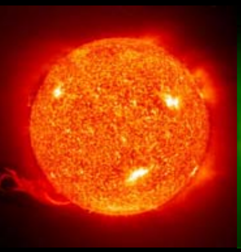
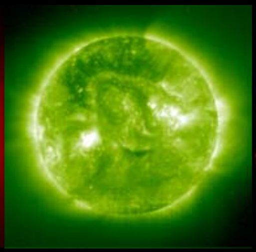
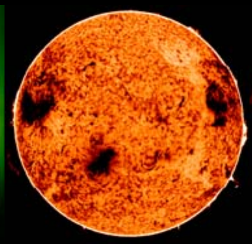
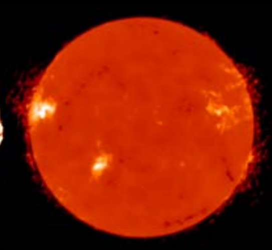
Lecture 4

Stars

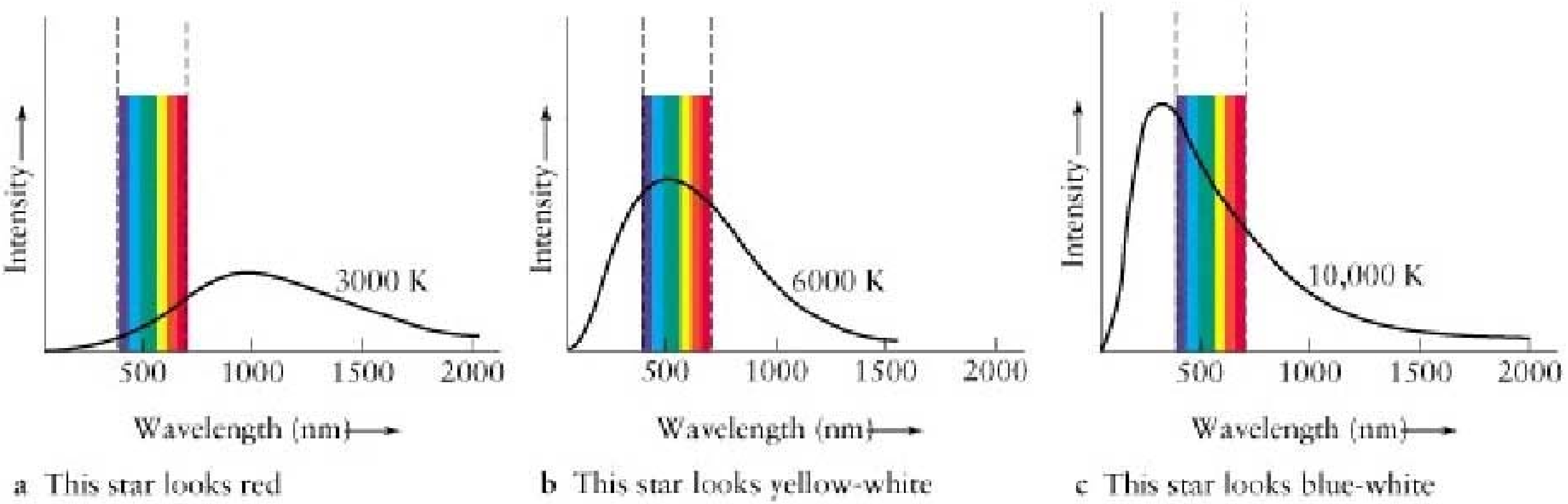
The physics of stars

- A star begins simply as a roughly spherical ball of (mostly) hydrogen gas, responding only to gravity and it's own pressure.

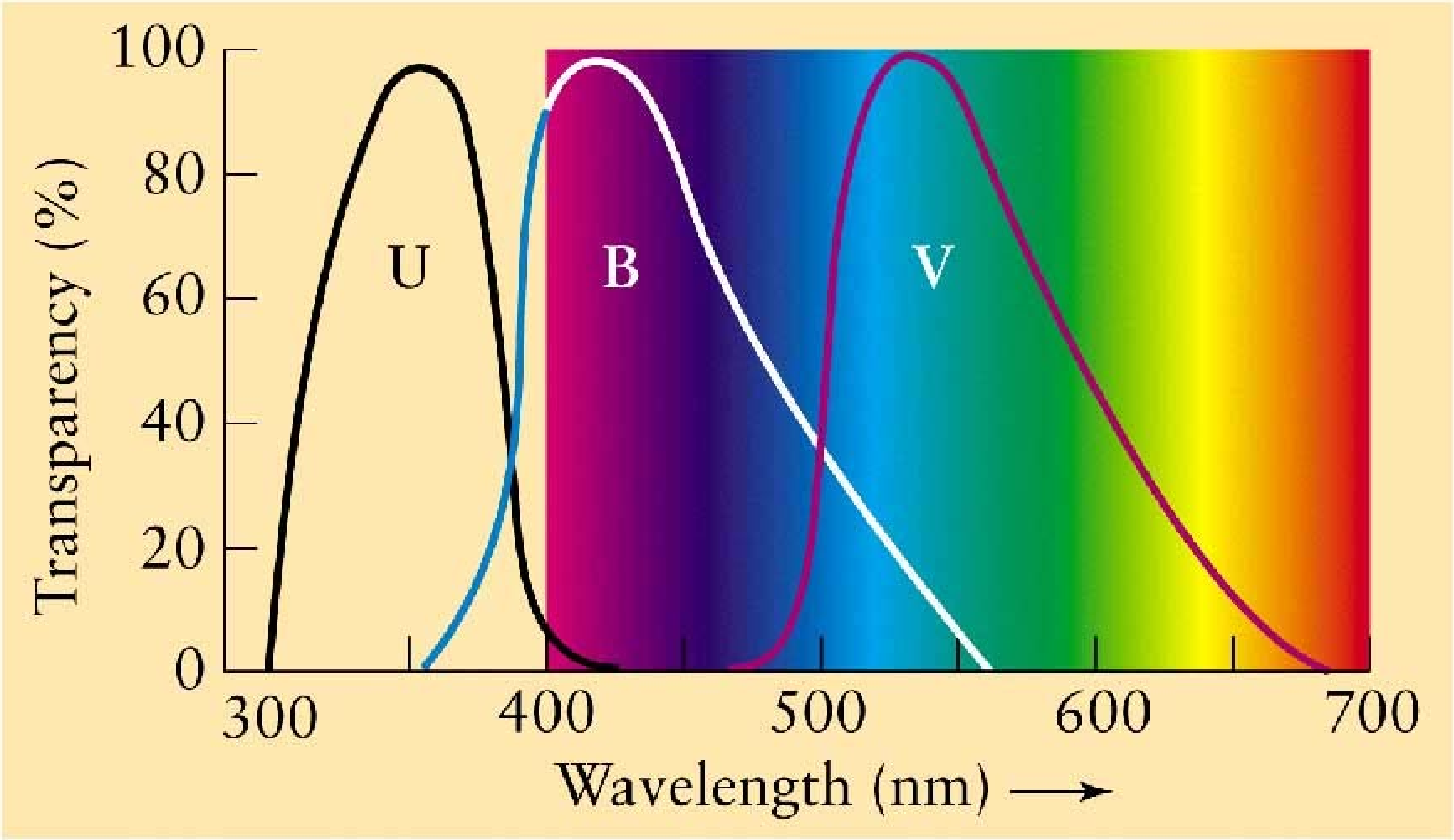
- To understand how this simple system behaves, however, requires an understanding of:
  1. Fluid mechanics
  2. Electromagnetism
  3. Thermodynamics
  4. Special relativity
  5. Chemistry
  6. Nuclear physics
  7. Quantum mechanics

A star's color depends on its surface temperature.



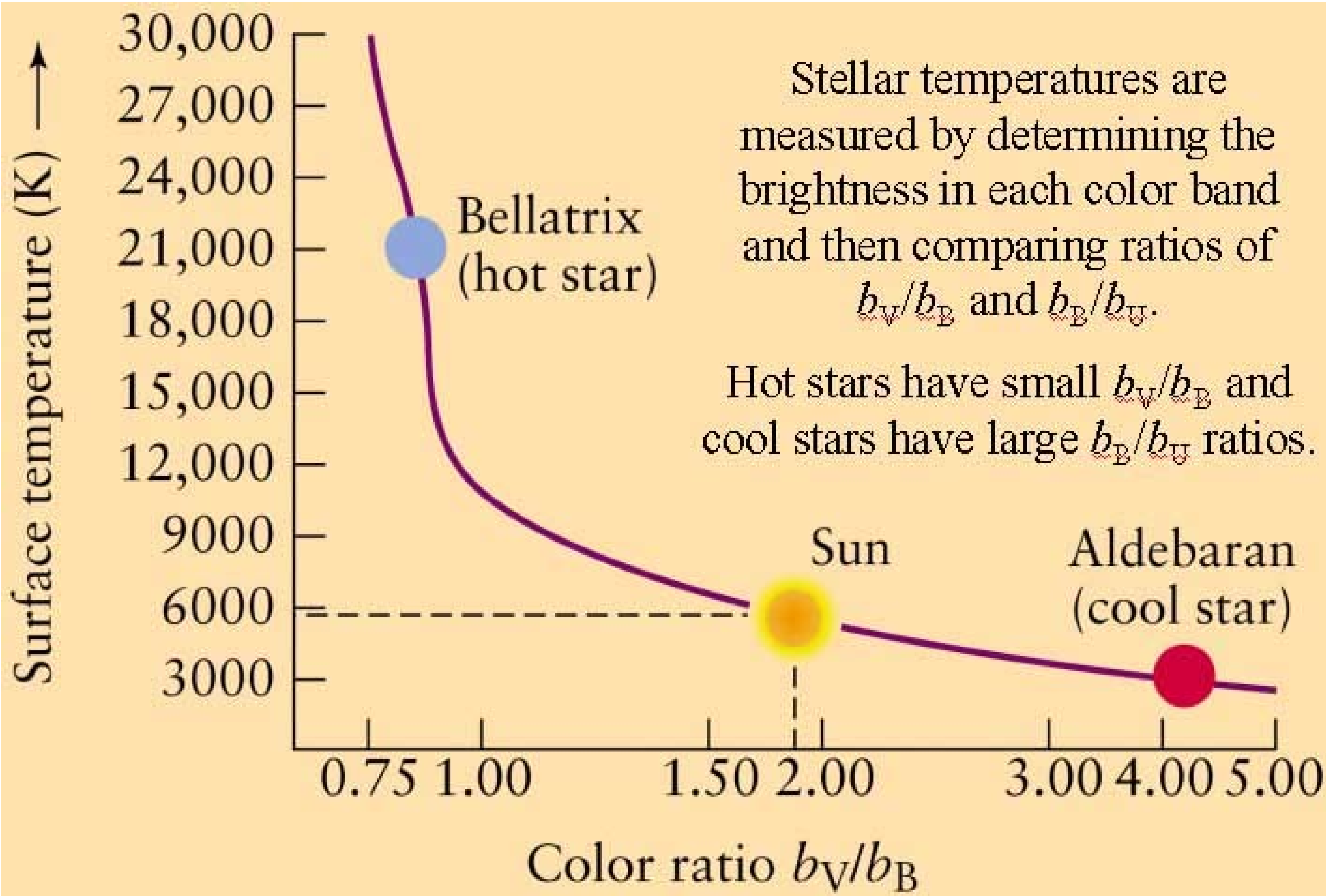
Wien's law

the hotter the object, the shorter the wavelength of its maximum emission.



UBV photometry is the process of systematically looking at intensity emitted by a star in three wavelength (color band) regions.

[U: ultraviolet, B: blue, V: visual]



Surface temperature (K)
30,000
27,000
24,000
21,000
18,000
15,000
12,000
9000
6000
3000
Bellatrix
(hot star)
Stellar temperatures are measured by determining the brightness in each color band and then comparing ratios of b_V/b_B and b_B/b_U.
Hot stars have small b_V/b_B and cool stars have large b_B/b_U ratios.
Sun
Aldebaran
(cool star)
0.75 1.00 1.50 2.00 3.00 4.00 5.00
Color ratio b_V/b_B

Stars come in a wide variety of sizes

Stefan-Boltzmann law relates a star's energy output, called LUMINOSITY, to its temperature and size.

$$\text{LUMINOSITY} = 4\pi R^2 \sigma T^4$$

LUMINOSITY *is measured in joules per square meter of a surface per second and* $\sigma = 5.67 \times 10^{-8}\ W\ m^{-2}\ K^{-4}$

- Small stars will have low luminosities unless they are very hot.
- Stars with low surface temperatures must be very large in order to have large luminosities.

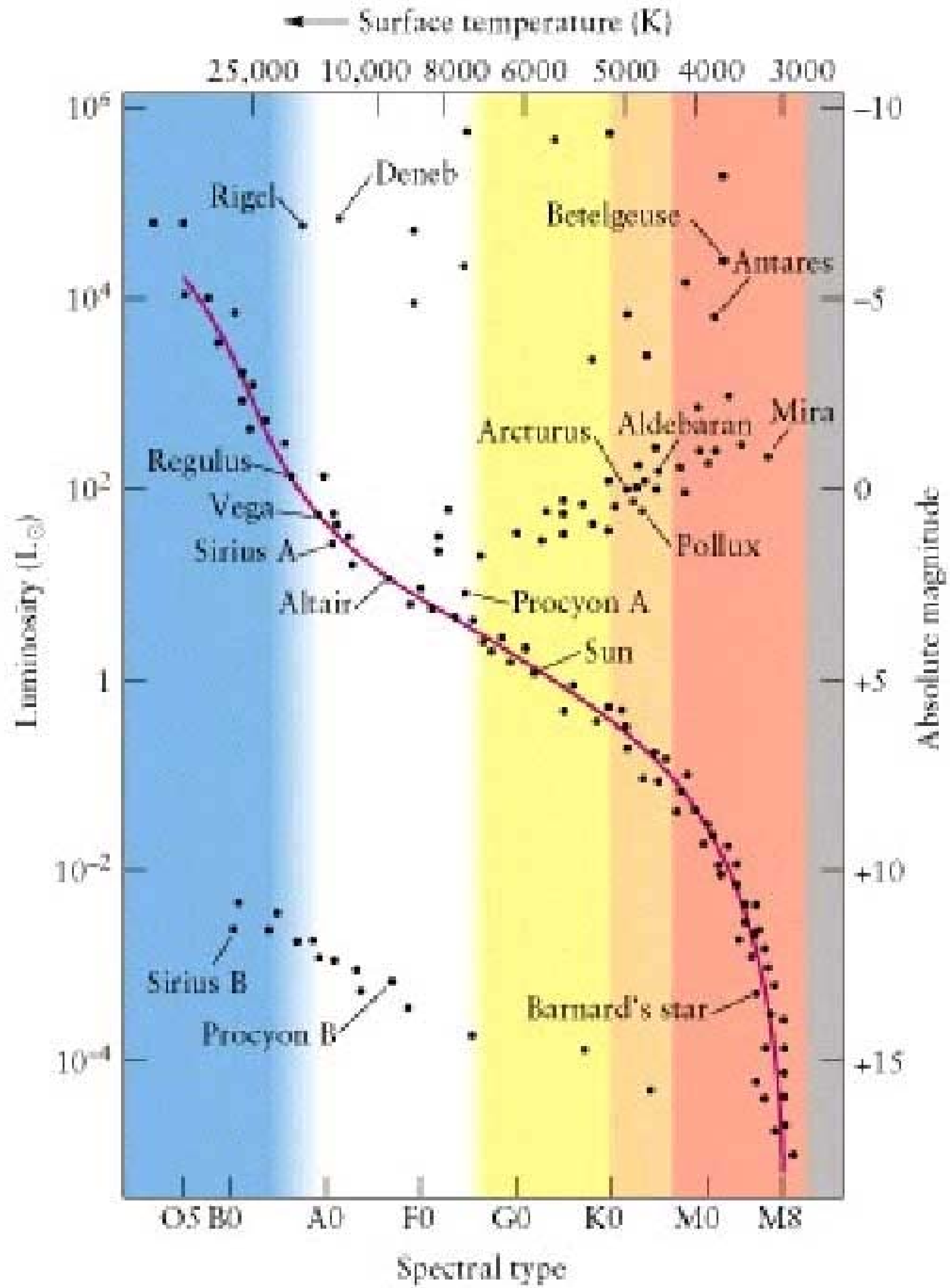
Hertzsprung-Russell (H-R) diagrams reveal the different kinds of stars.

