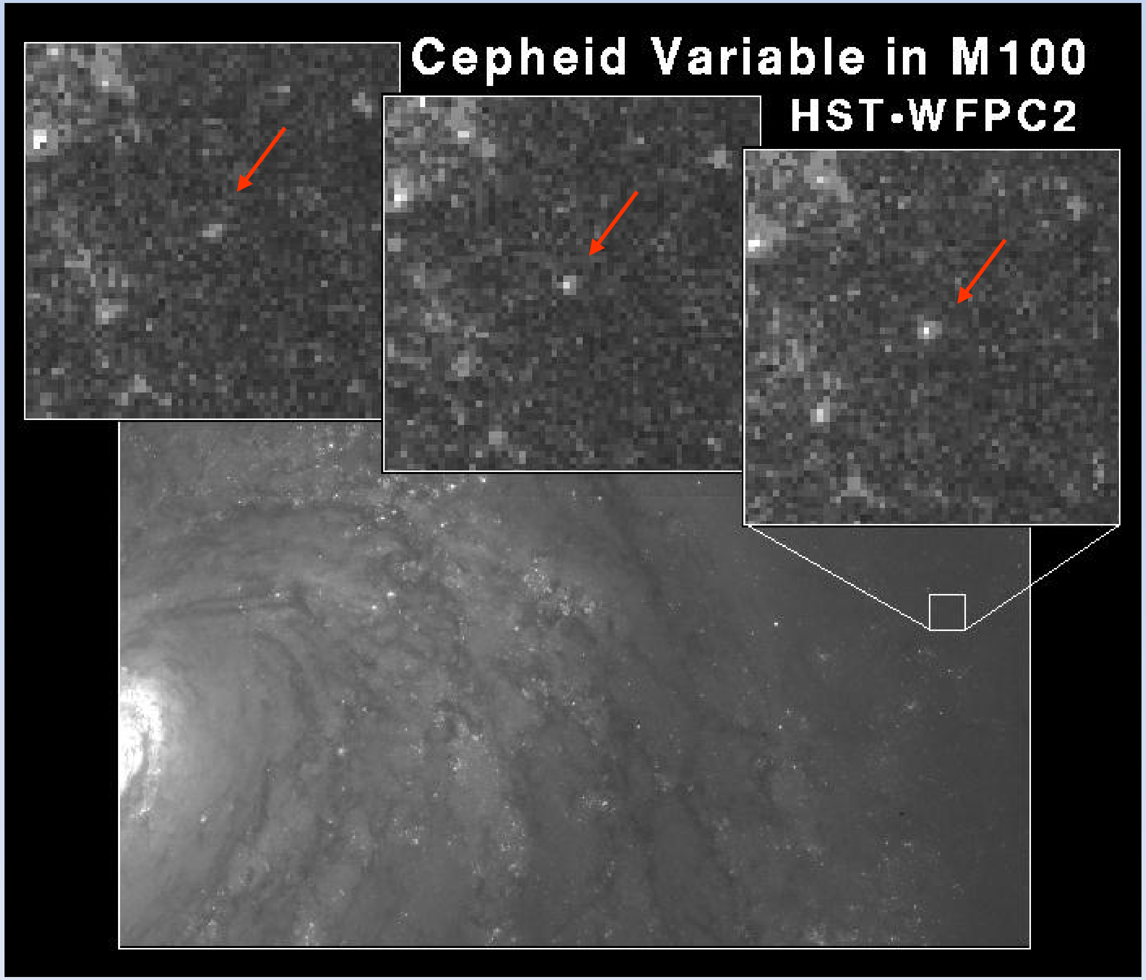
突然有个想法：写一个未来时期的地球，那时的人们（如果有）会怎么回忆人们呢？

9.2 Variable stars



- ✓ δ Cephei (仙王座δ,造父一): first among a type of variable stars, discovered by J. Goodricke in 1784
- ✓ becomes the prototype of Cepheid variable stars

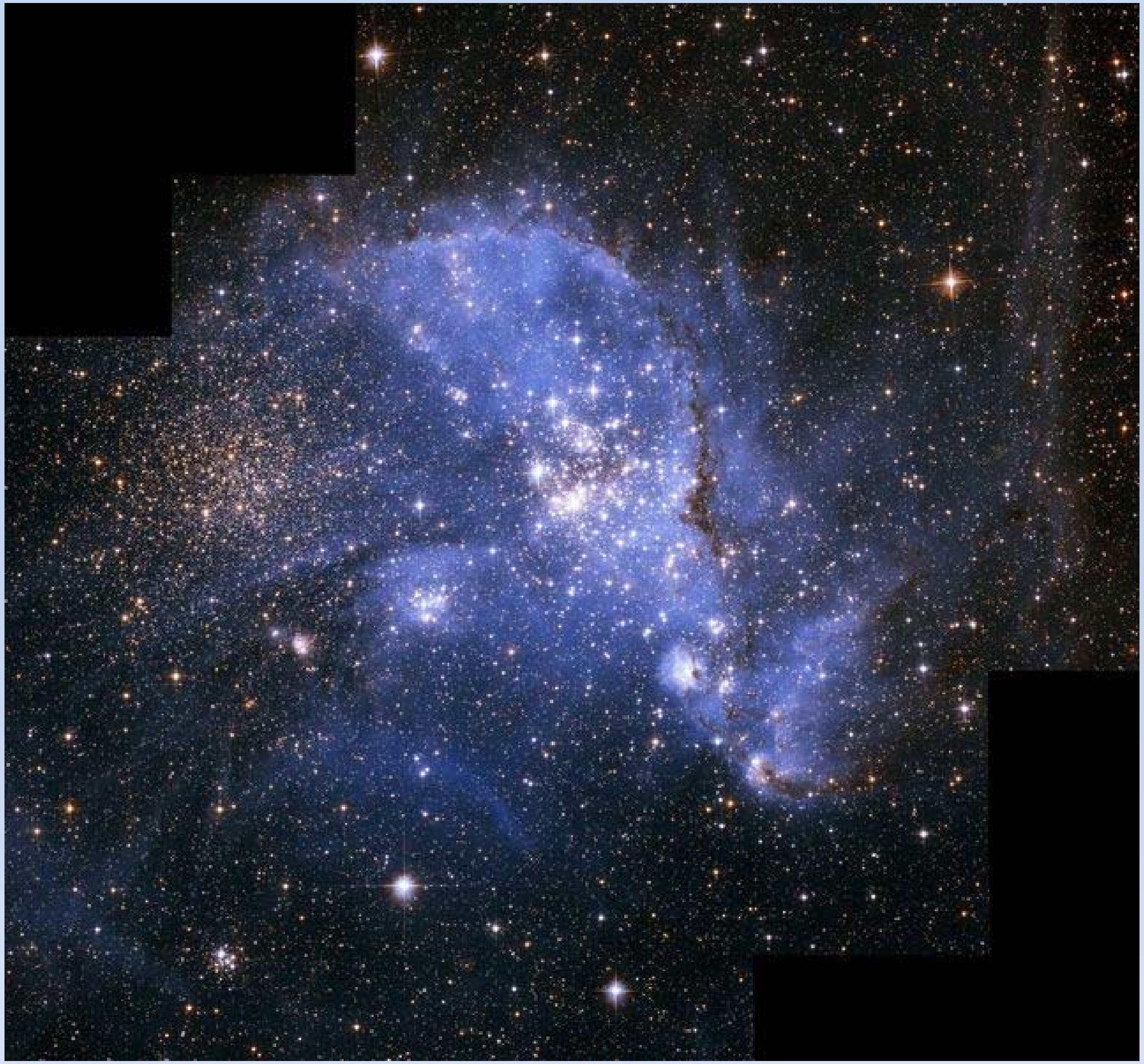
9.2 Variable stars



Polaris (北極星):
period ~ 4 days,
brightness change
by 0.1 magnitude;

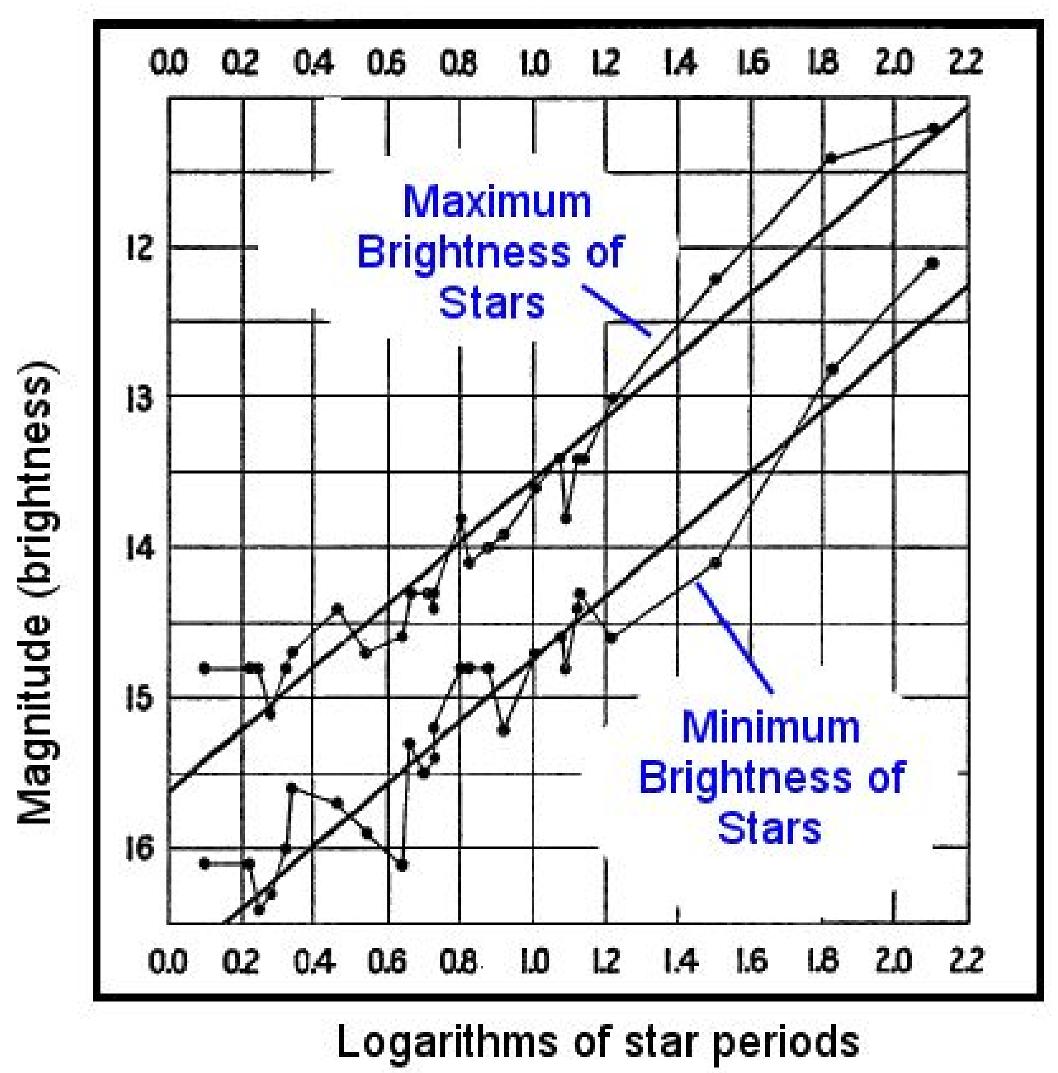
The Harvard "computers" examining photographic plates

Henrietta Swan Leavitt (1868–1921)



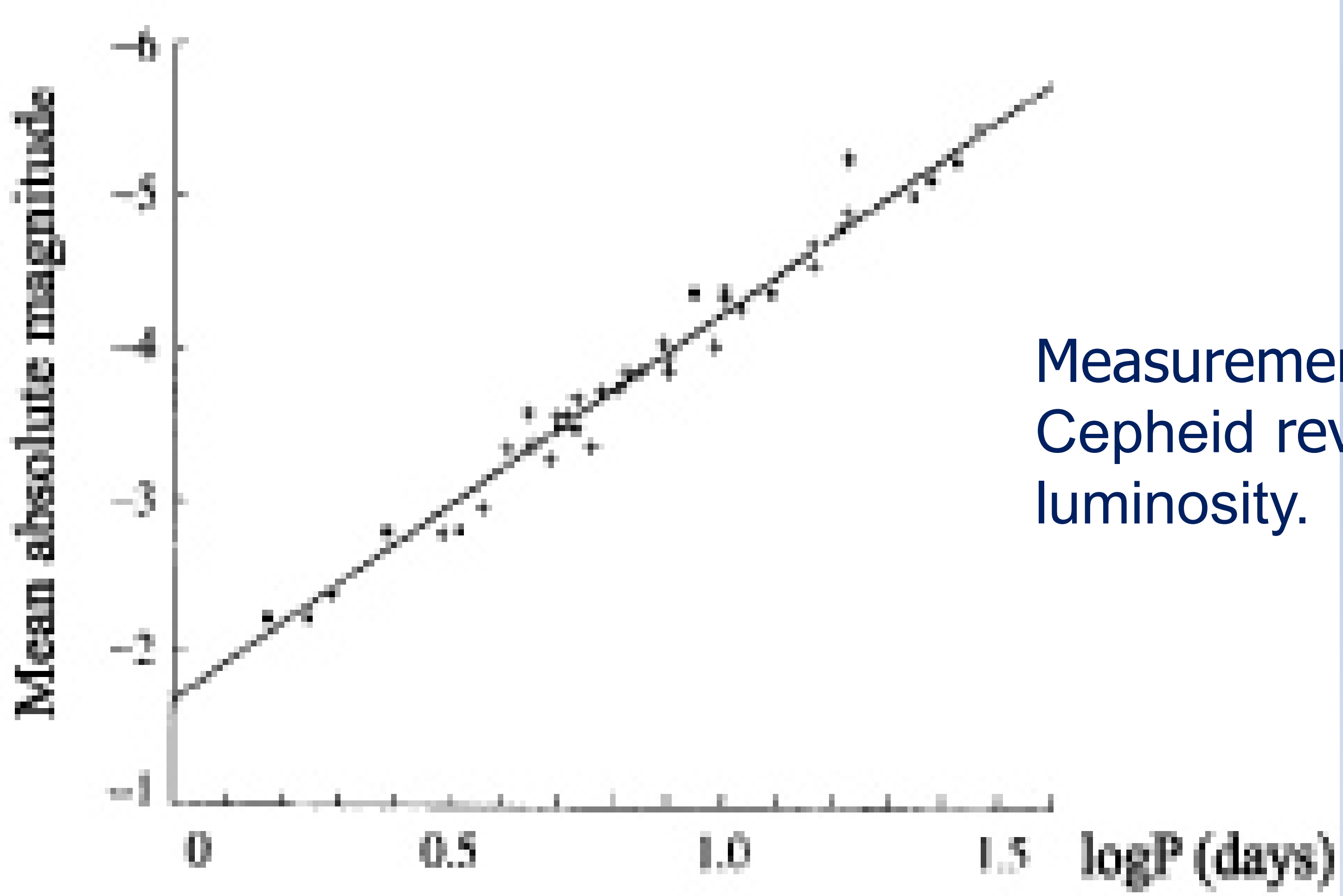
Leavitt identified 25 Cepheids in SMC and found that brighter stars always have a longer period between the peaks in brightness

Small Magellanic Cloud (小麥哲倫星系); Distance: ~200 kly



What can you tell from this findings?

Since all Cepheids in SMC roughly the same distance, an apparently brighter star is intrinsically more luminous.



Measurements of a Cepheid reveal its luminosity.

For example, two Cepheids have the same periods, i.e., luminosity approximately the same.

But one has apparent brightness 9 times fainter than the other. It is due to the difference their distances, it is 3 times farther away.

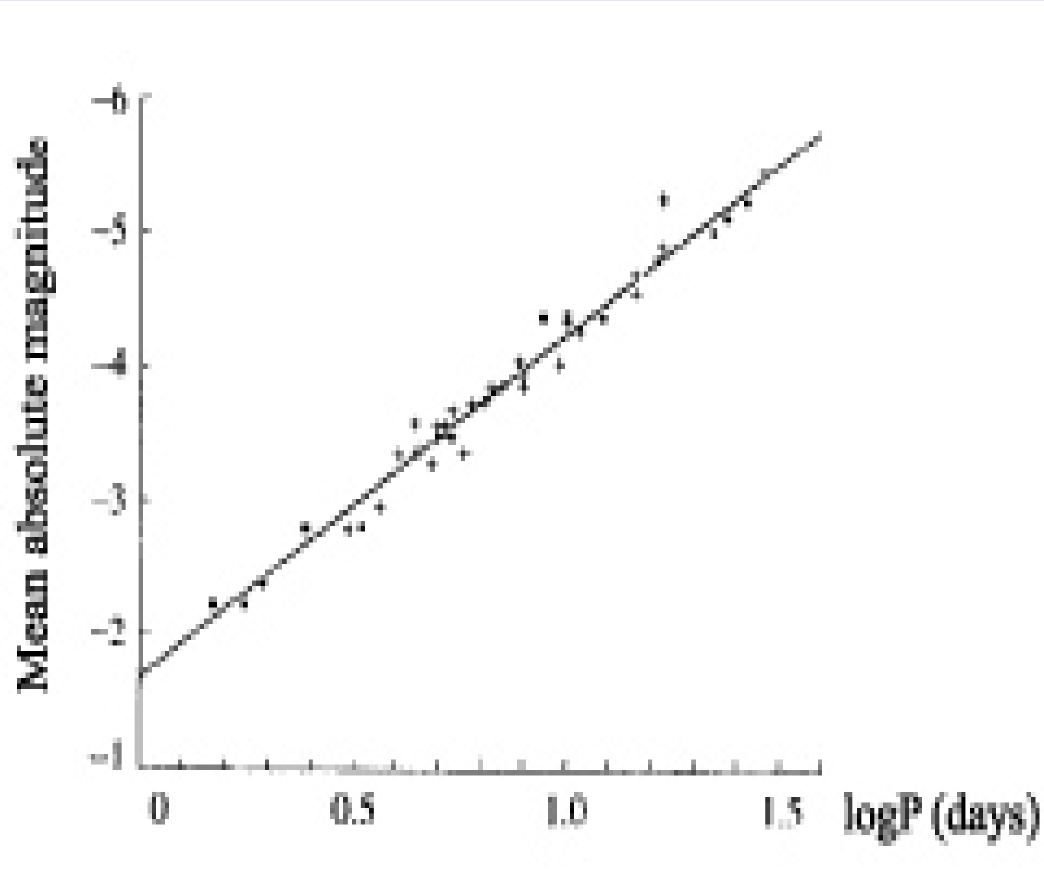
It is standard candle.