HR DIAGRAM

Absolute magnitude vs temperature

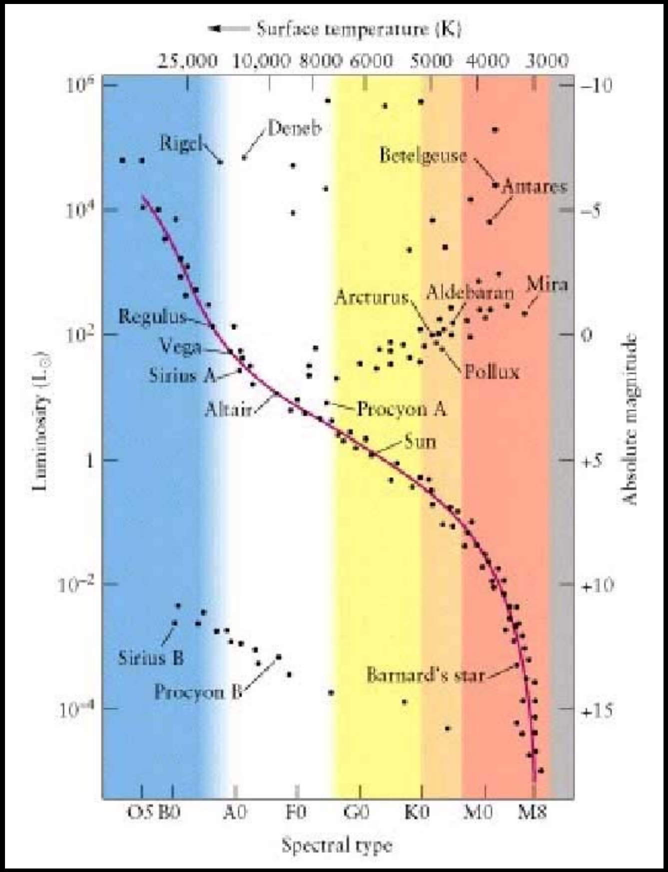
or

luminosity vs spectral type



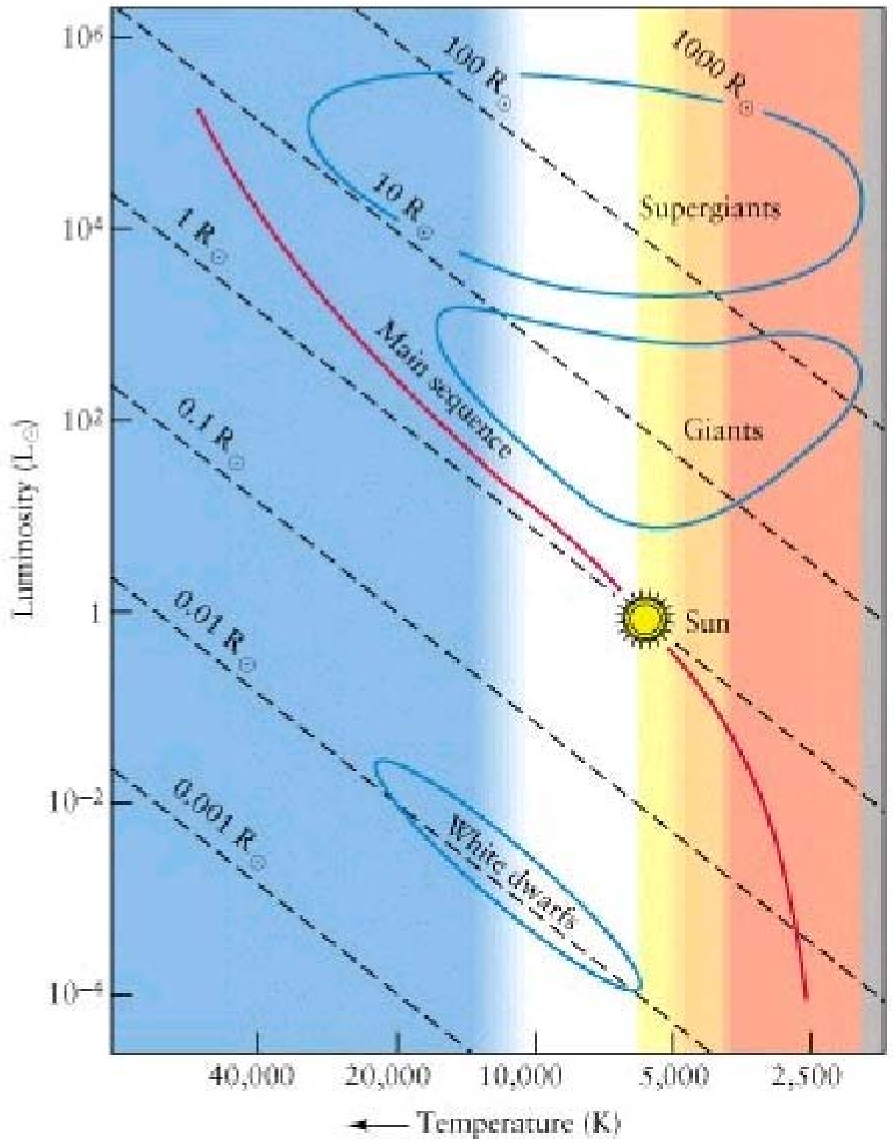
Hertzsprung-Russell (H-R) diagrams reveal the different kinds of stars.

- Main sequence stars
  - Stars in hydrostatic equilibrium found on a line from the upper left to the lower right.
  - Hotter is brighter
  - Cooler is dimmer
- Red giant stars
  - Upper right hand corner (big, bright, and cool)
- White dwarf stars
  - Lower left hand corner (small, dim, and hot)



Determining the Sizes of Stars from an HR Diagram

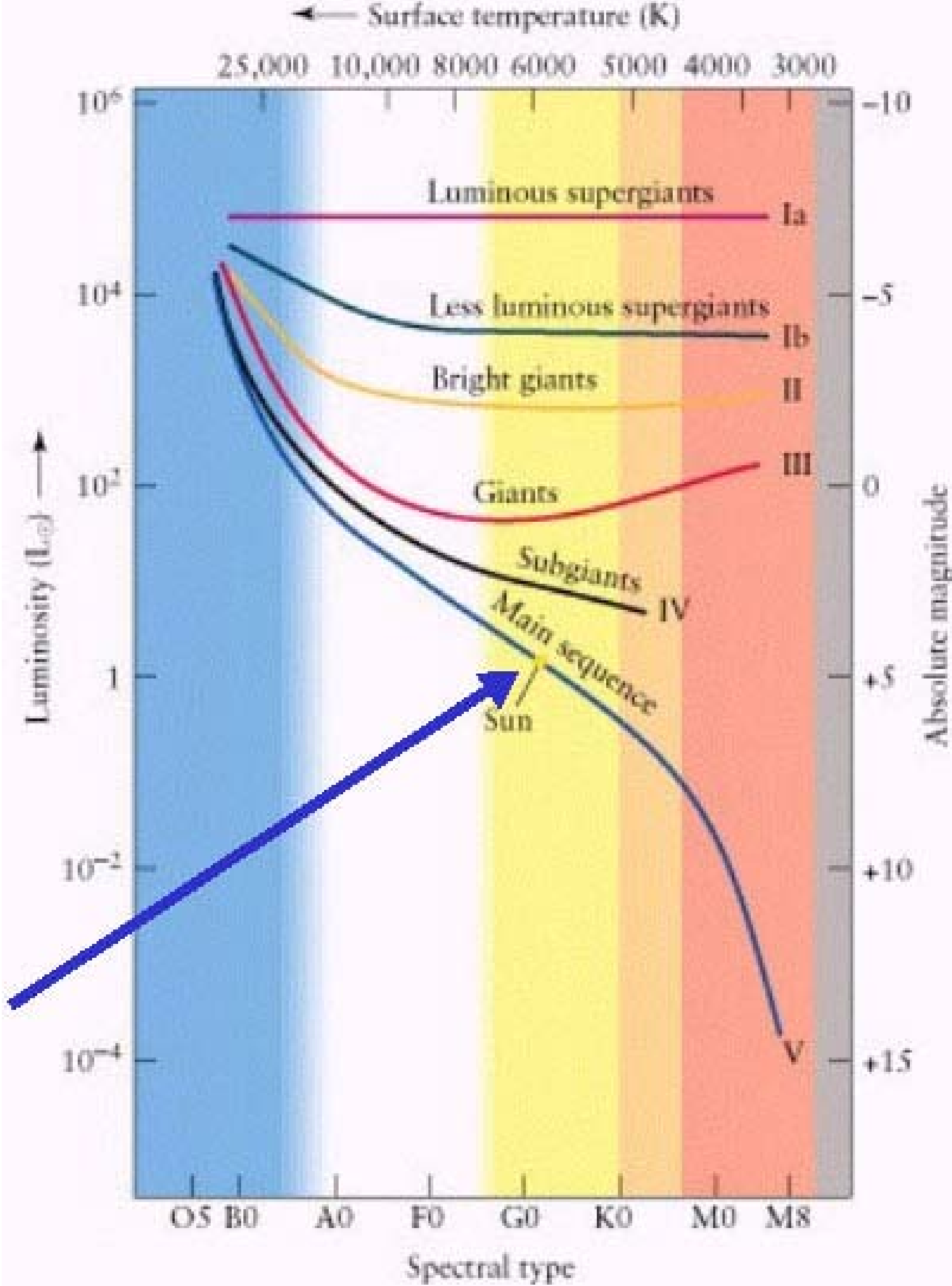
- Main sequence stars are found in a band from the upper left to the lower right.
- Giant and supergiant stars are found in the upper right corner.
- Tiny white dwarf stars are found in the lower left corner of the HR diagram.

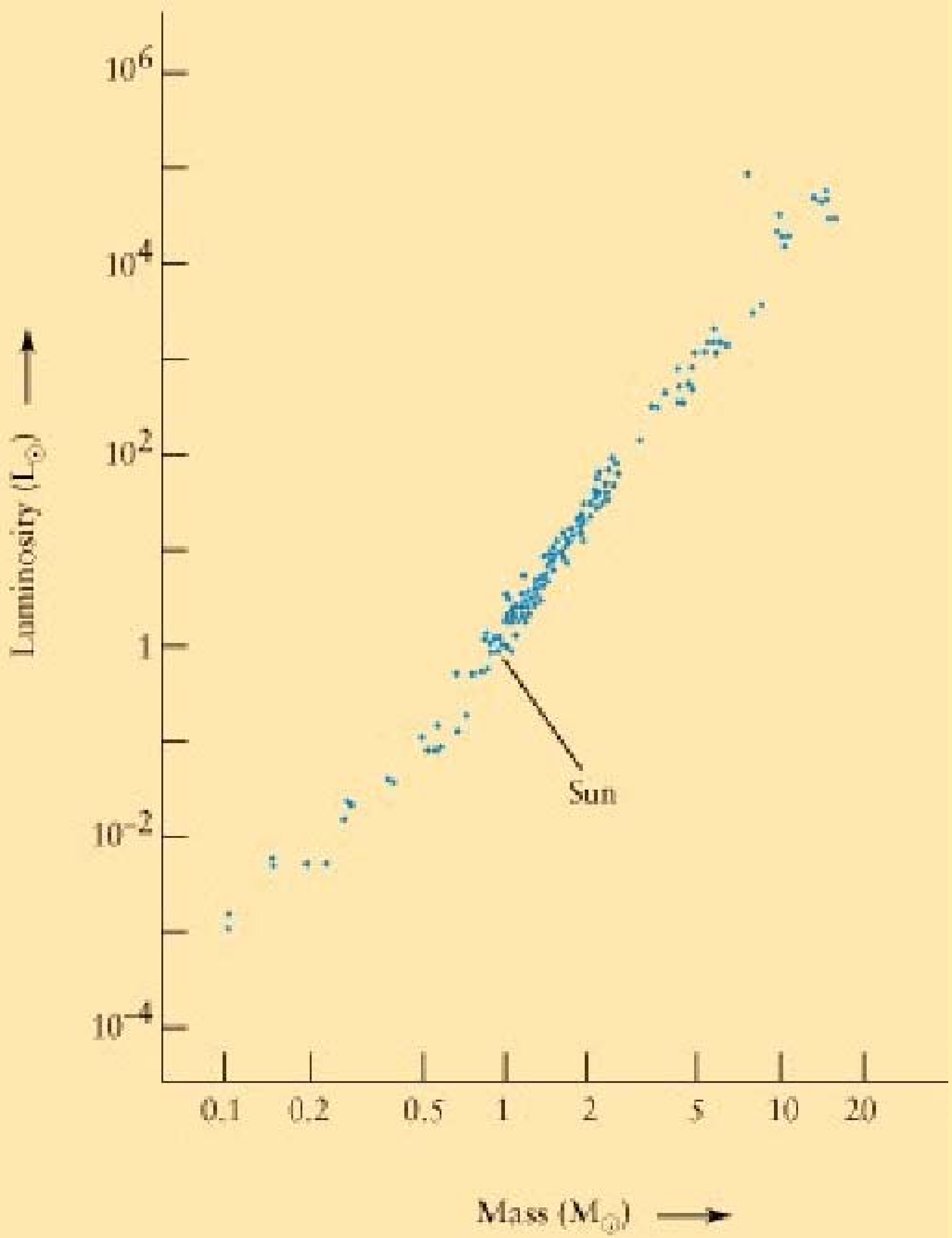


Details of a star's spectrum reveal whether it is a giant, a white dwarf, or a main-sequence star.

Luminosity classes

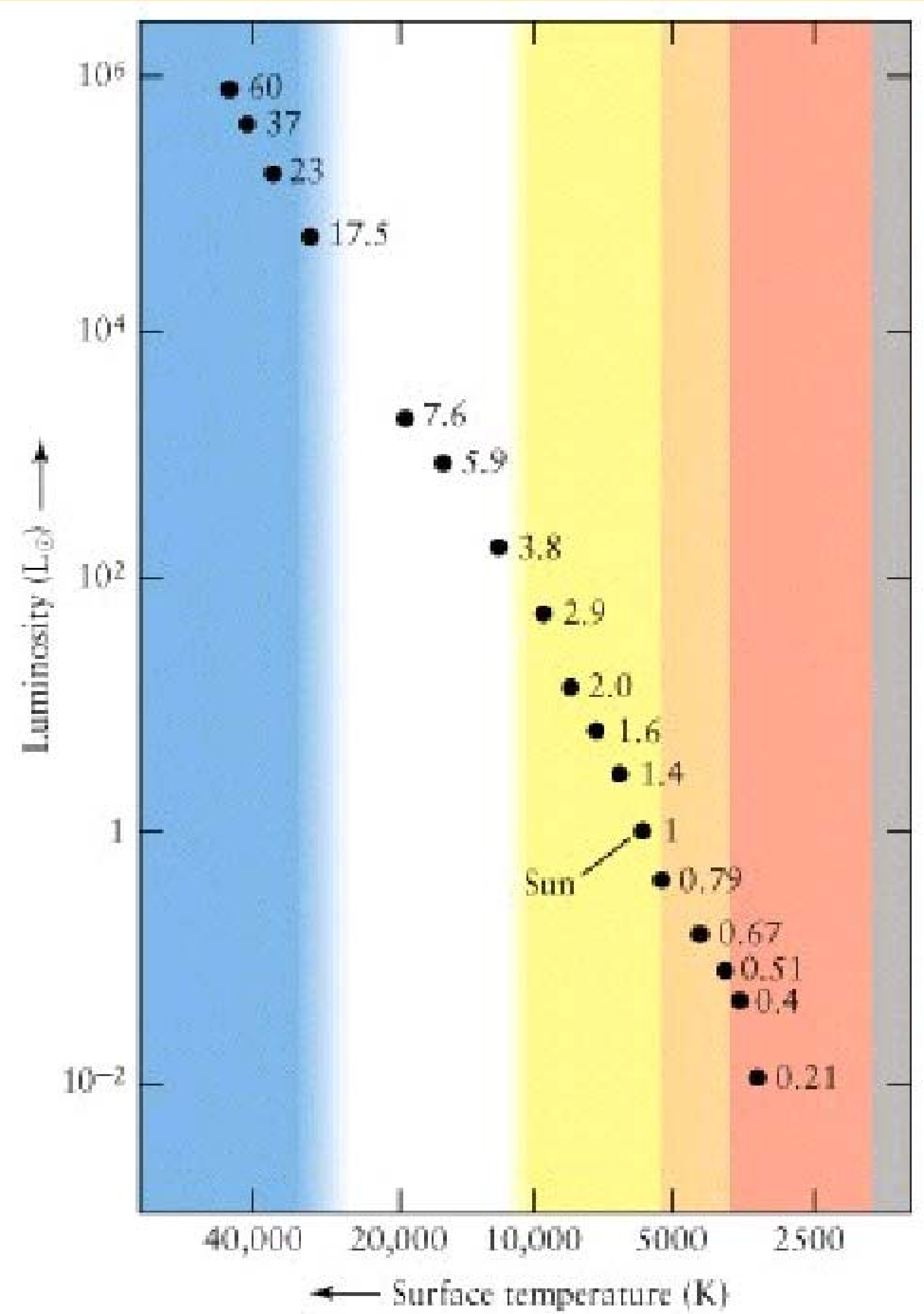
- Class I includes all the supergiants.
- Class V includes the main sequence stars.
- e.g., the Sun is a G2 V





There is a relationship between mass and luminosity for main-sequence stars.