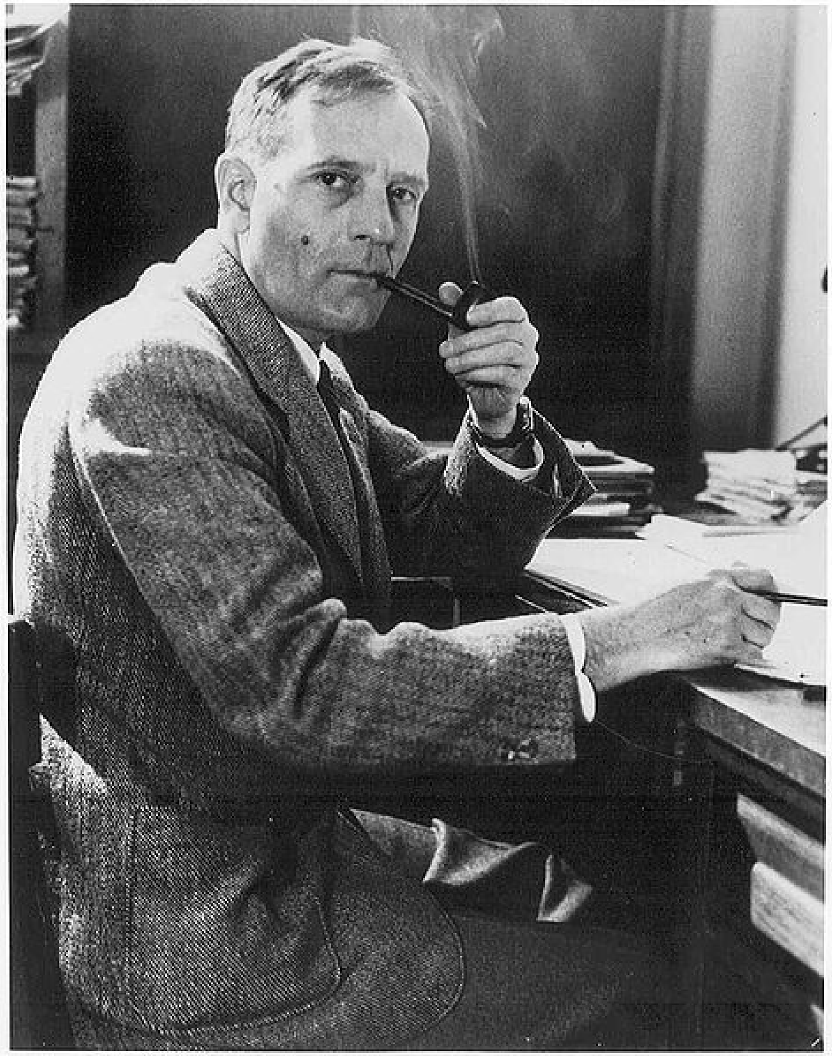
By finding the distance to one Cepheid, the distance to other Cepheids would be measured.

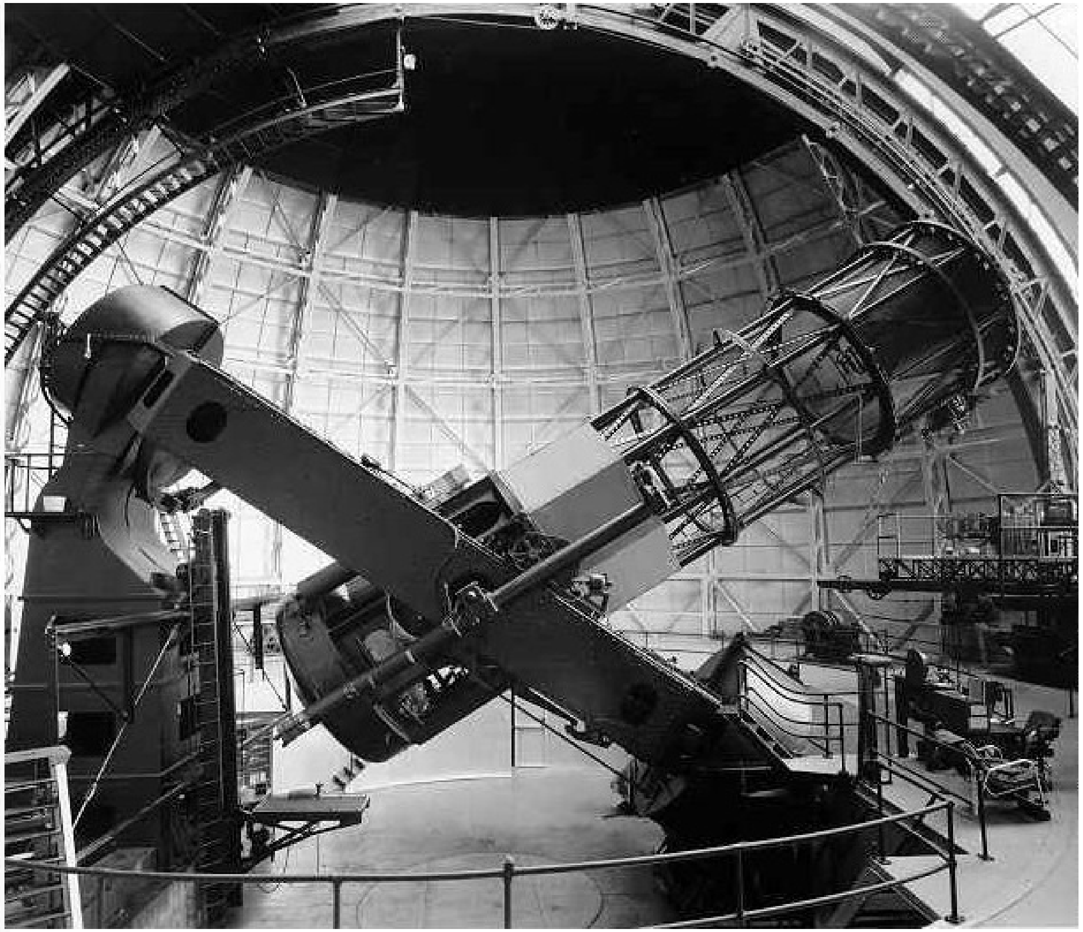
9.2 Variable stars

Period-luminosity correlation

Since the period can be measured accurately at a great distance, Cepheid variables are important in measurements of the comic ladder.







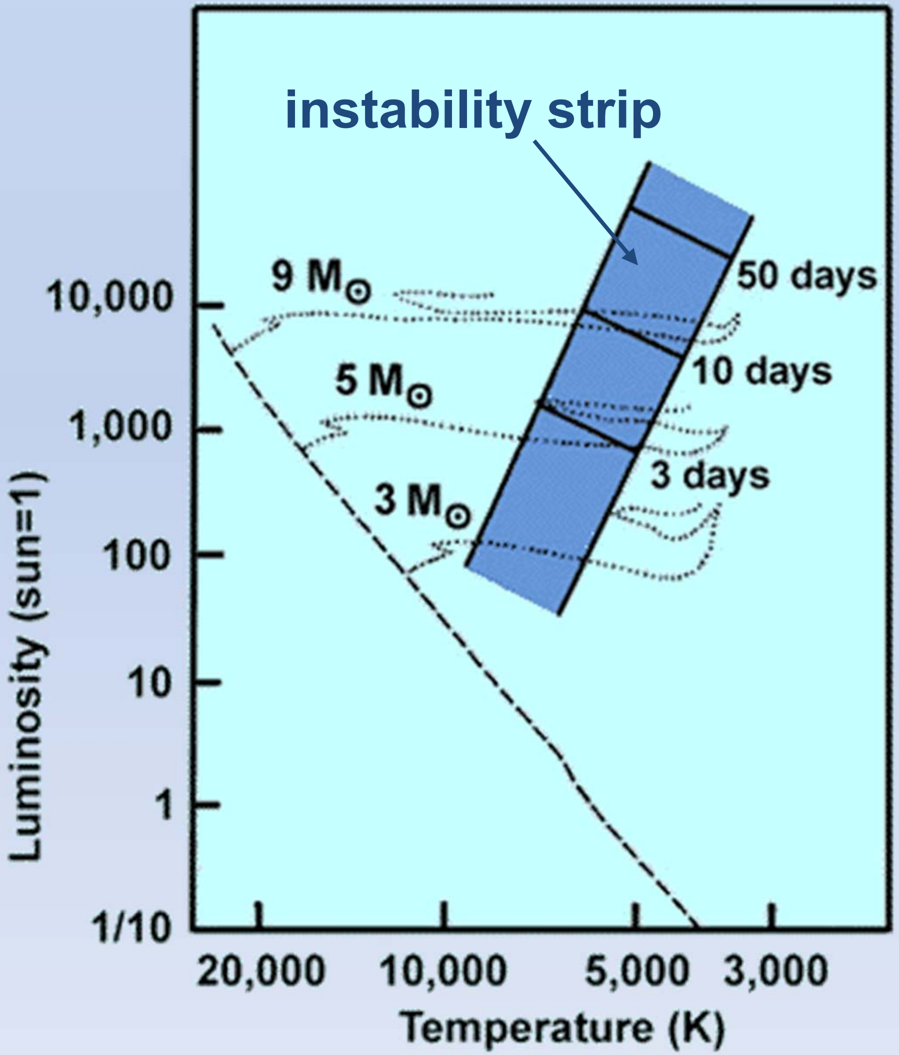
Edwin Hubble (1889-1953) and Hooker Telescope (2,5m), Mt.Wilson Observatory
Sources: Wikipedia, http://www.astro.caltech.edu/

哈勃 (Edwin Hubble, 1889-1953)

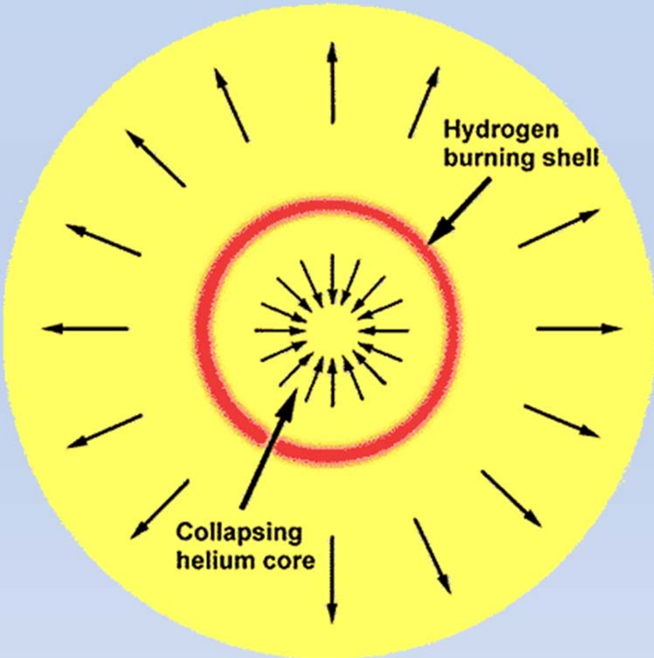
9.2 Variable stars

Why are some stars changing their brightness

- ✓ When giants moves left and right in the H-R diagram, may enter the instability strip
- ✓ outer layers oscillate, vary in brightness, radius
- ✓ Cepheid variables: radii changes by 5-10%, brightness changes by 0.1-2 magnitude



Box 9.2 Why does a Cepheid pulsate periodically (for reference)

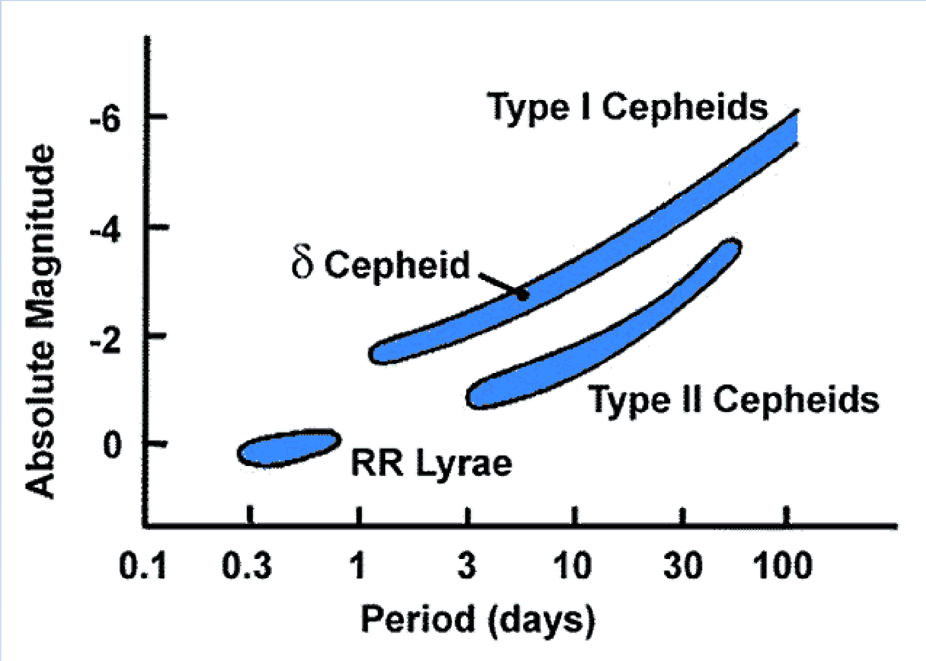


- ✓ 3 regions:
  - ➢ outer layer (not ionized)
  - ➢ partially ionized region
  - ➢ fusion region (fully ionized)
- ✓ when star contracts,

  more atoms are ionized → EM radiations are trapped efficiently → star expands due the to heat
- ✓ star expansion → ions recombination → less EM radiations trapped → star contracts again

Box 9.2 Why does a Cepheid pulsate periodically (for reference)

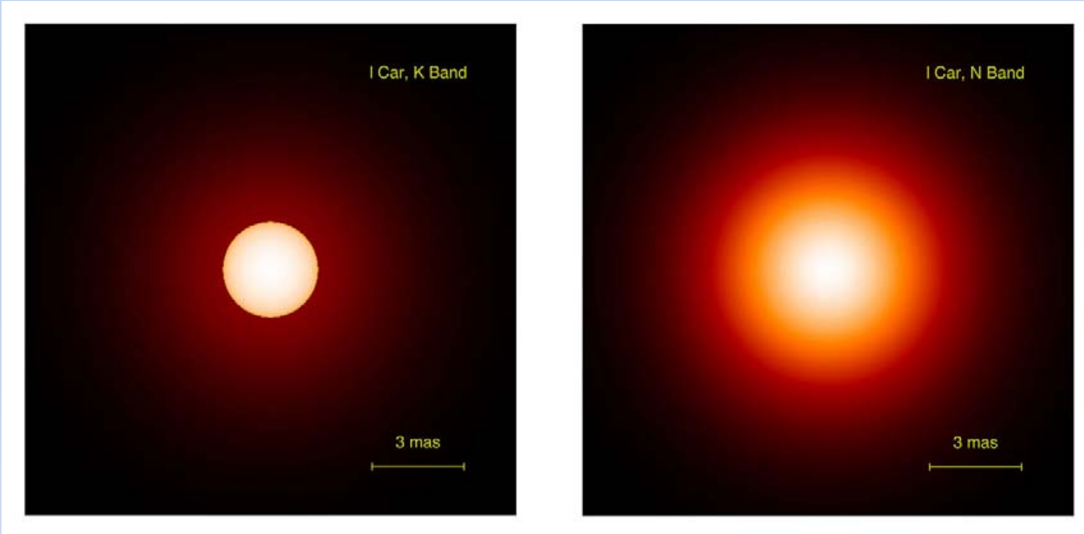
Cepheids are classified according to their metal content. If the star is metal-rich, it is called Type I Cepheid; if it is metal-poor, it is called Type II Cepheid.



9.2 Variable stars

Period-luminosity correlation

- ✓ Massive Cepheid has a large inertia, oscillate slowly and hence has a longer period.

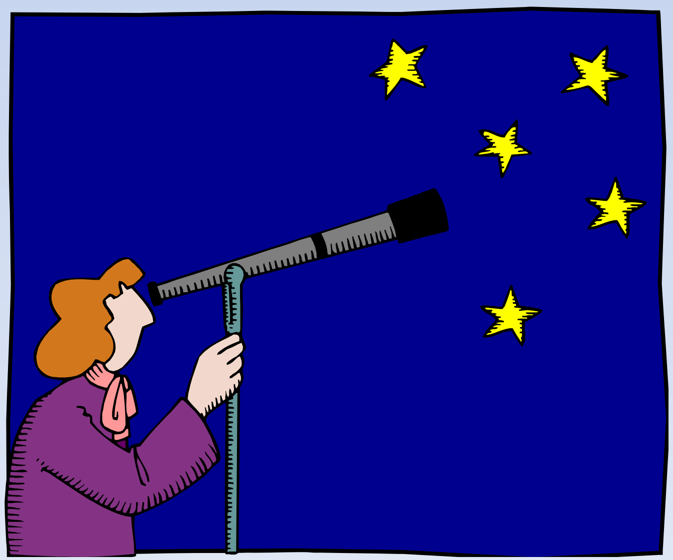


Credit: ESO

- ✓ Thus, the period provides information about its mass and luminosity (through mass-luminosity relation, $L = kM^{3.5}$)