Bigger is brighter!



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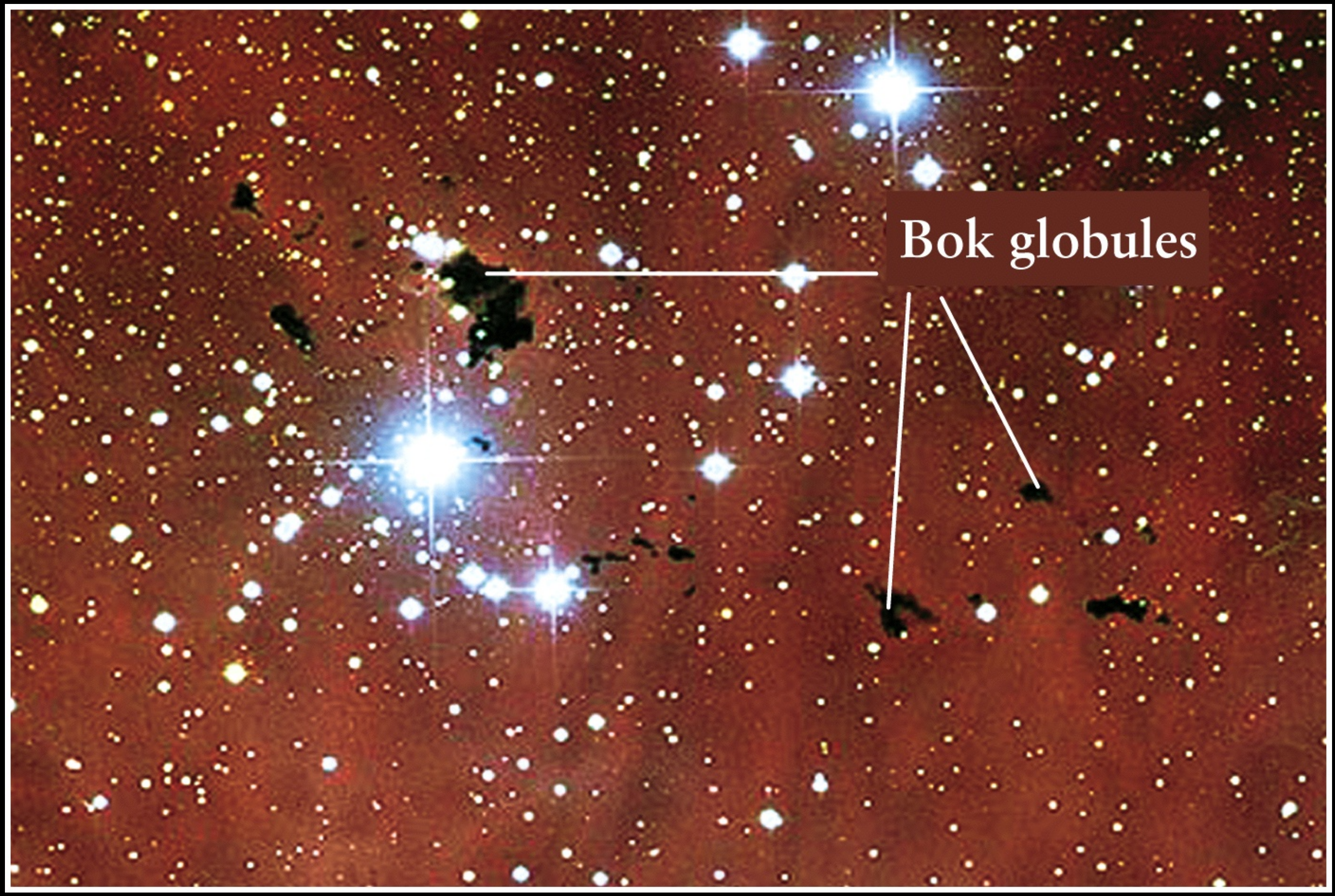
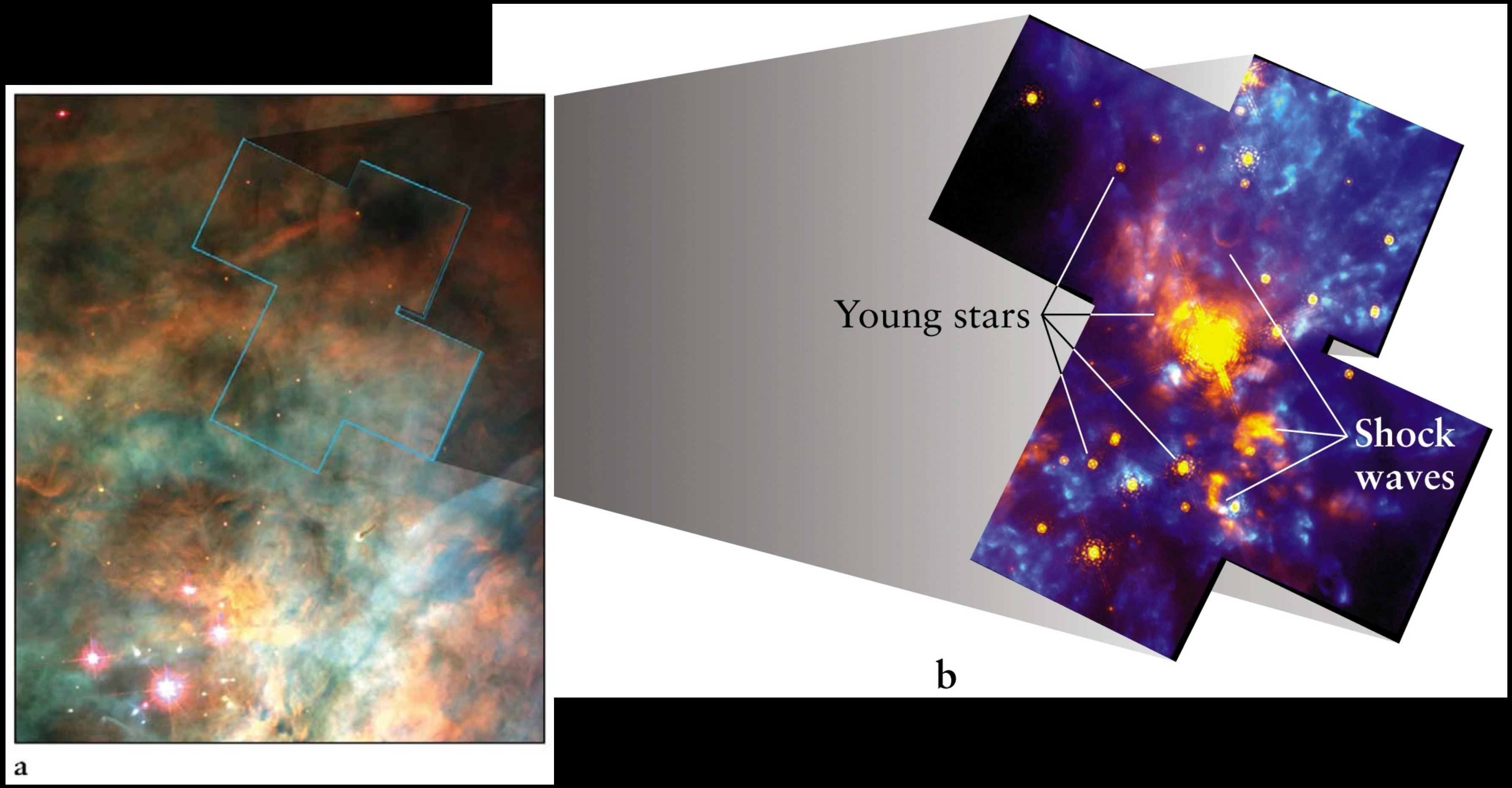
Protostars form in cold, dark nebulae



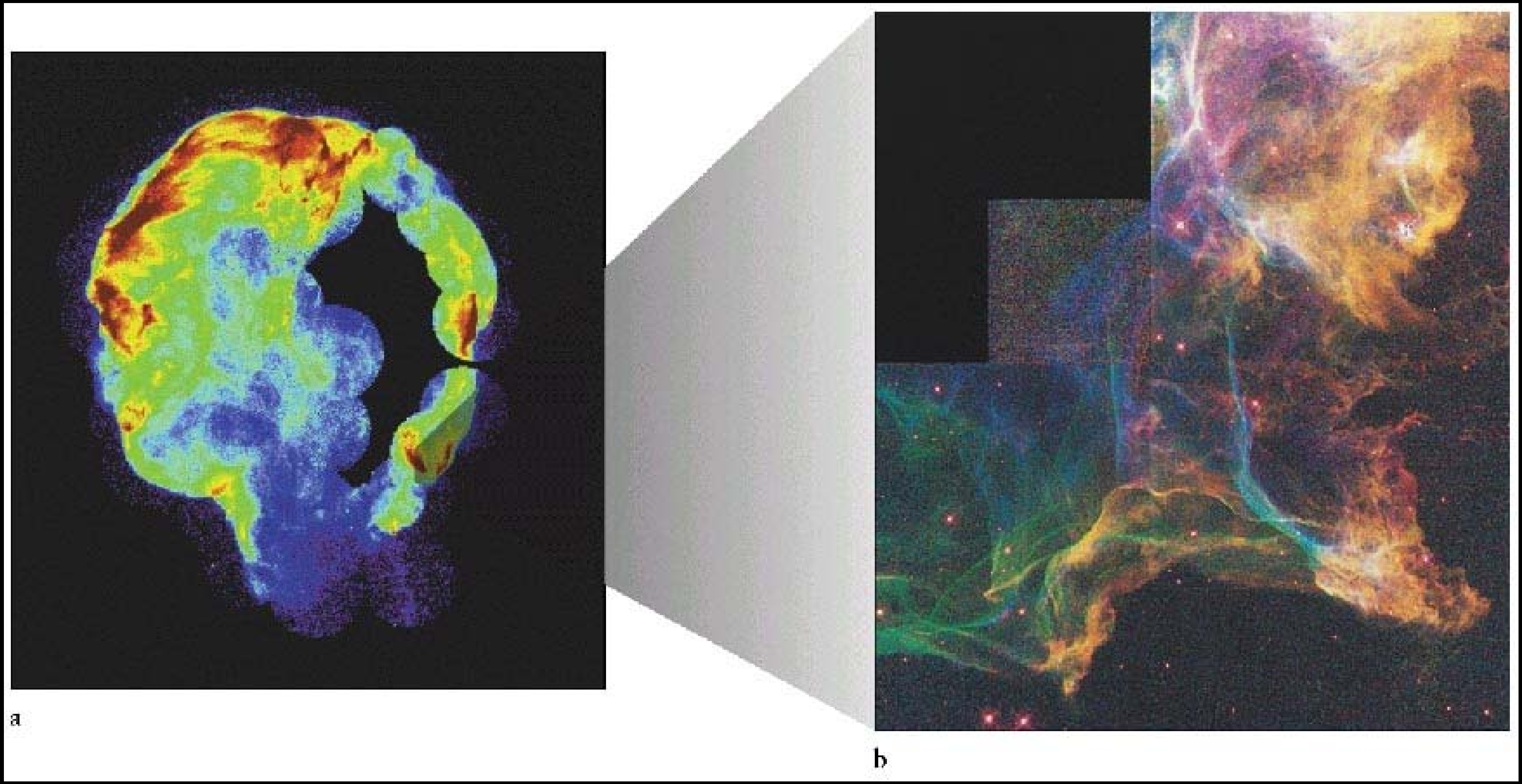
The only parts of the ISM with a high enough density and a low enough temperature for protostars to form are the dark nebulae. These larger of these dense regions are called *Barnard objects* and the smaller are called *Bok globules*.

Protostars form in cold, dark nebulae



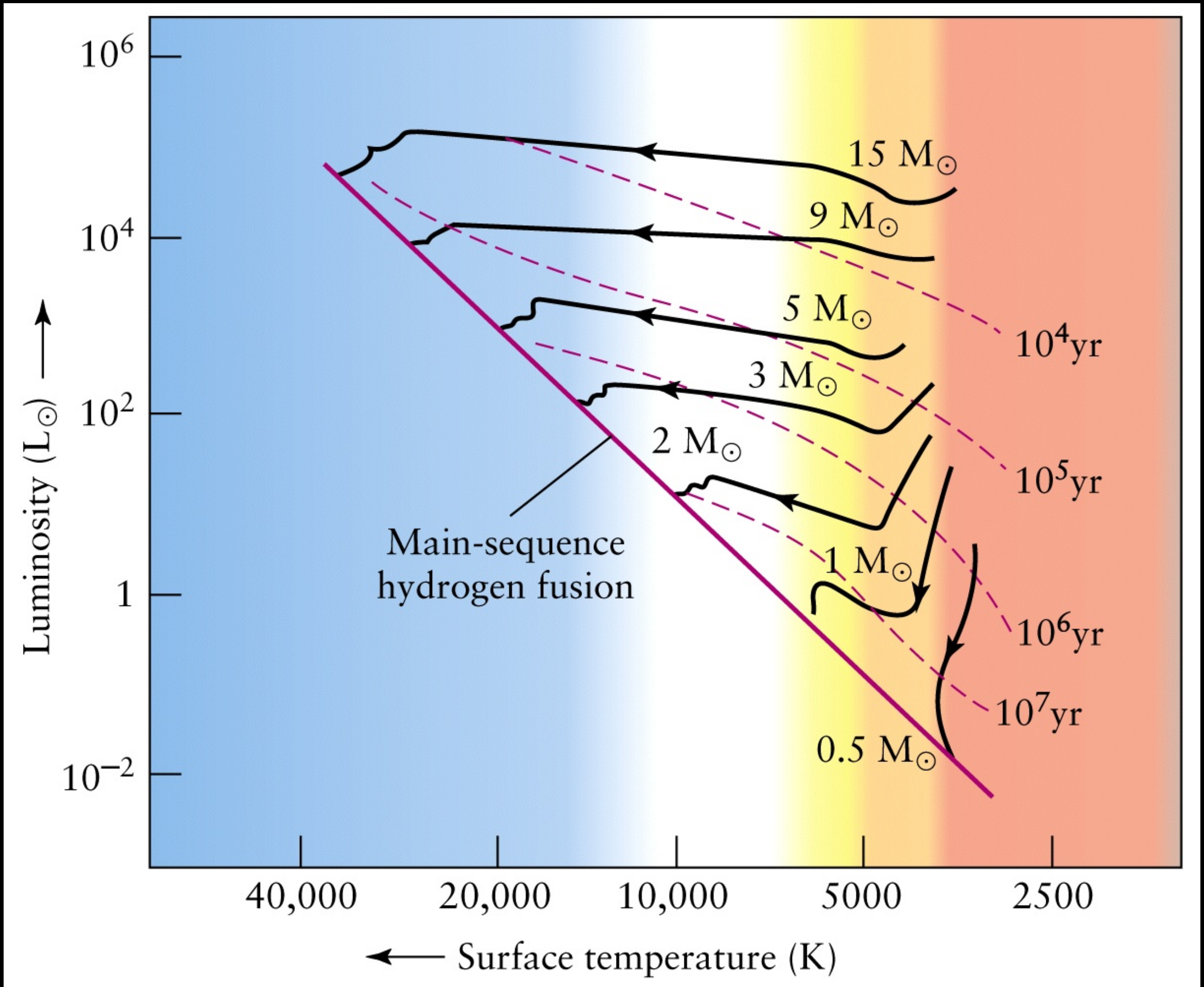
Visible (left) and infrared (right) views of the Orion nebula show new stars. These new stars can only been seen in IR because the protostar’s cocoon nebula absorbs most of the visible light.

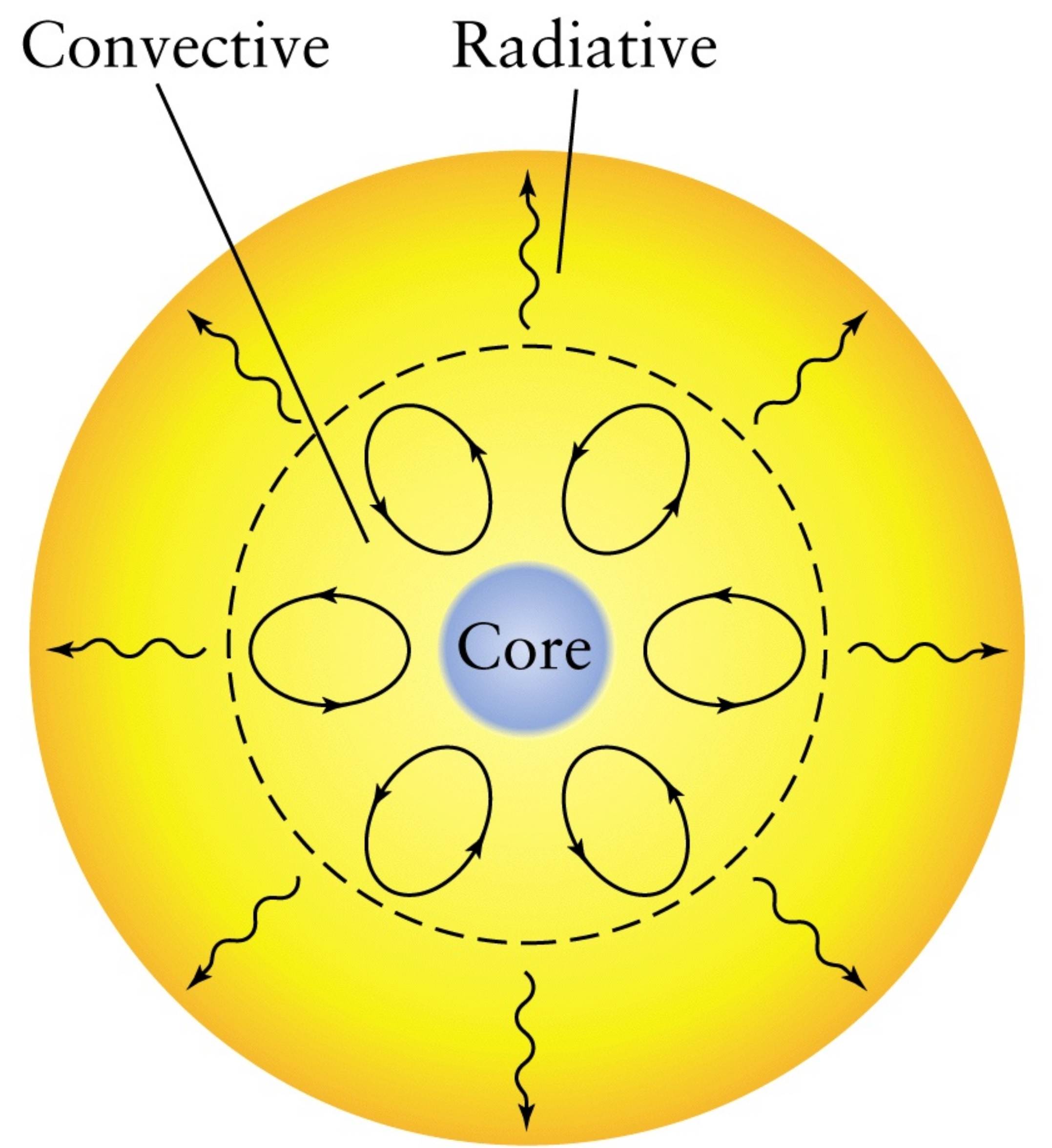
Supernovae compress the interstellar medium and can trigger star birth.



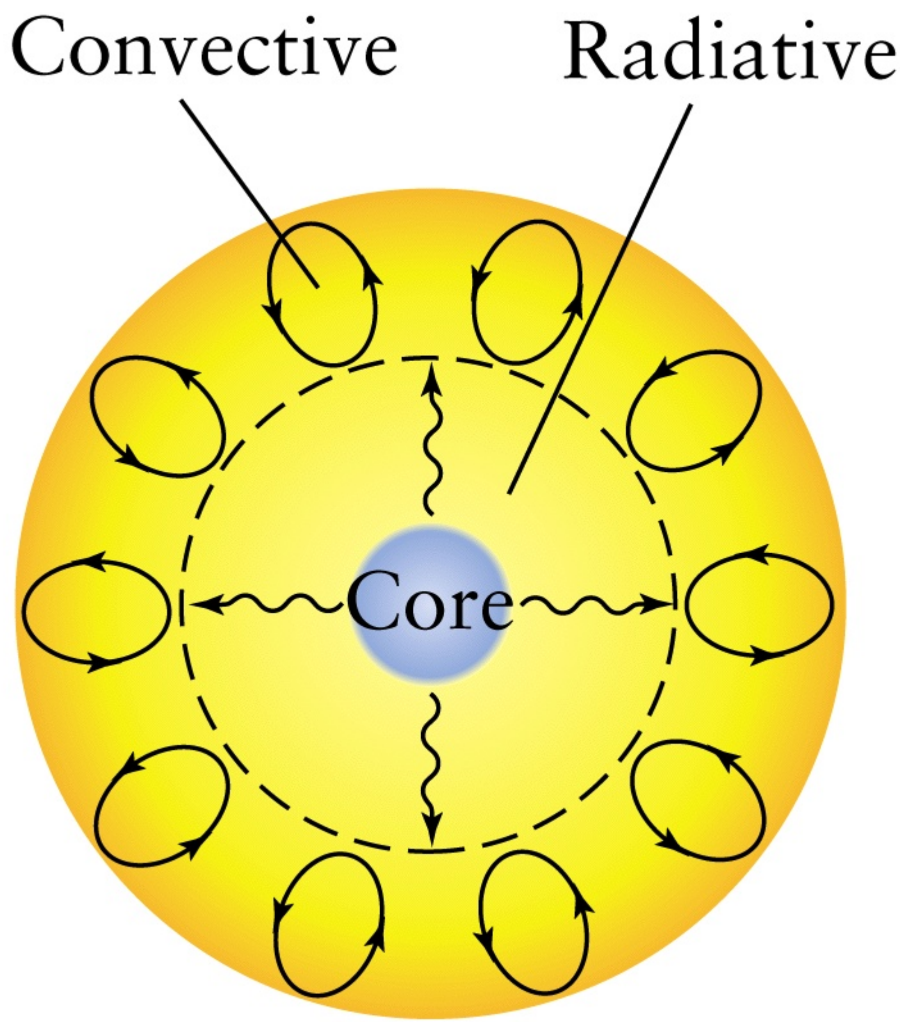
Supernovae are exploding stars. The remnants of such an explosion add material to the ISM and their shockwaves can initiate protostar formation.

Protostars evolve into main-sequence stars

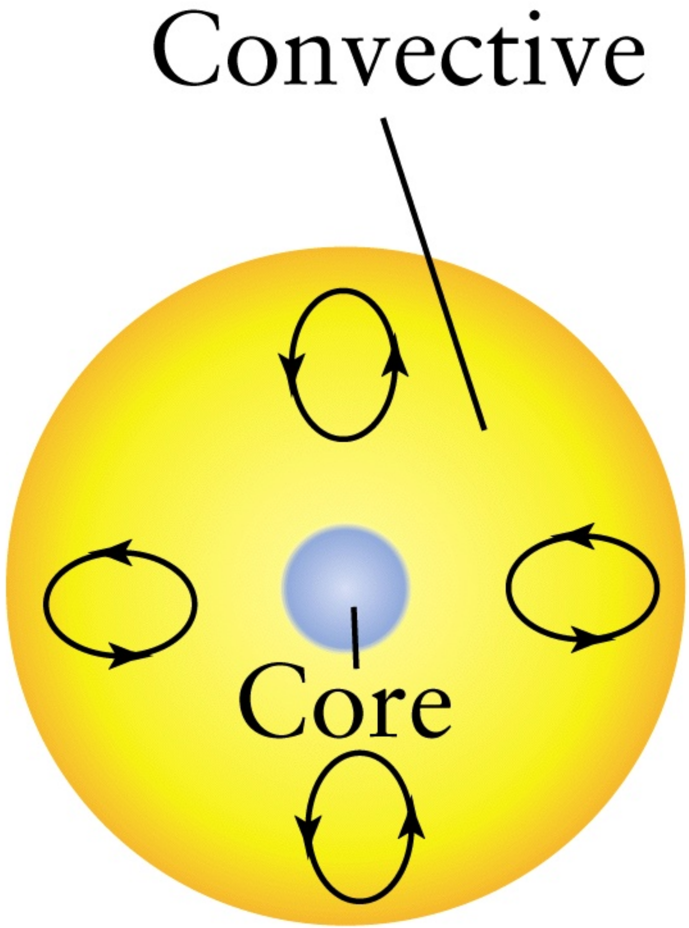




a Mass more than about 4 $M_\odot$

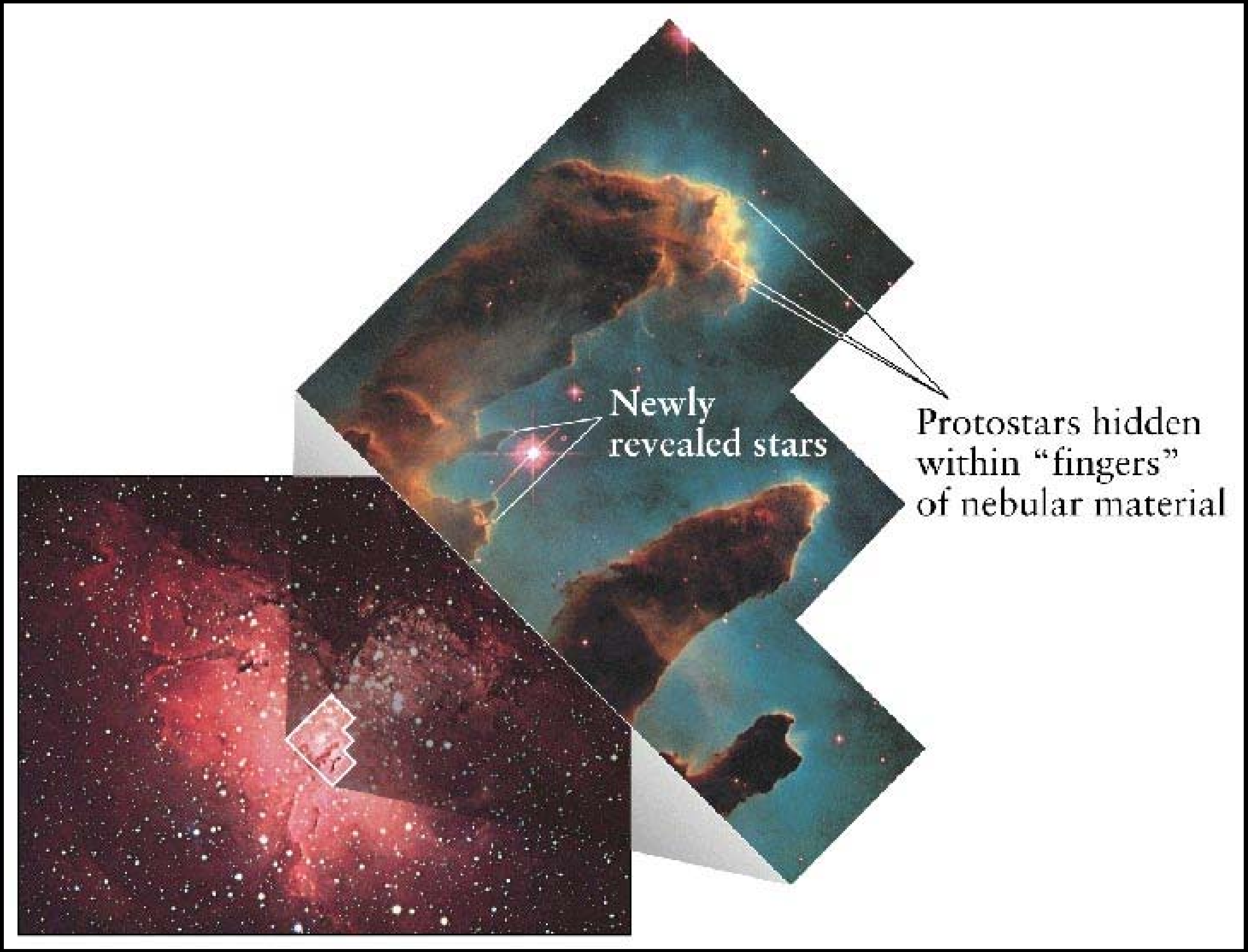


b Mass between about $4\ M_\odot$ and $0.8\ M_\odot$

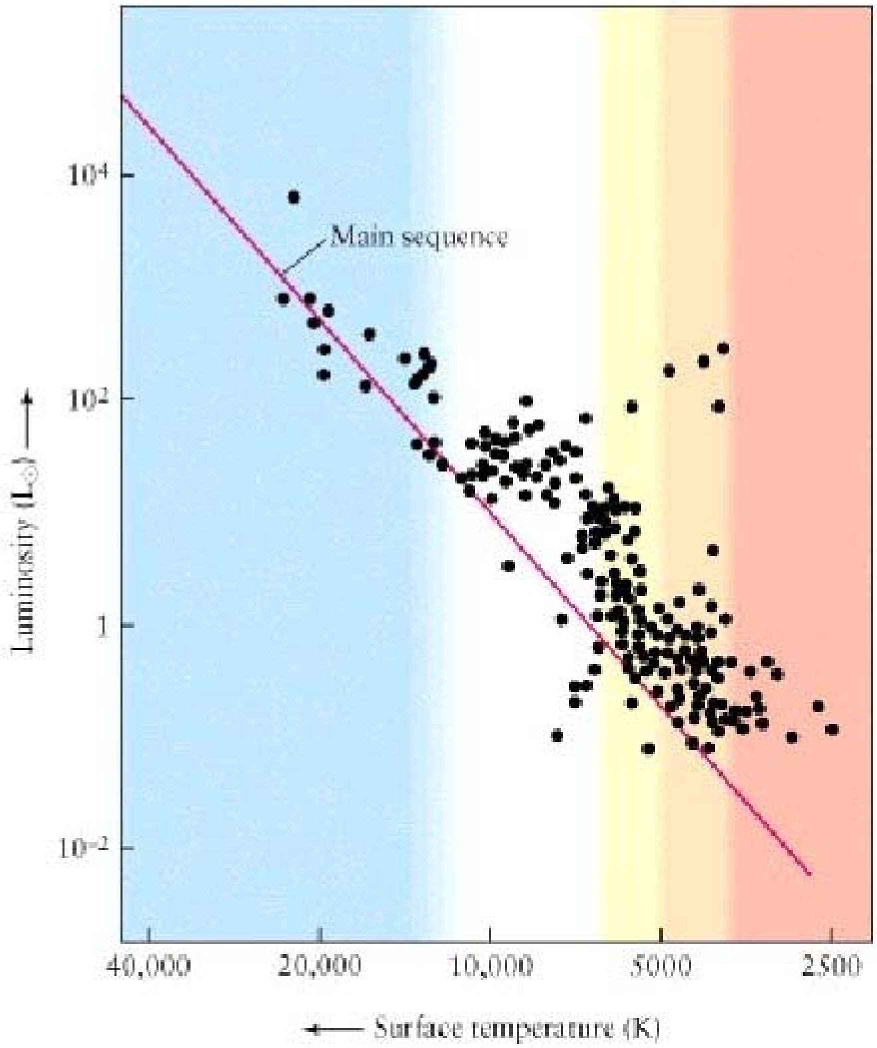


c **Mass less than $0.8\ M_{\odot}$**

Young star clusters give insight into star formation and evolution.