9.3 Star clusters

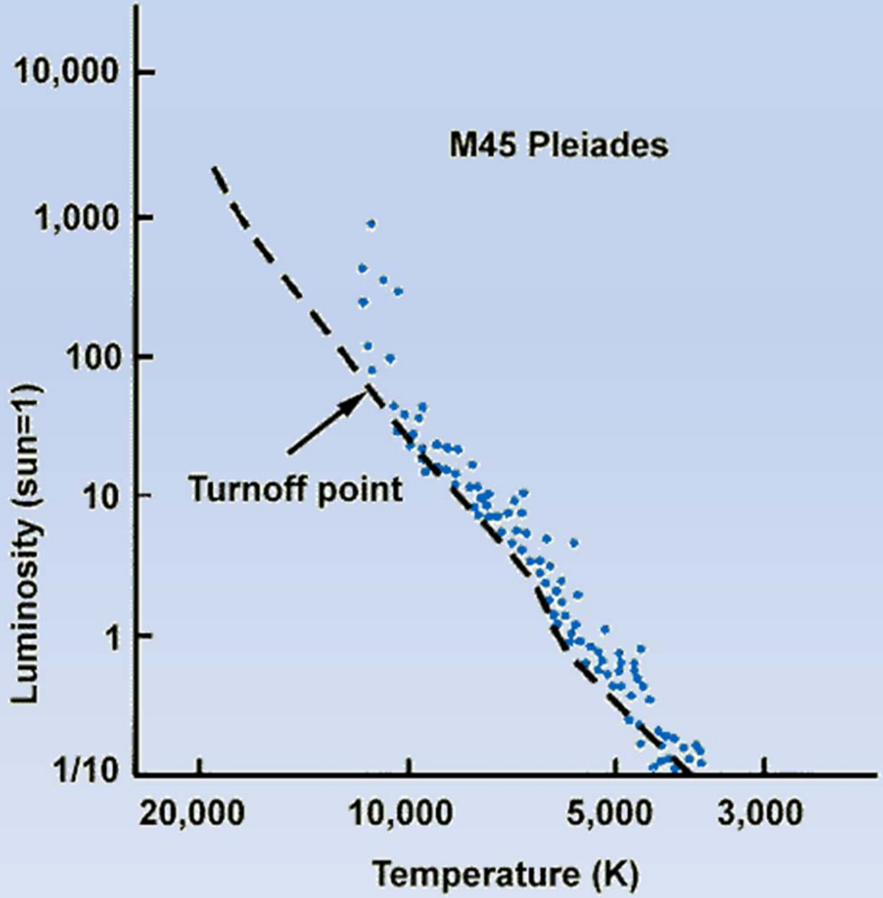
- ✓ Stars in the same clusters formed from the same cloud
- ✓ Similar ages and *initial* composition, but different in mass
- ✓ Stars in a clusters are about the same distance from us




Taurus M45 (金牛座昴宿星團，七姊妹), 400 ly from us

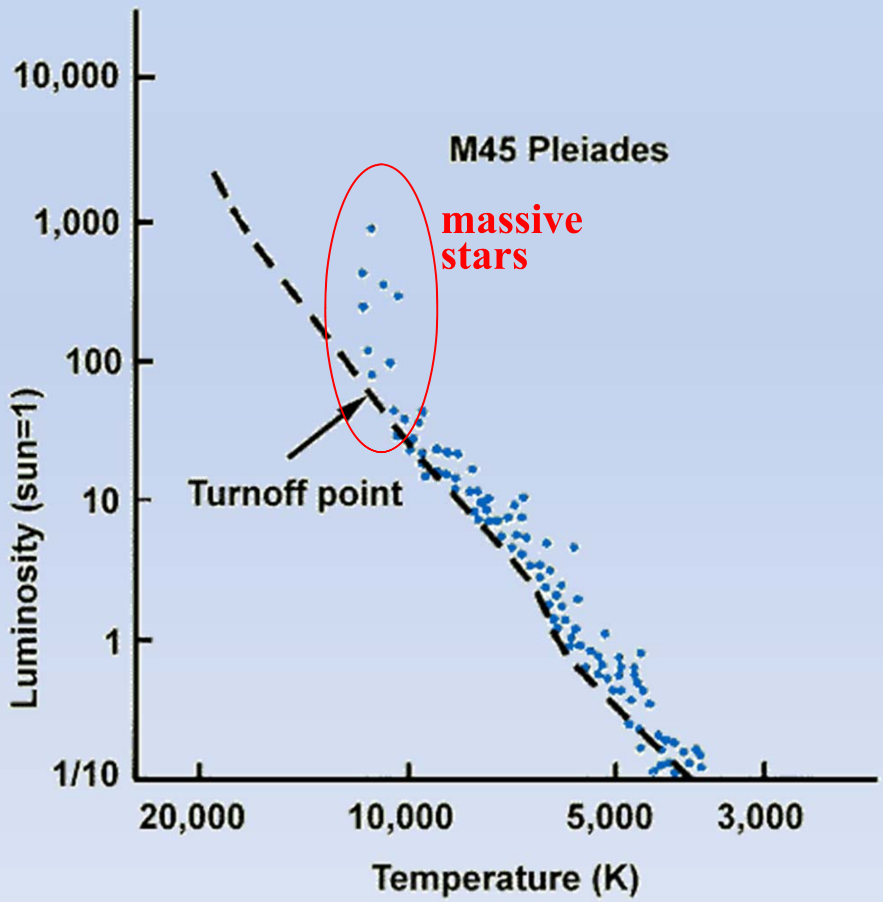
9.3 Star clusters

- ✓ But the stars differ in luminosity (mass) and surface temperature (colors)
- ✓ located at different positions on the H-R diagram



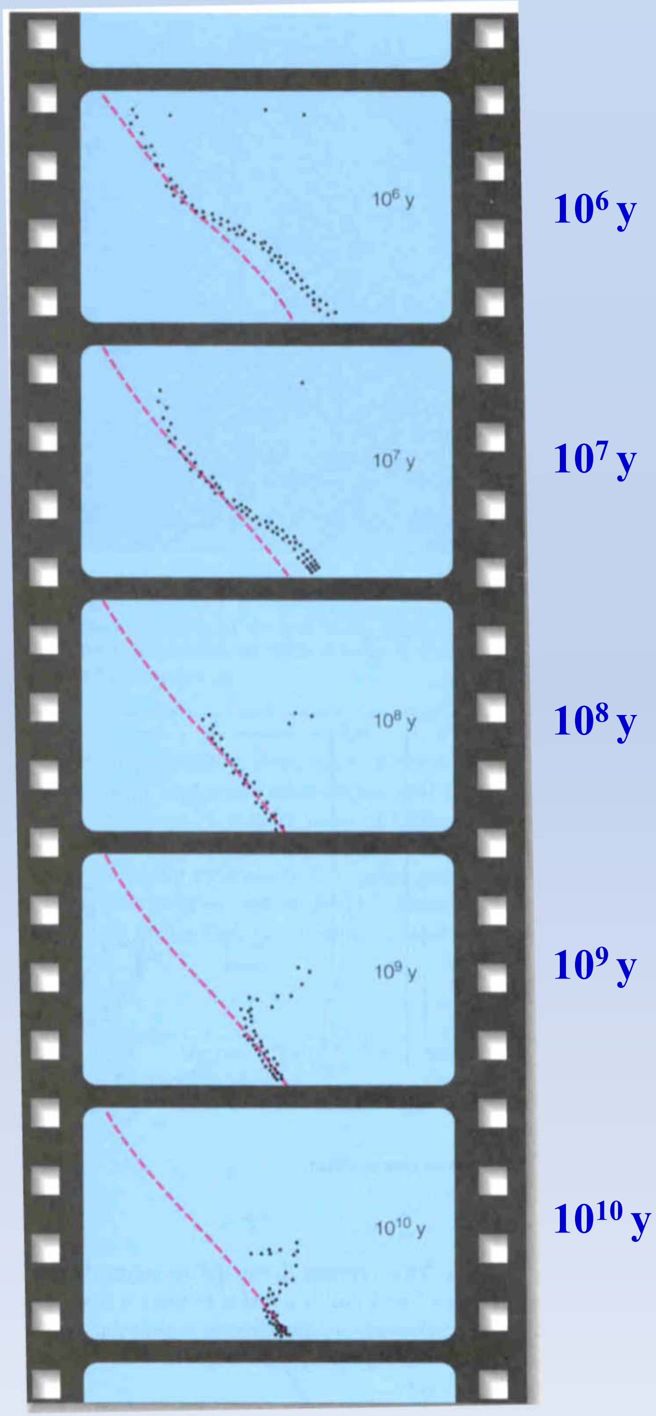
9.3 Star clusters

- ✓ Higher-mass members (more luminous) leave the main sequence and become giants, lower-mass members still lie on the main sequence
- ✓ Evidences of the evolution picture that more massive stars have shorter lives