Plotting all the stars from a cluster on an H-R diagram reveals its age.



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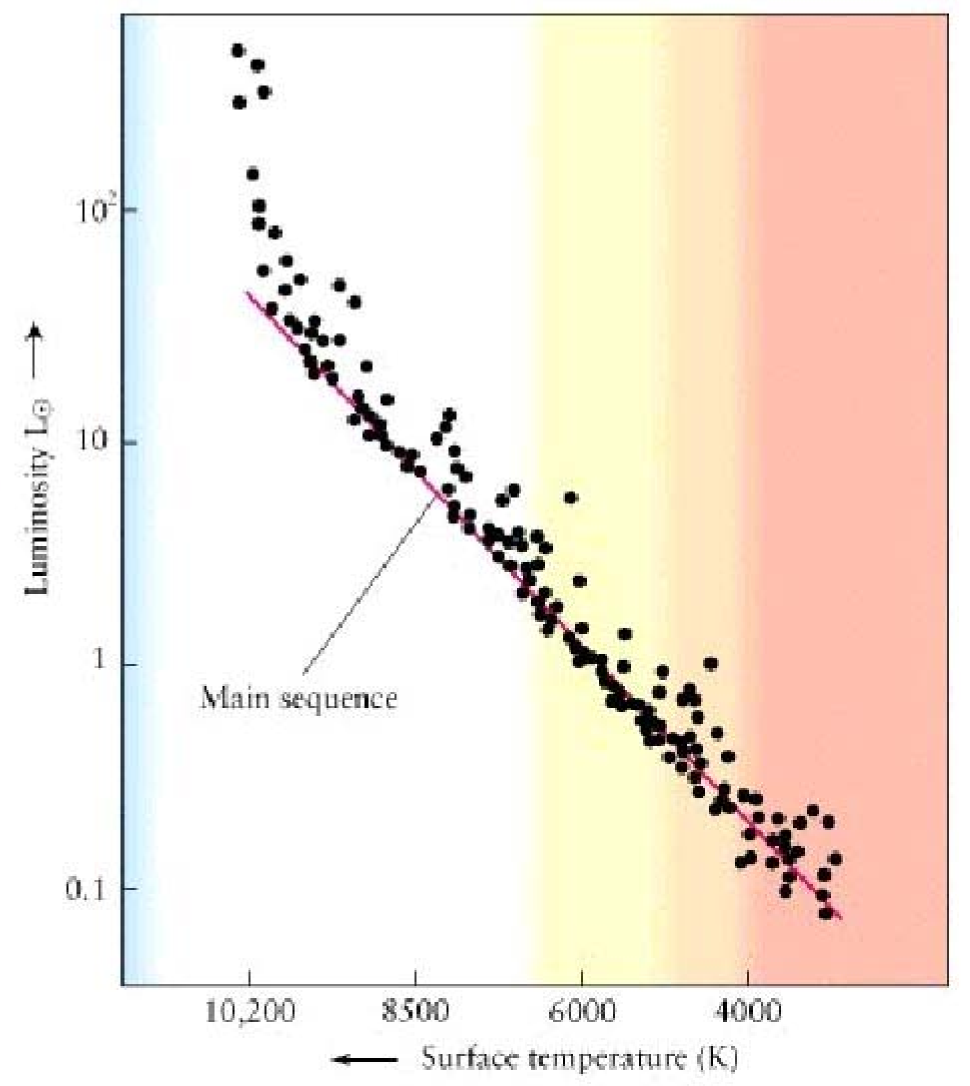
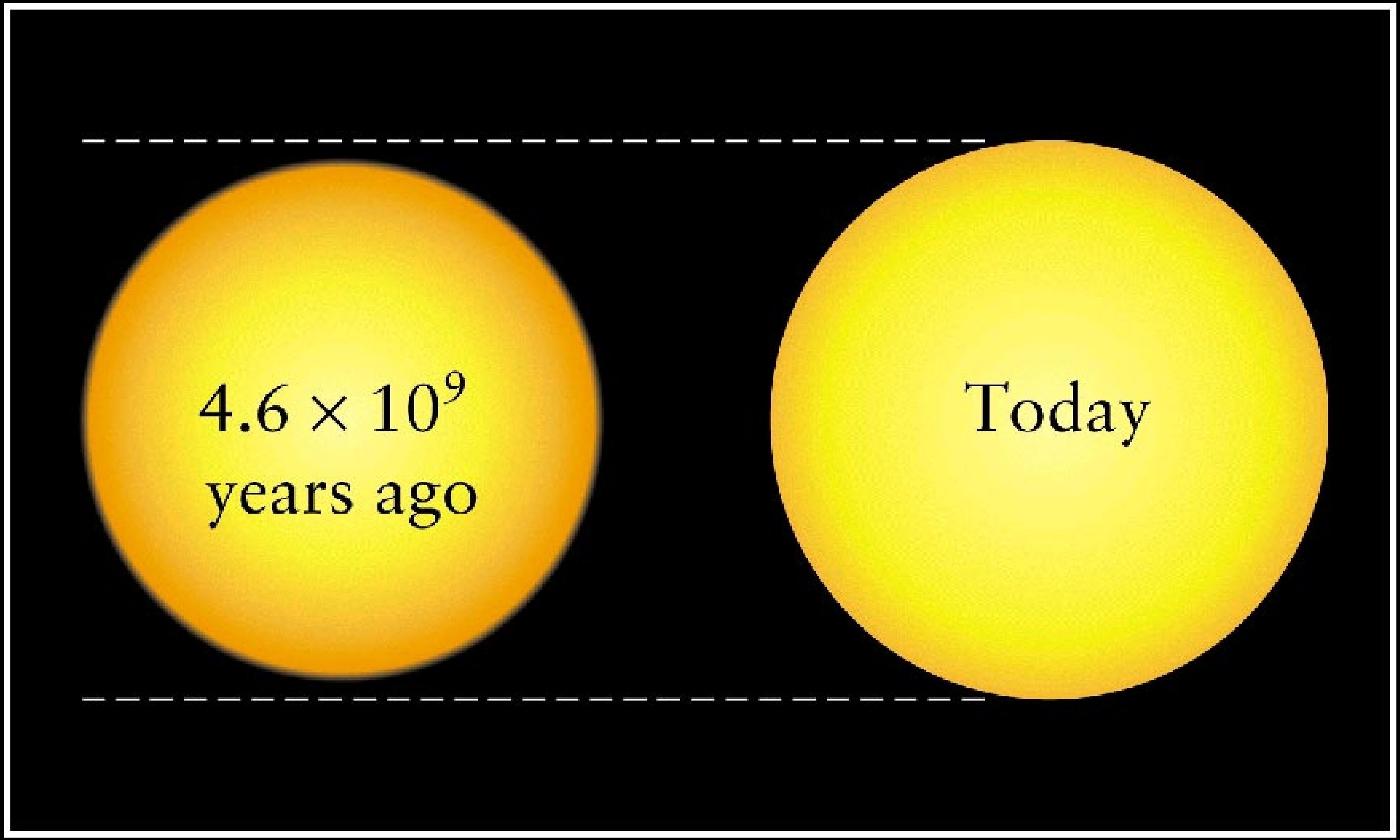
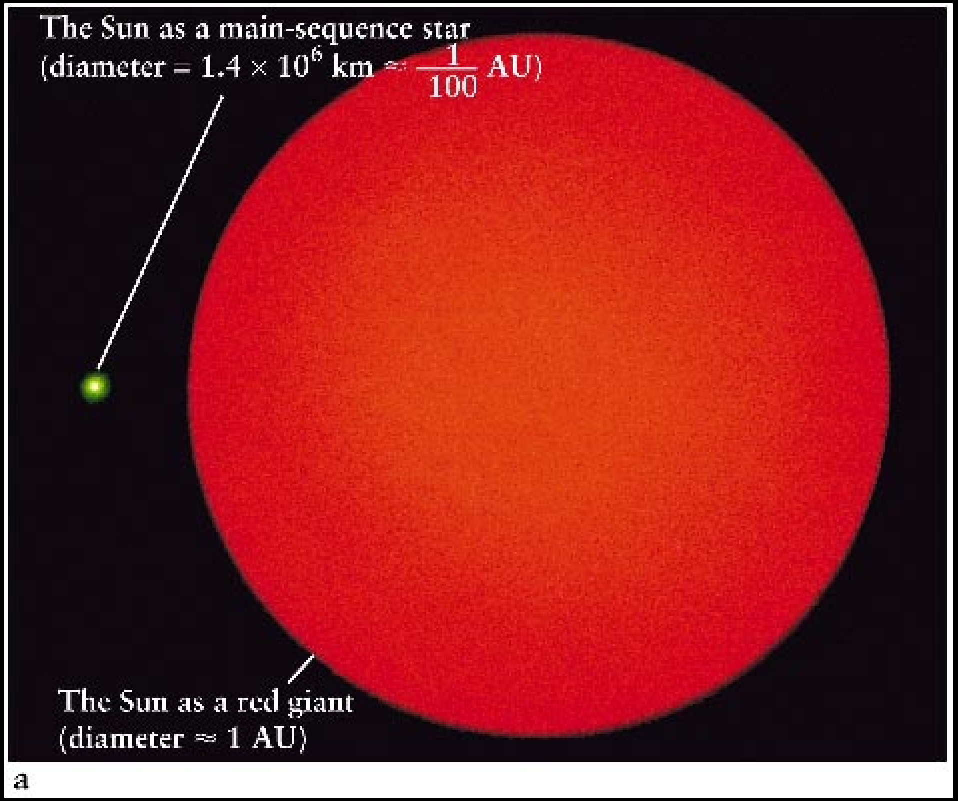




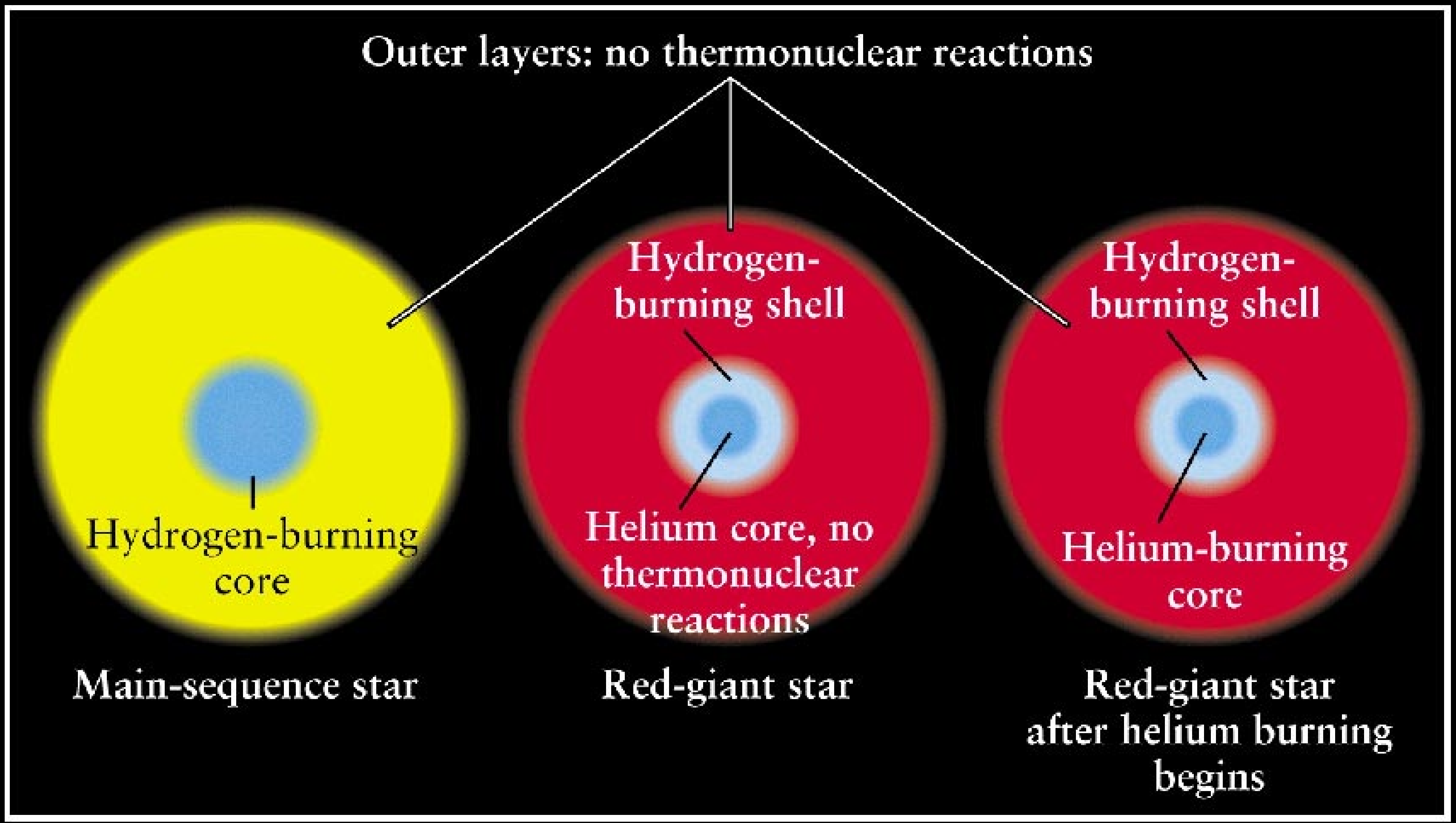
Over the past 4.6 billion years, the Sun’s luminosity has increased about 40% and this has caused the outer layers to expand by 6%.

When core hydrogen burning ceases, a main-sequence star becomes a red giant.

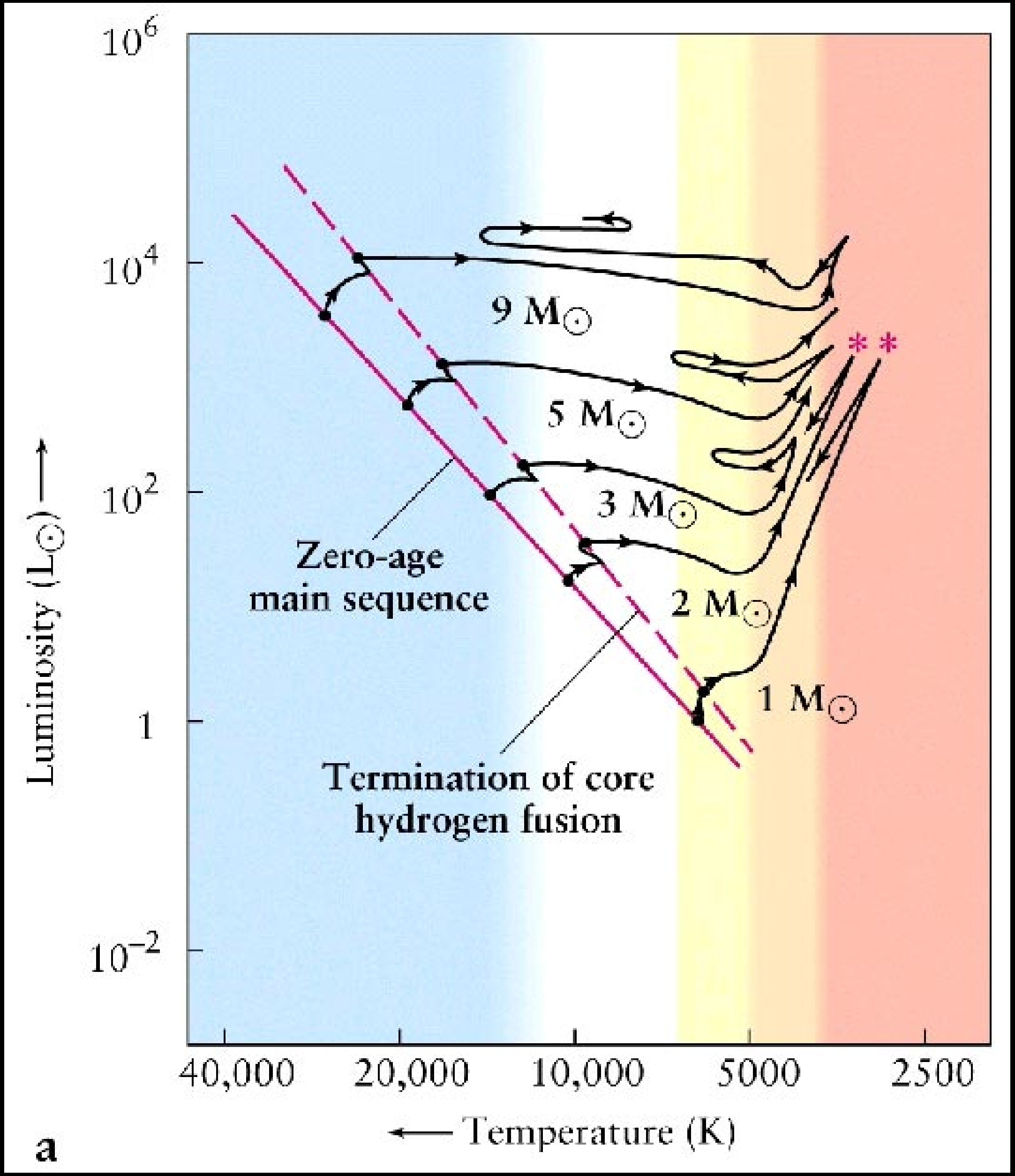
- When all of the hydrogen in the core has been depleted, the interior can no longer repel the inward pull of gravity.
- The core heats under pressure, causing the outer layers to expand and swell.
- These outer layers get farther from the hot core and cool, resulting in a red color.



Helium burning begins at the center of a red giant.



H-R diagrams and observations of star clusters reveal how red giants evolve.



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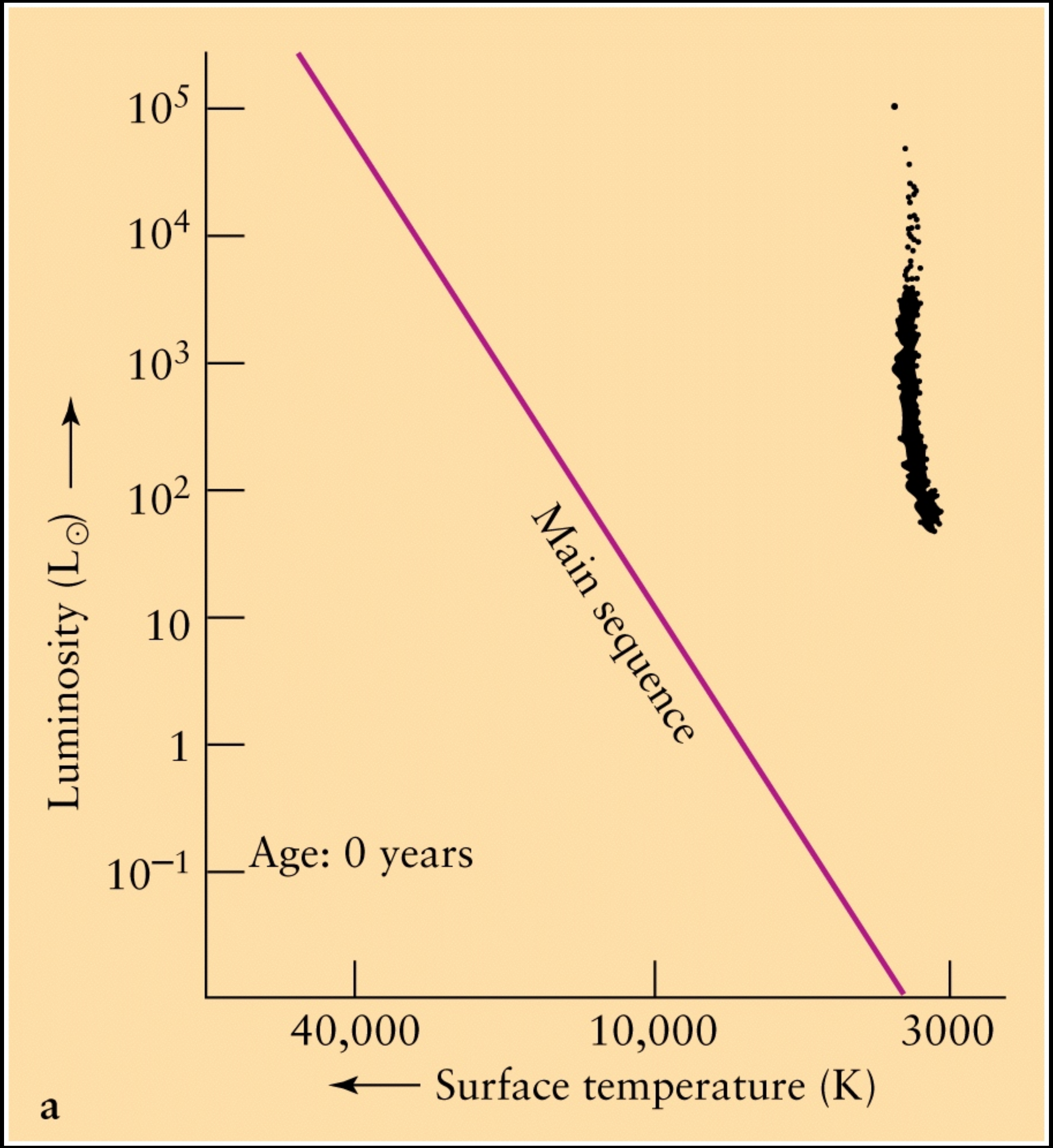

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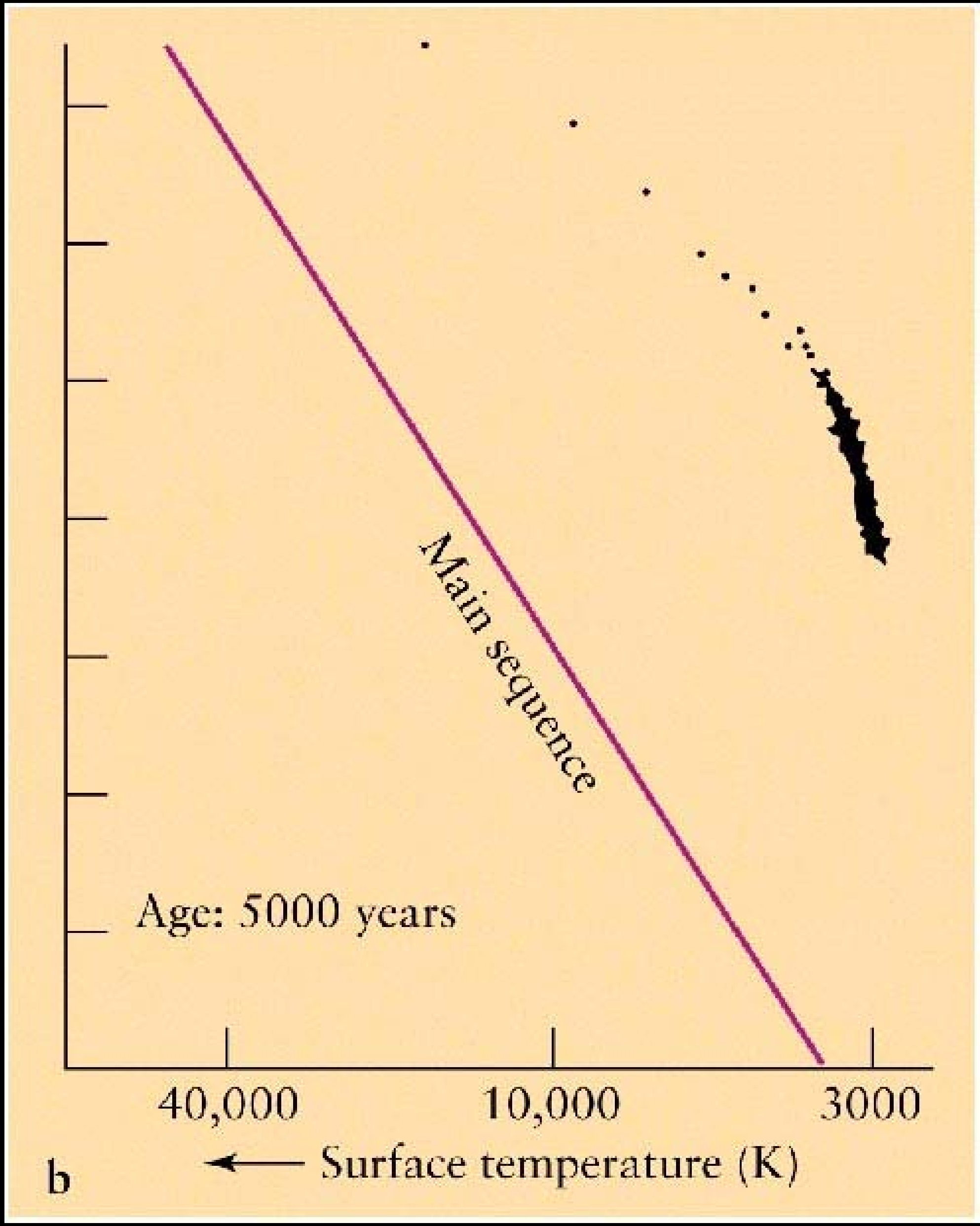

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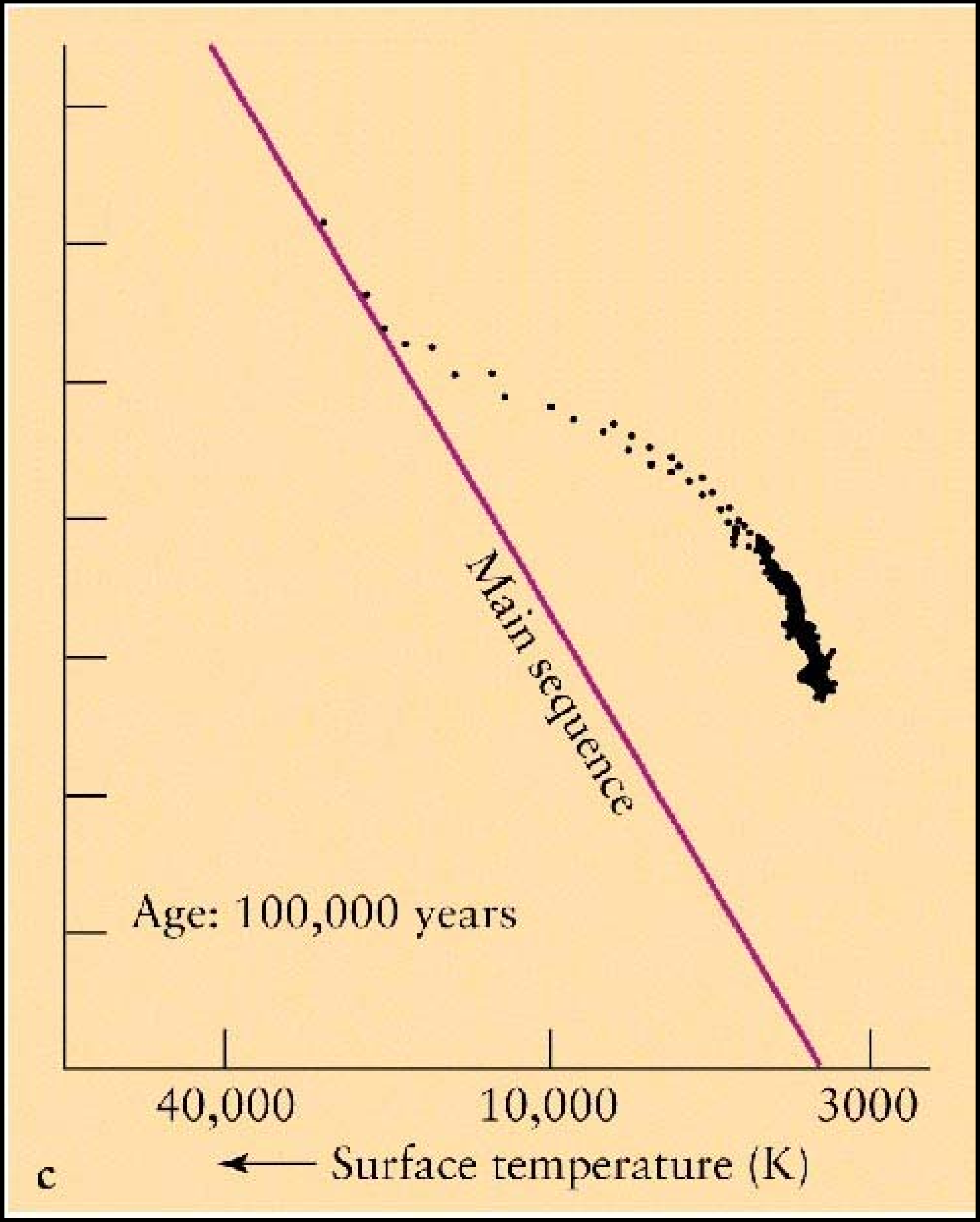

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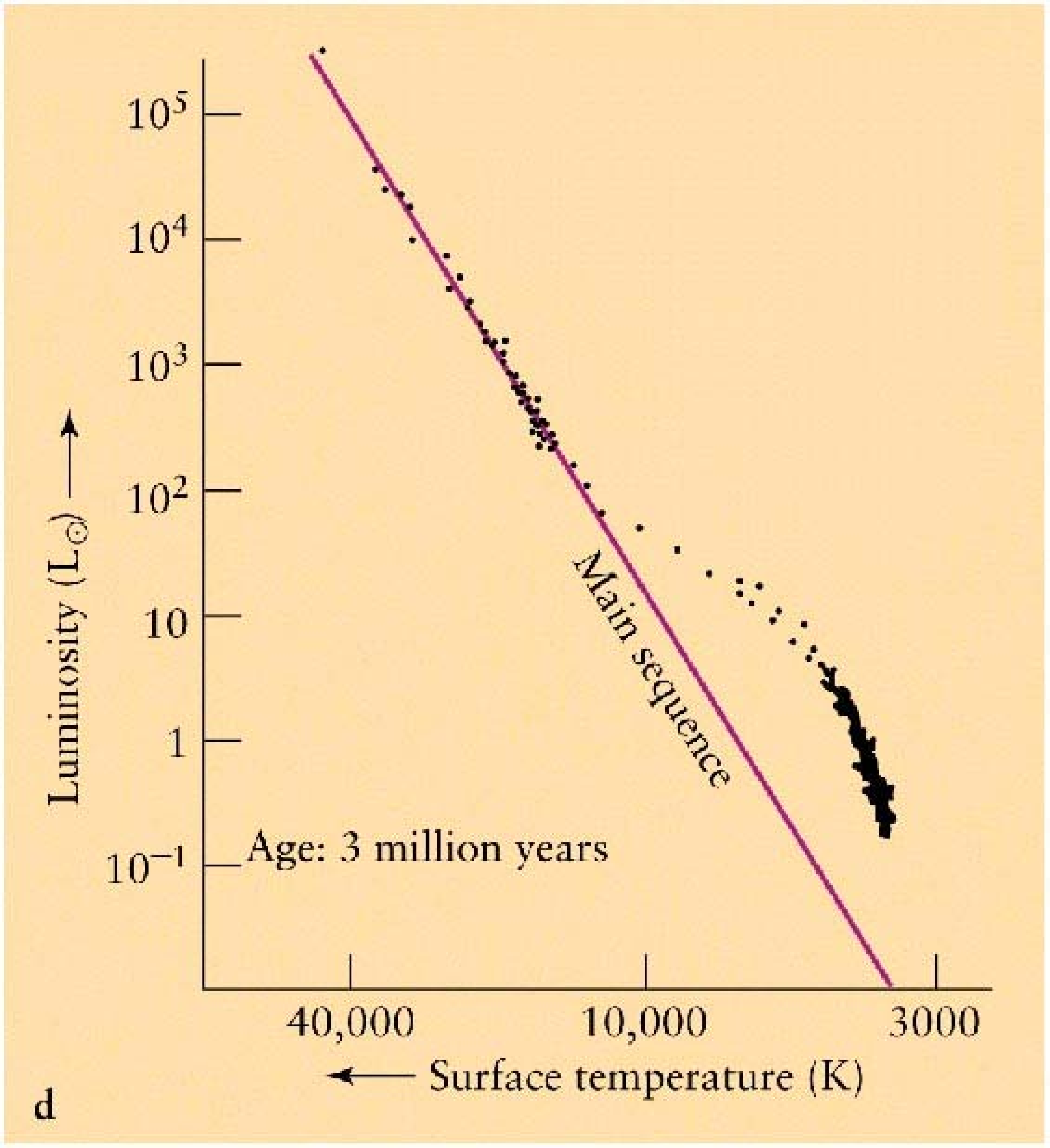