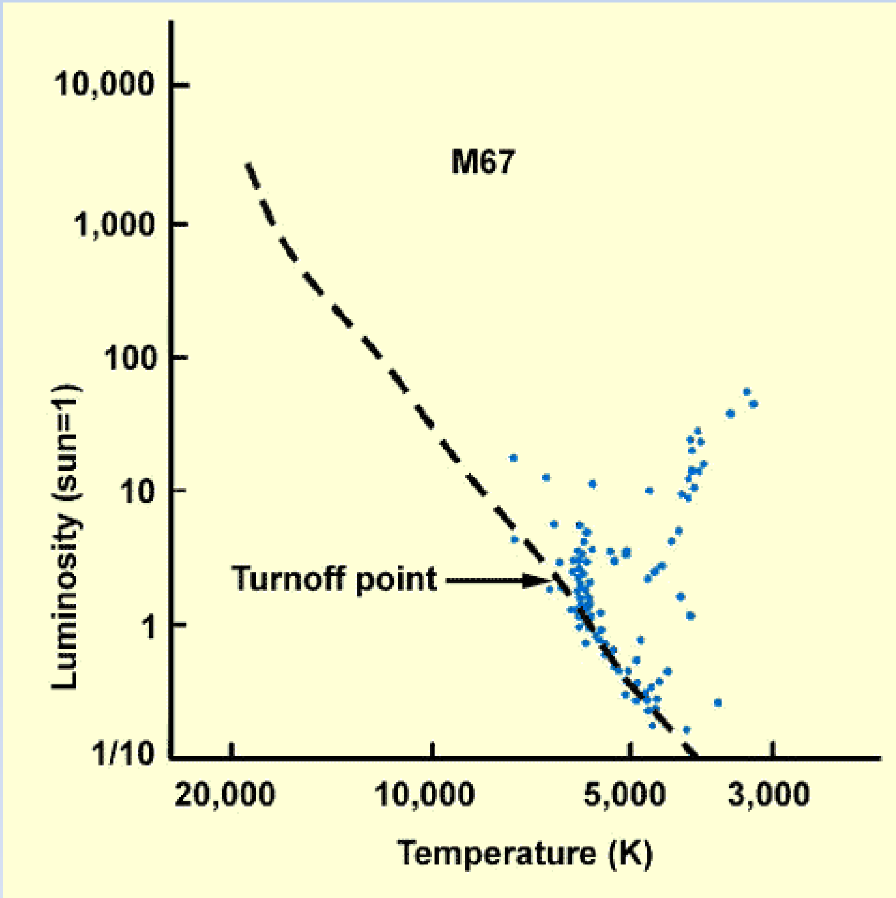
9.3 Star clusters

- ✓ locating the turnoff point of a cluster in the H-R diagram
- ✓ useful for determining the cluster's age by stellar evolution theory



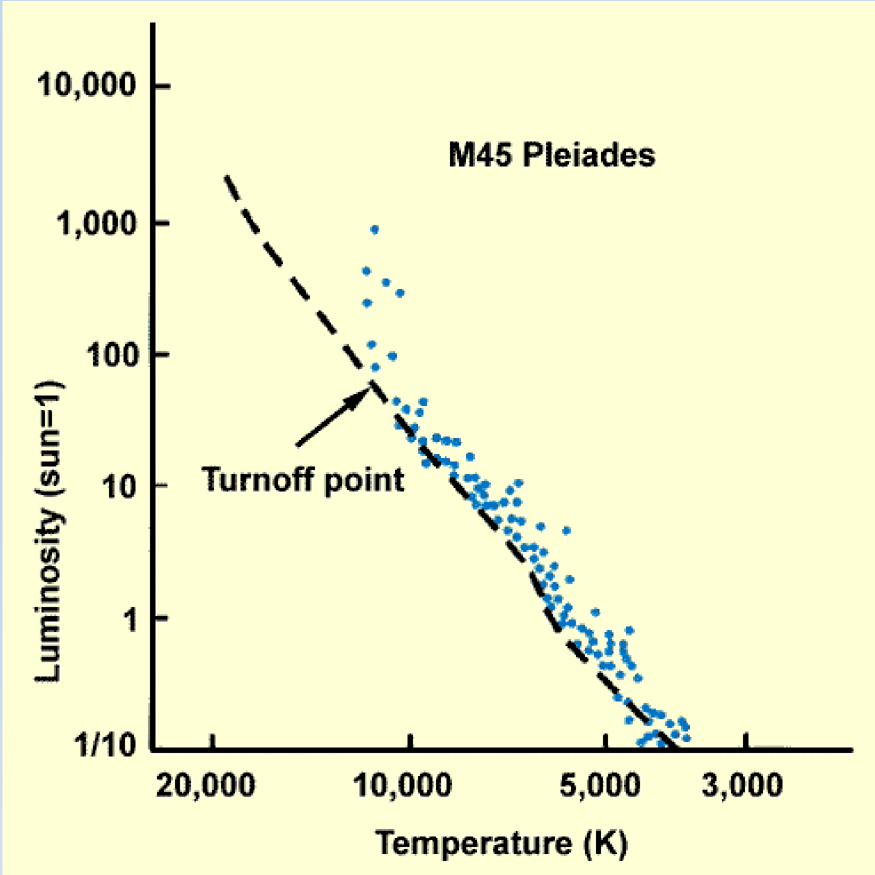
Open Cluster M67 (NGC 2682), in Cancer

Distance: 2.7 (kly), Visual Brightness: 6.1,
Apparent Dimension: 30.0 (arc min)