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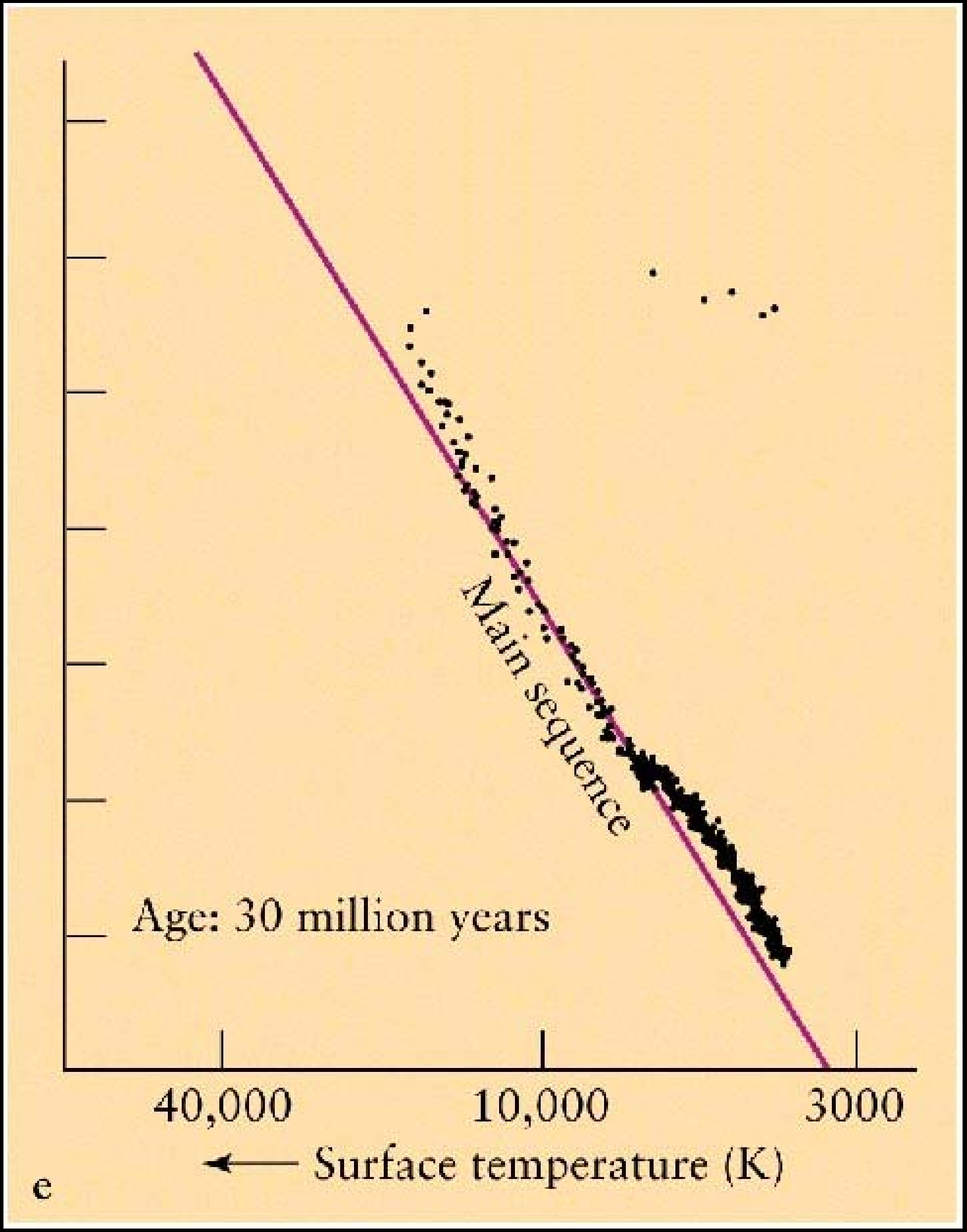

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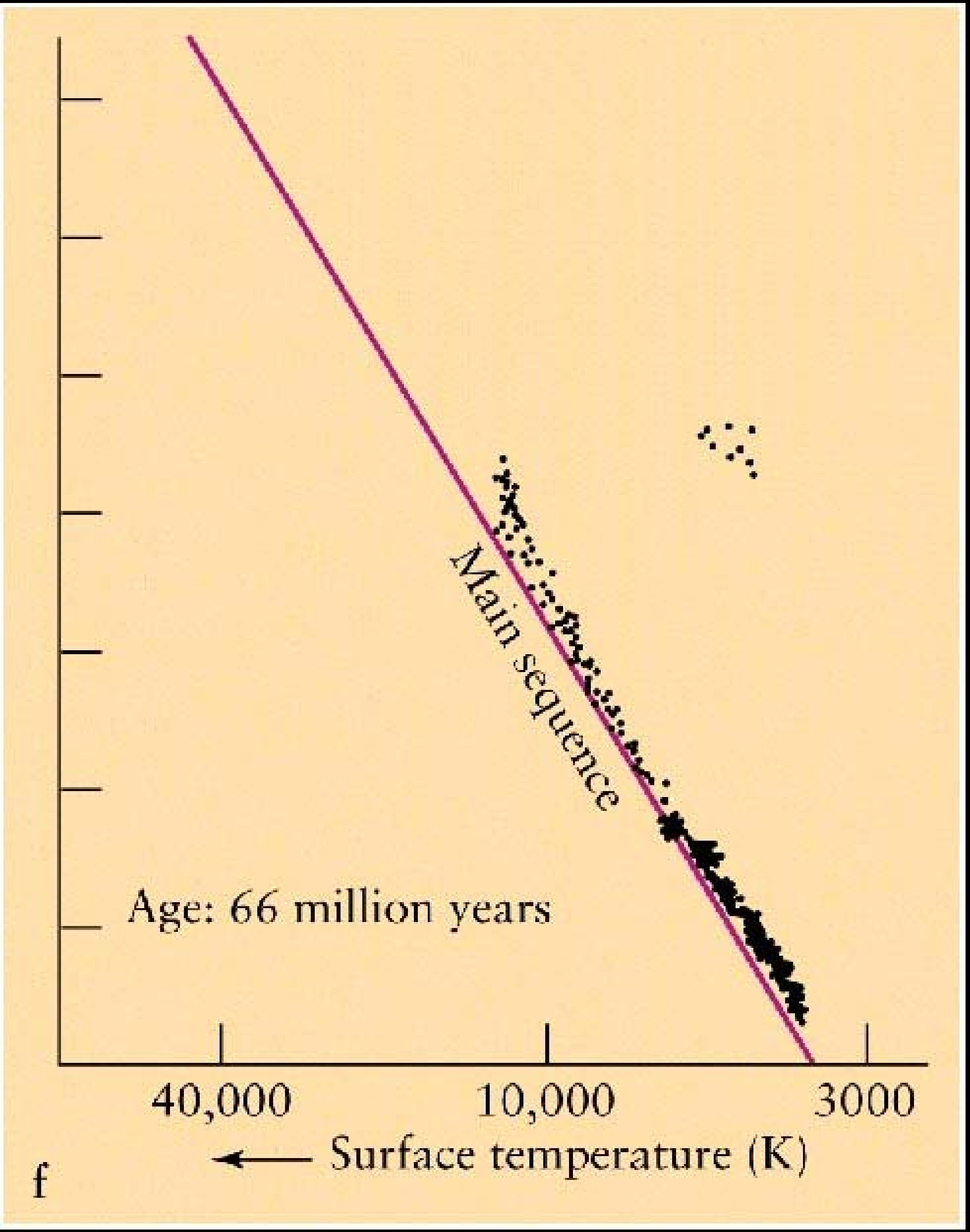

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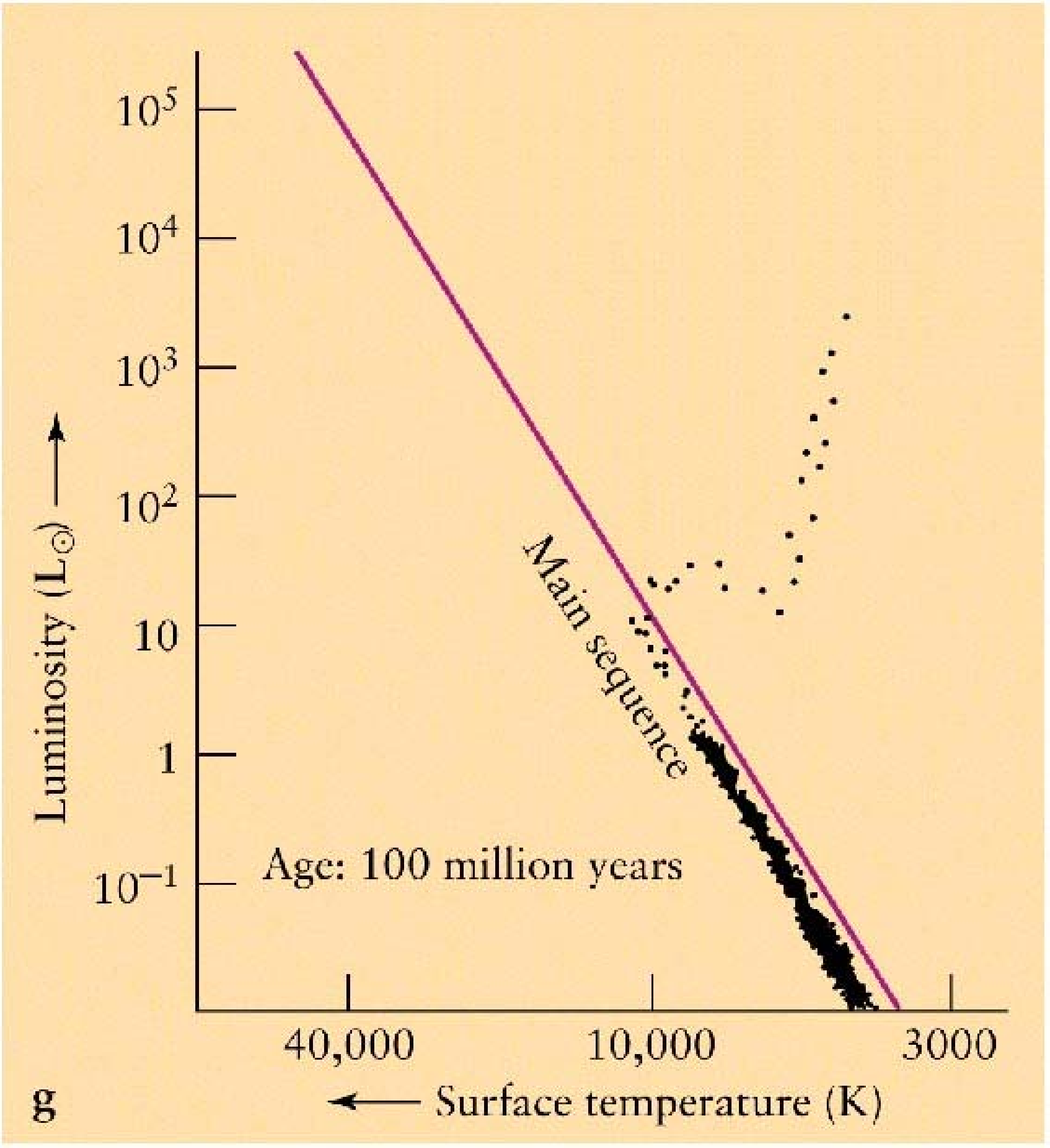