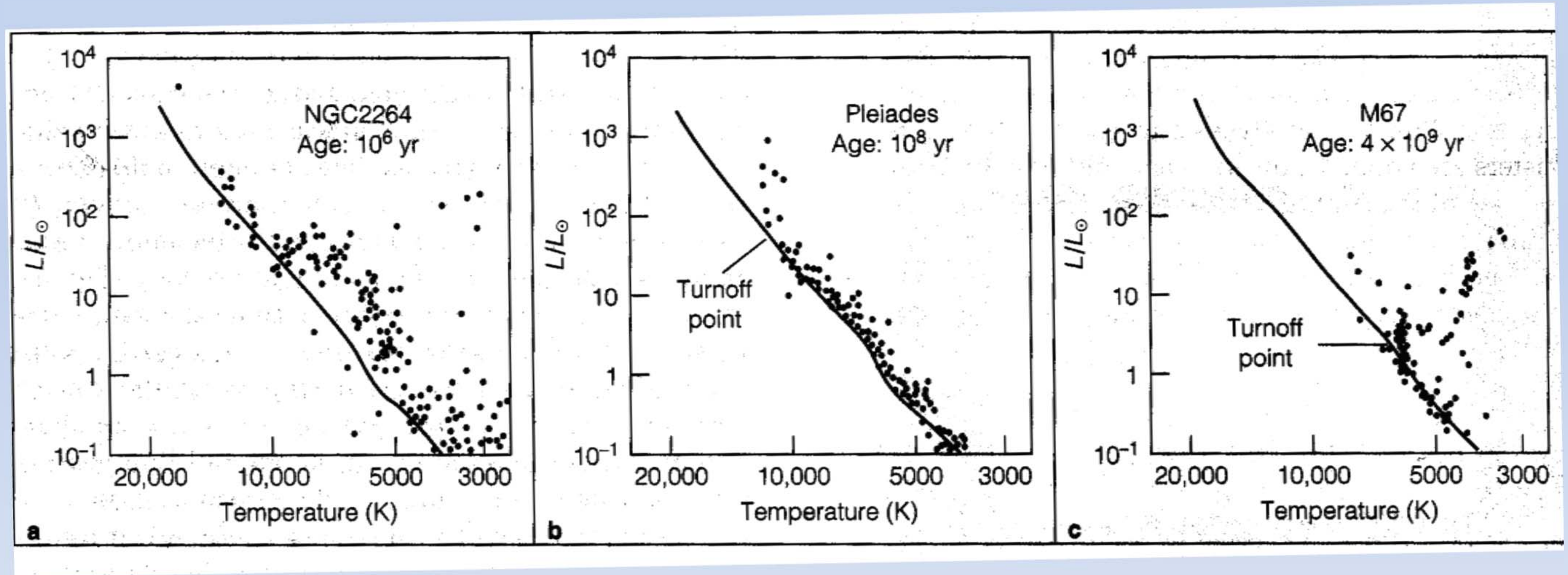
age ~ 5 billion years

M45, open cluster with mainly B-type stars

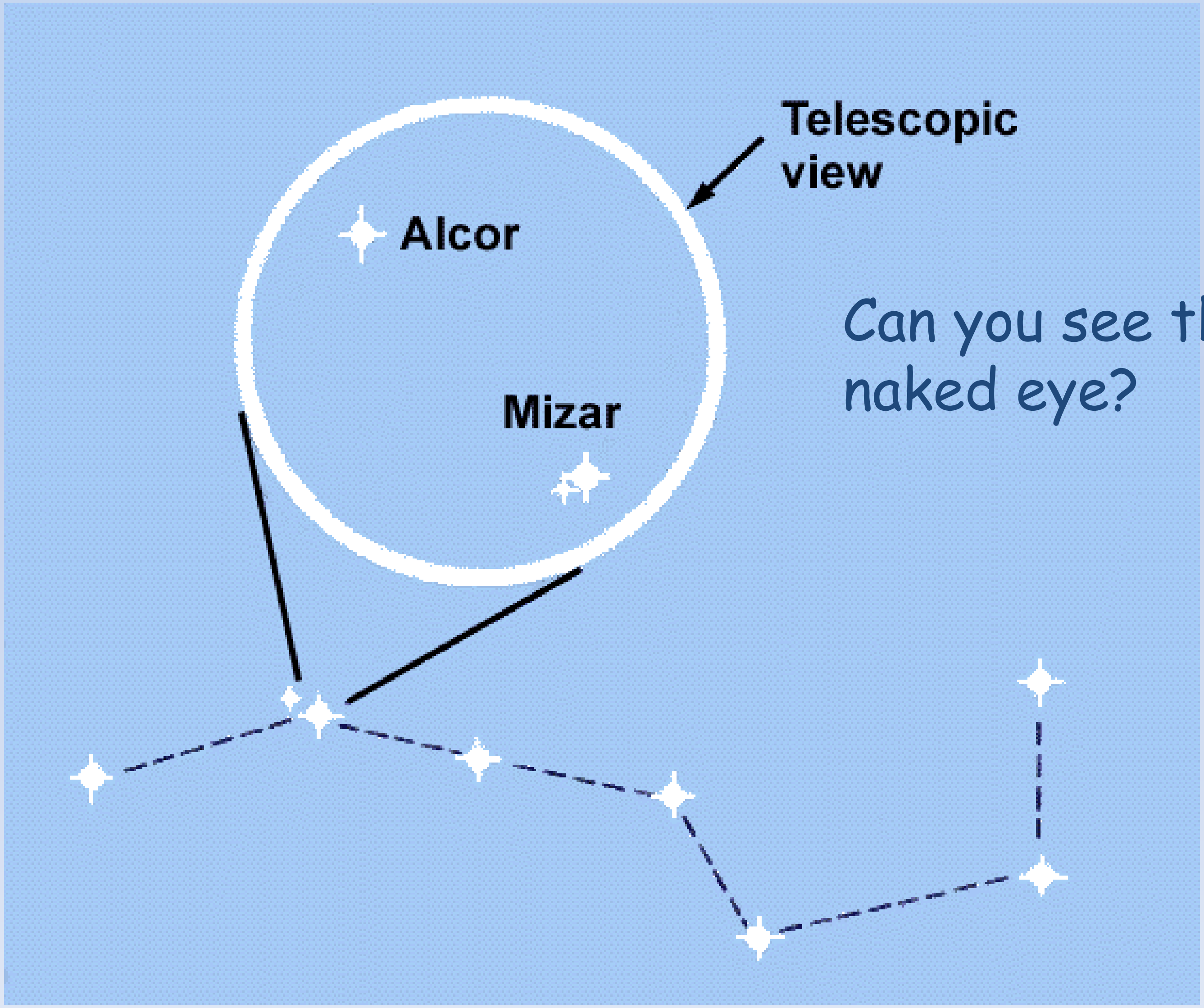


A younger cluster of age ~ 100 million years

9.3 Star clusters



9.4 Evolution of binary stars

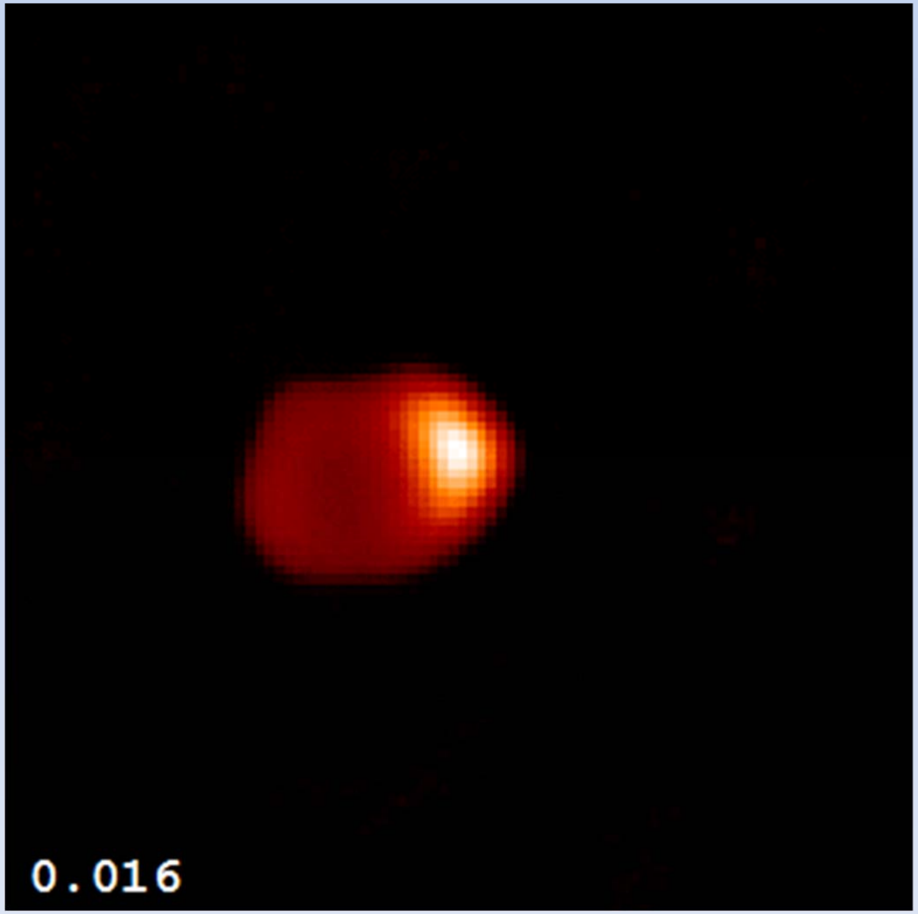


Can you see this with naked eye?

9.4 Evolution of binary stars

Here's an example of eclipsing binaries. By measuring light curve (brightness as a function of time) and the spectra, we can learn a lot about individual stars in the system.

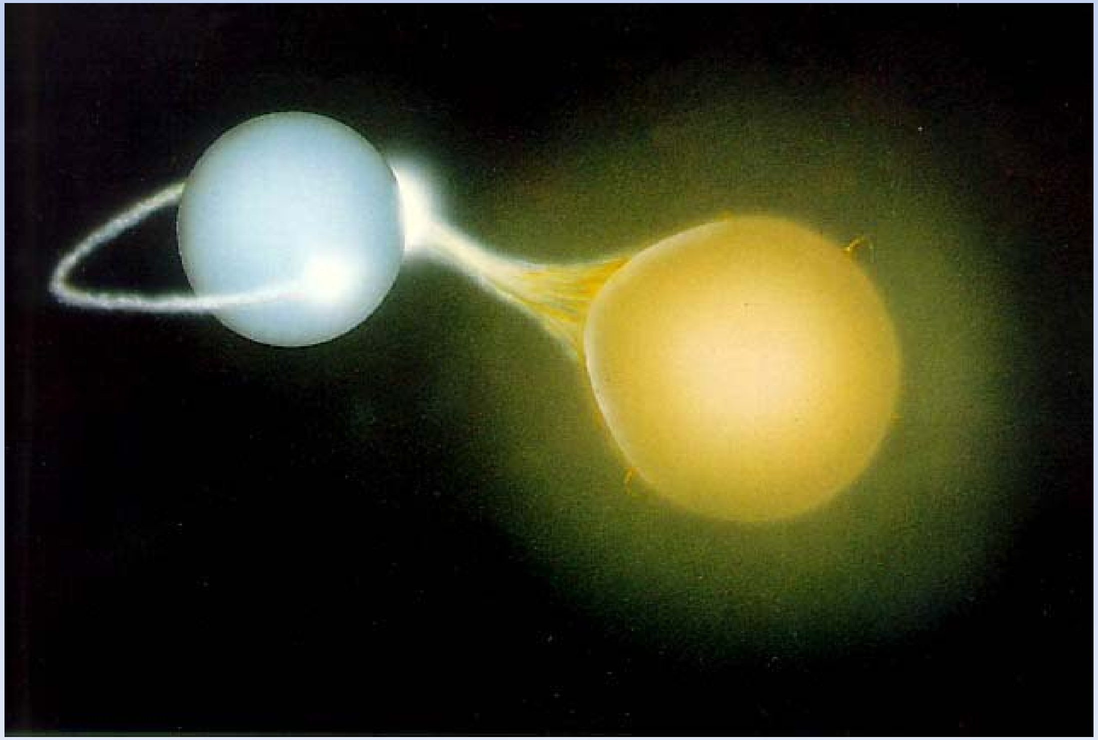
Algol (大陵五), observed by using the CHARA interferometer



Credit: CHARA, GSU, Wikimedia Commons

9.4 Evolution of binary stars

Algol paradox (大陵五佯謬): In some binary systems, the *less massive star is a giant* while the *more massive one remains on the main sequence.*

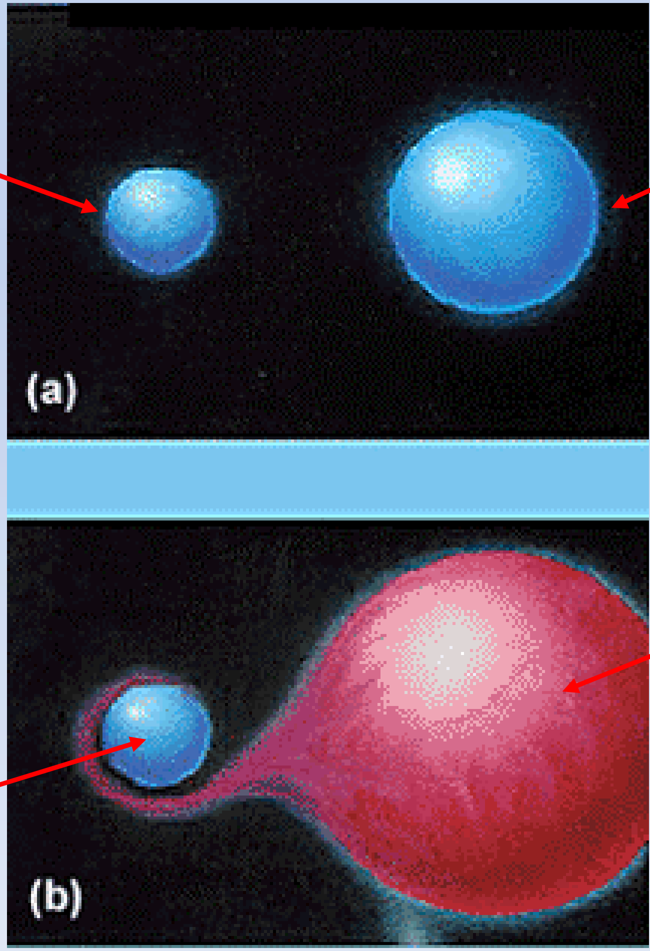


9.4 Evolution of binary stars

Resolving the Algol paradox

less massive star

more massive star

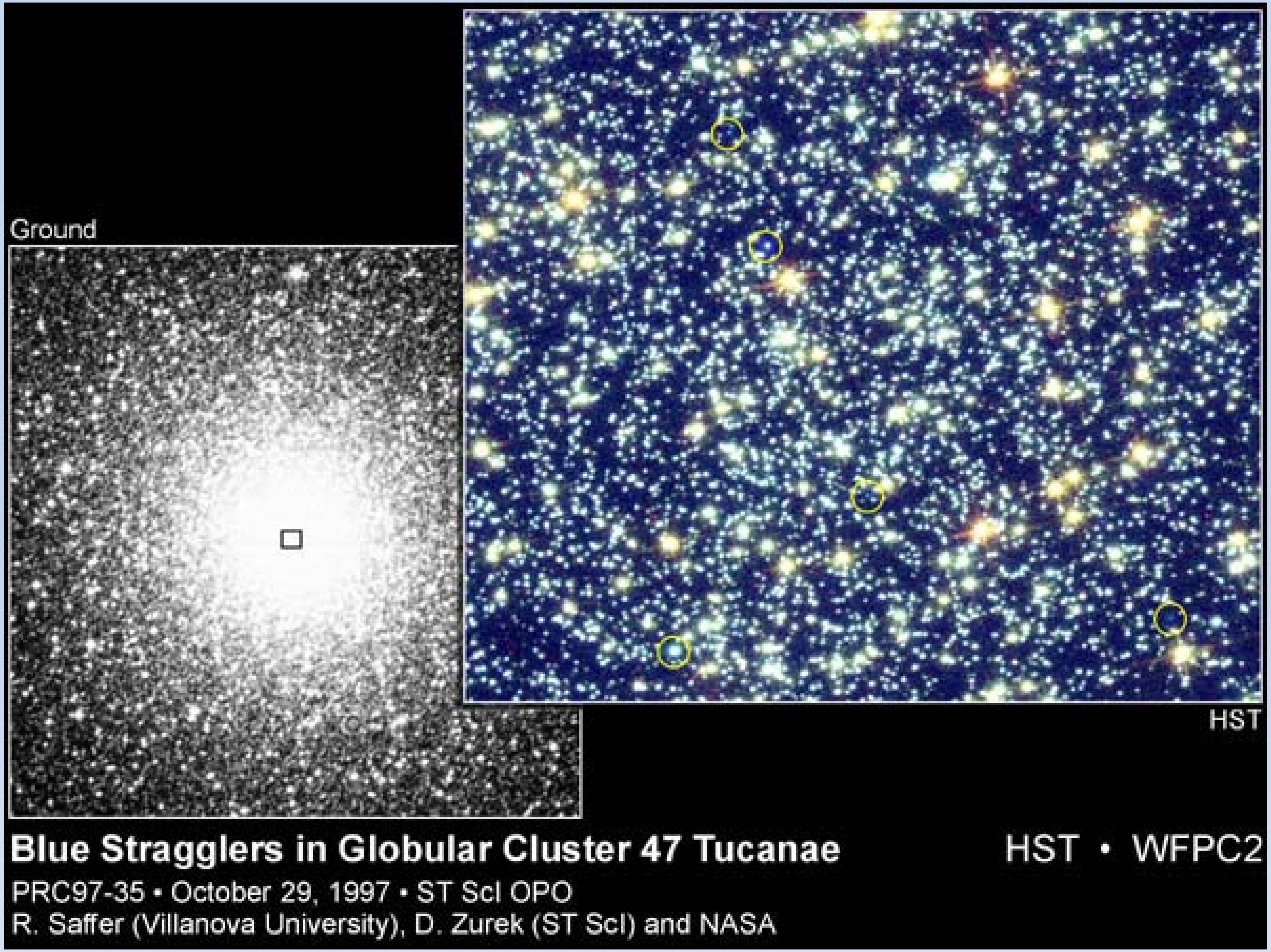


Become a giant first, outer layer easily transfer to its companion

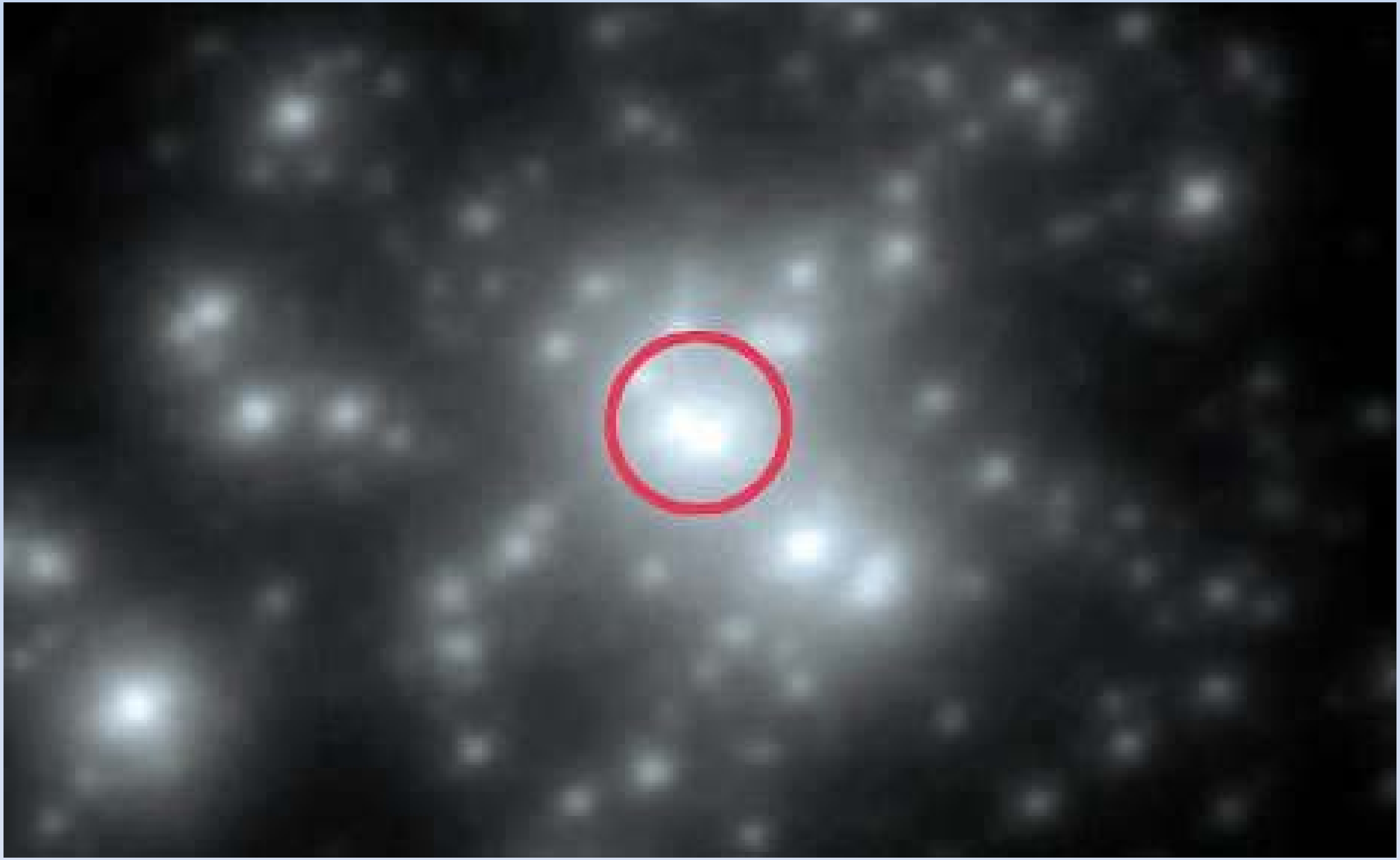
Finally, become a massive star, but still on the main sequence

9.4 Evolution of binary stars

- ✓If both stars are close, and become red giants
- ✓They may merge together to form **supergiant**



If both members swell into *giants*, they could merge together to form one rapidly-spinning supergiant – blue straggler



The massive star on record: a blue Wolf-Rayet star R136a1 (in Dorado, 劍魚座), estimated over 300 solar masses!

Revision

1. When a main-sequence star enters a giant phase, how does its core and surface change? Hotter or cooler, denser or less dense.
2. What is the heaviest element does a massive star can make in its core?
3. What quantity can be measured by the period of a Cepheid? Temperature or density or distance.
4. What is Algol paradox?