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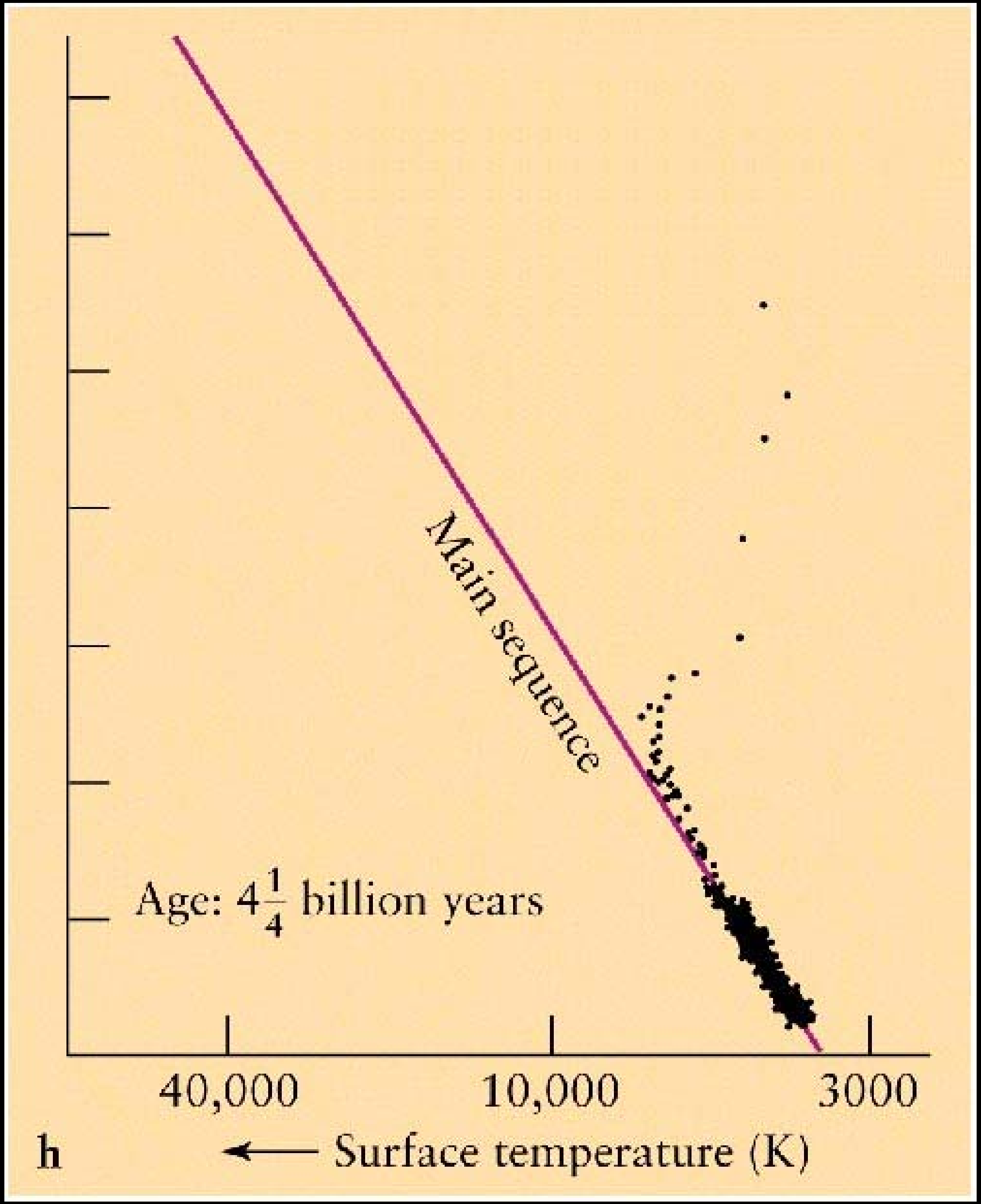
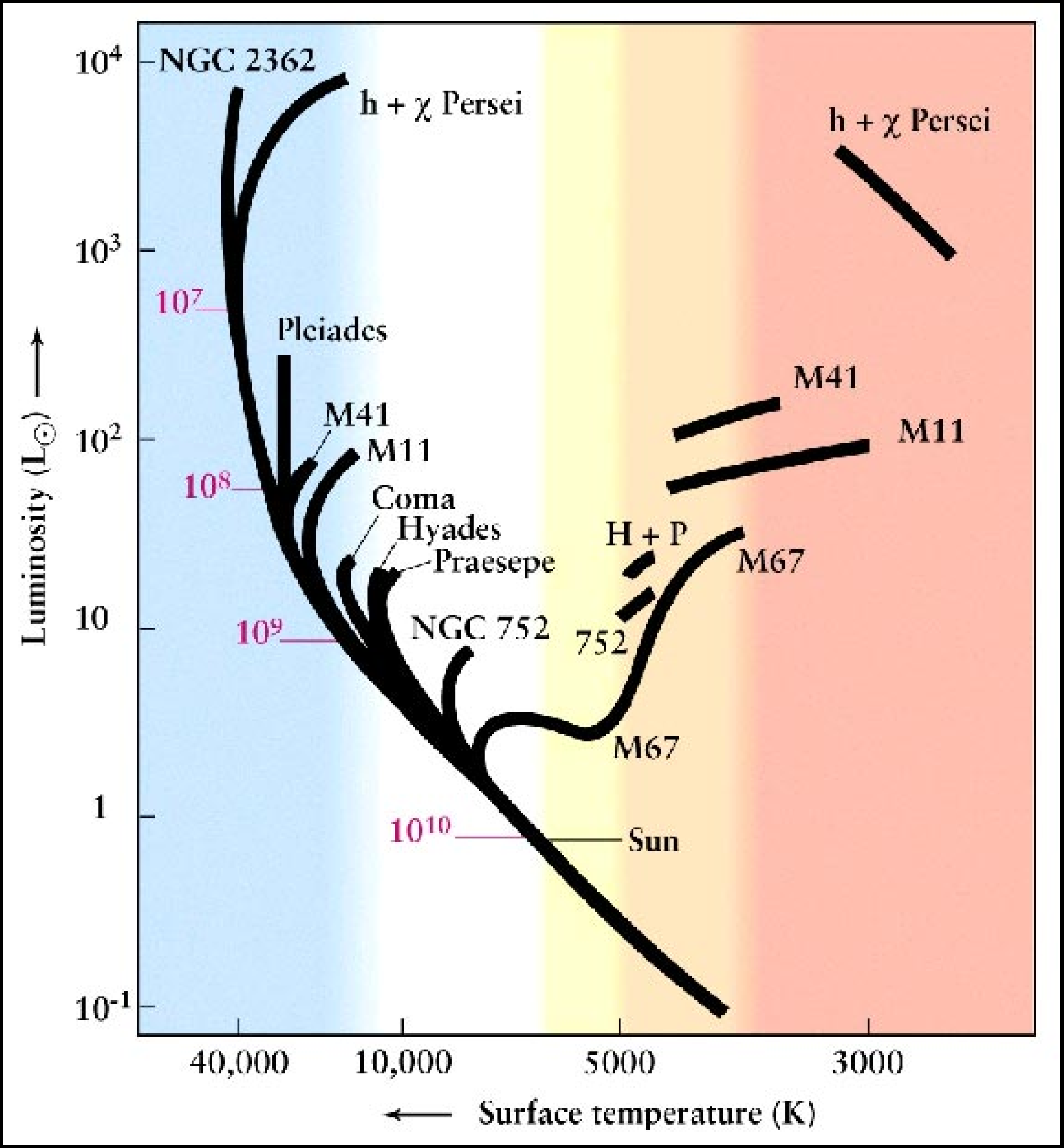
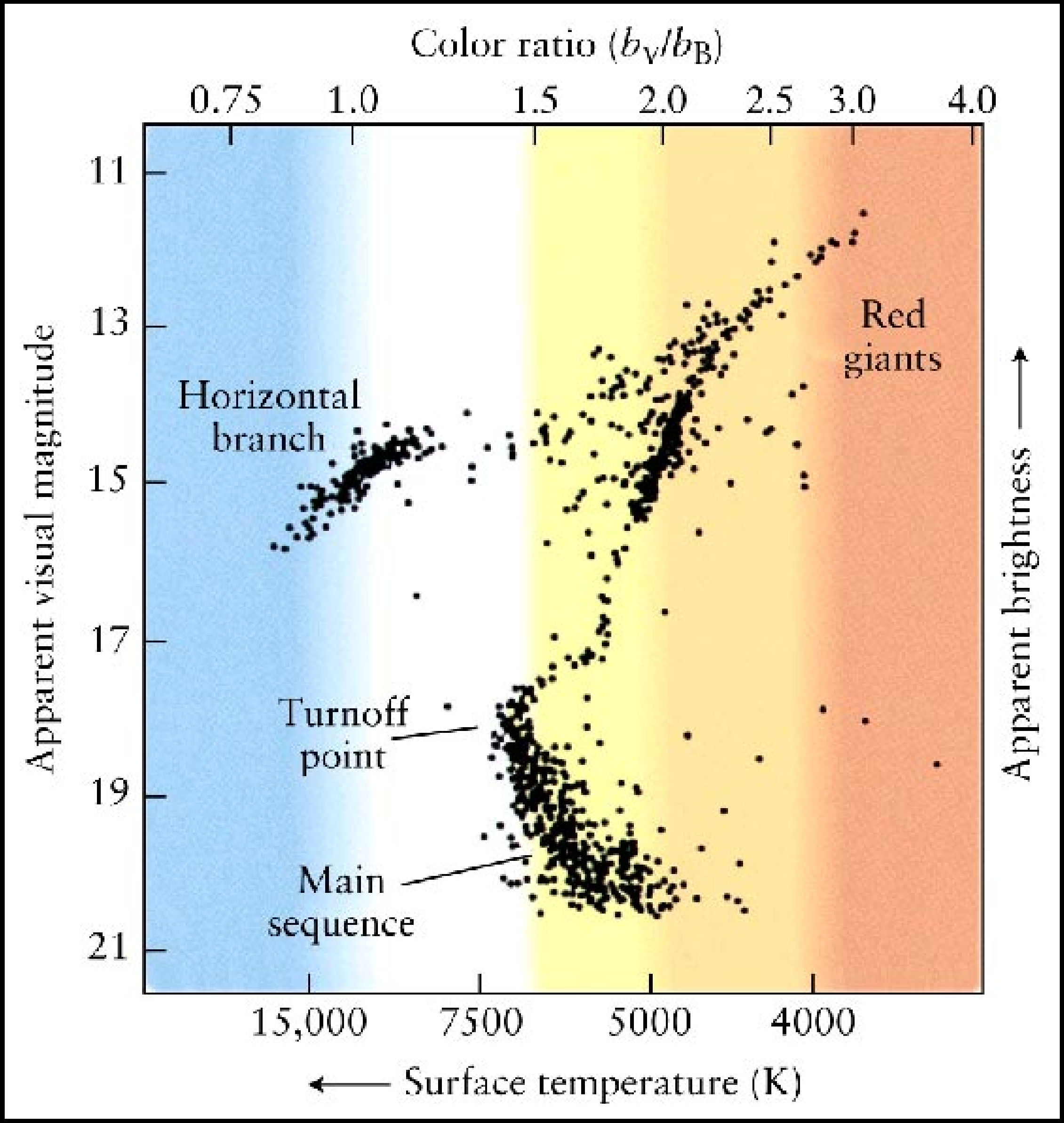




HR diagram for young, open star clusters. The age can be determined by the *turn-off point* because the most massive stars mature first.

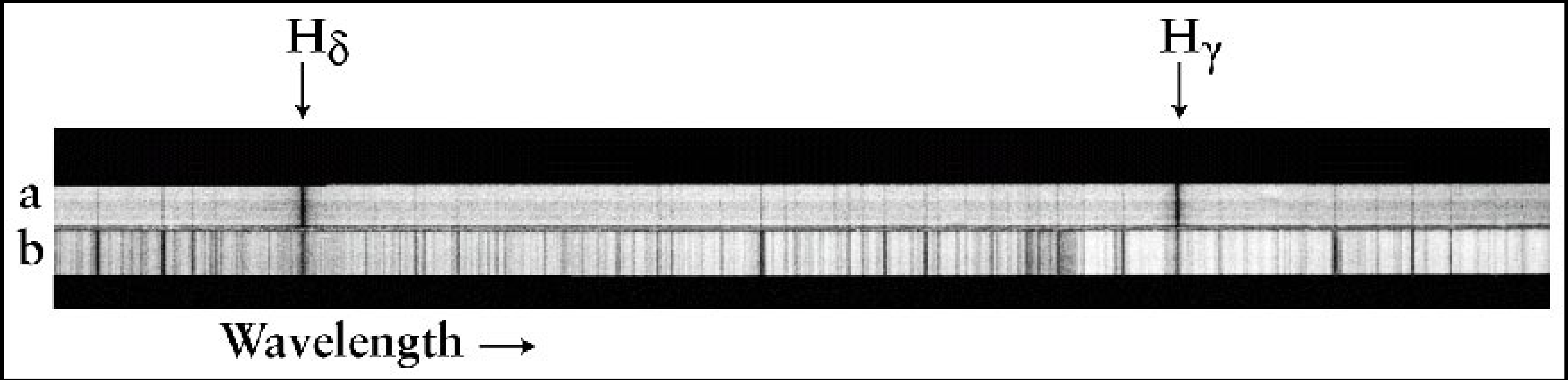
The farther left the *turn-off point*, the younger the cluster.



HR diagrams for ancient globular clusters show a group of stars that have both stable core helium burning and shell hydrogen burning.

These stars are called *horizontal branch stars* and eventually will move back to the red-giant region.

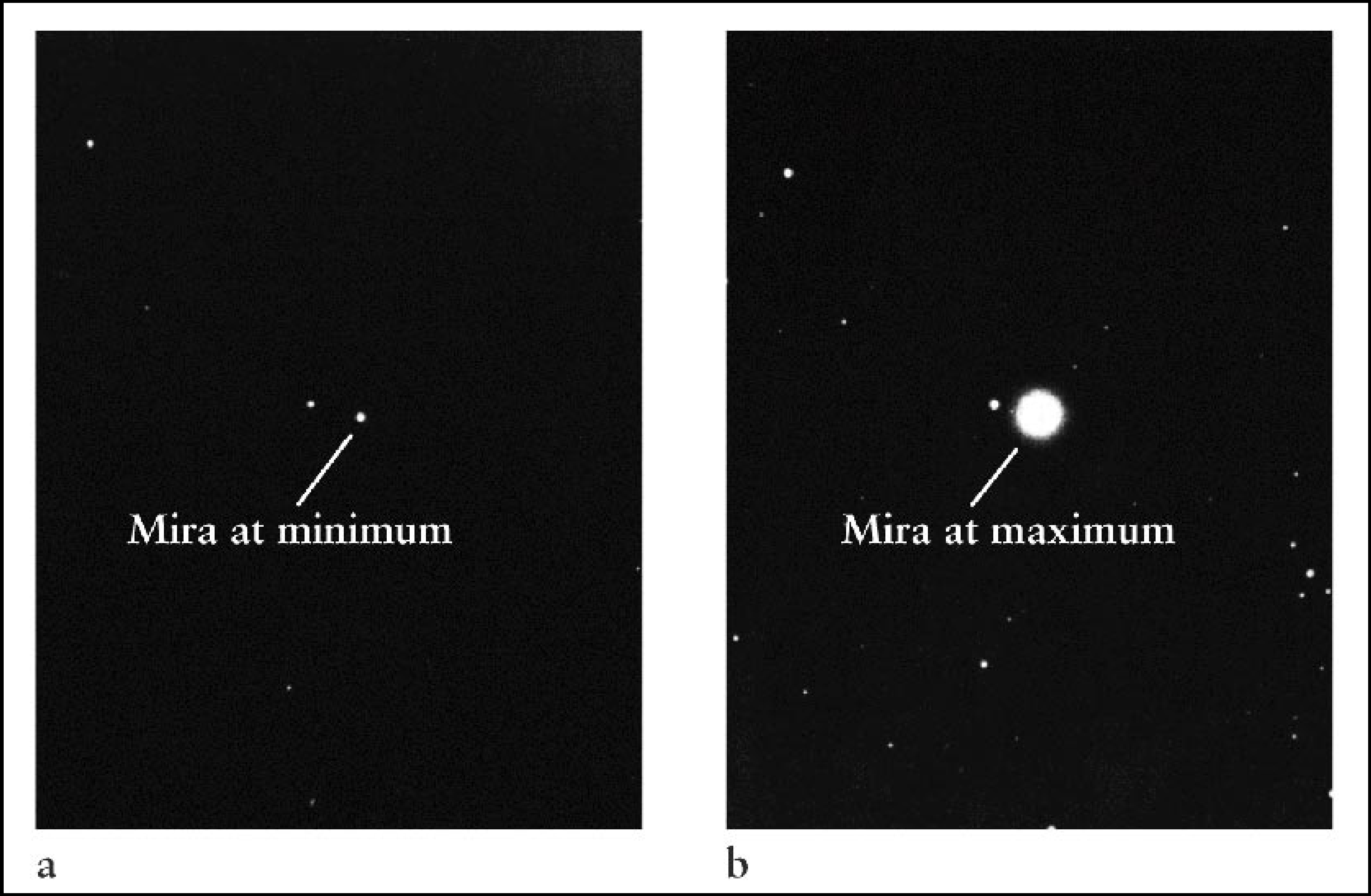
Stellar evolution has produced two distinct populations of stars.



- Population I stars: Young, disk stars, like the Sun, that have numerous absorption lines in addition to hydrogen and helium (metal rich). Formed from debris from earlier stars.
- Population II stars: Old halo stars, like those in distant globular clusters, that are metal poor.

Metal rich stars are stars that have prominent lines of elements in addition to hydrogen & helium.

Many mature stars pulsate



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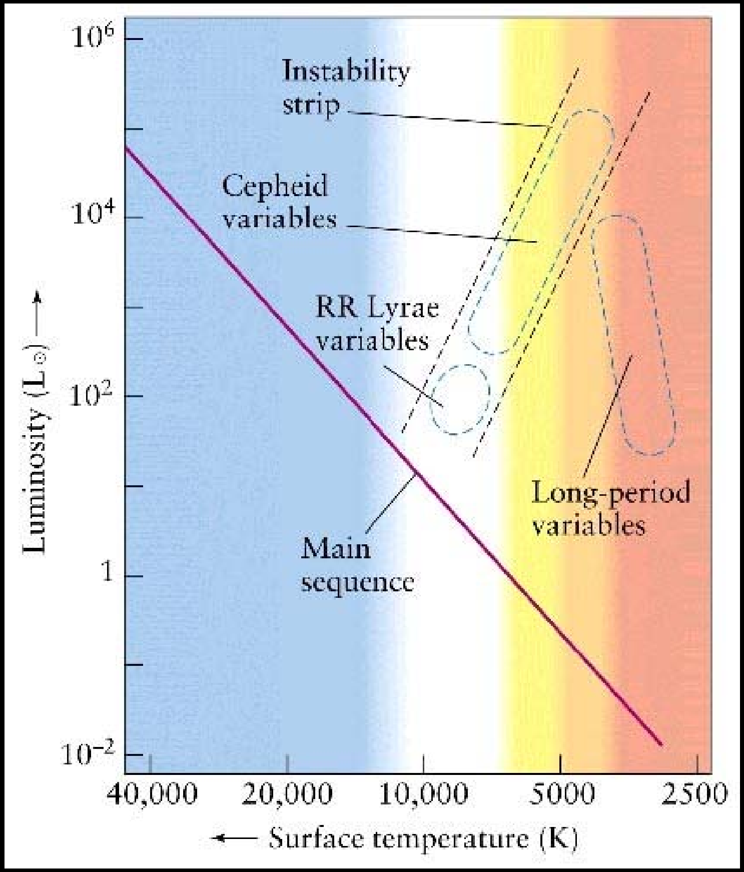
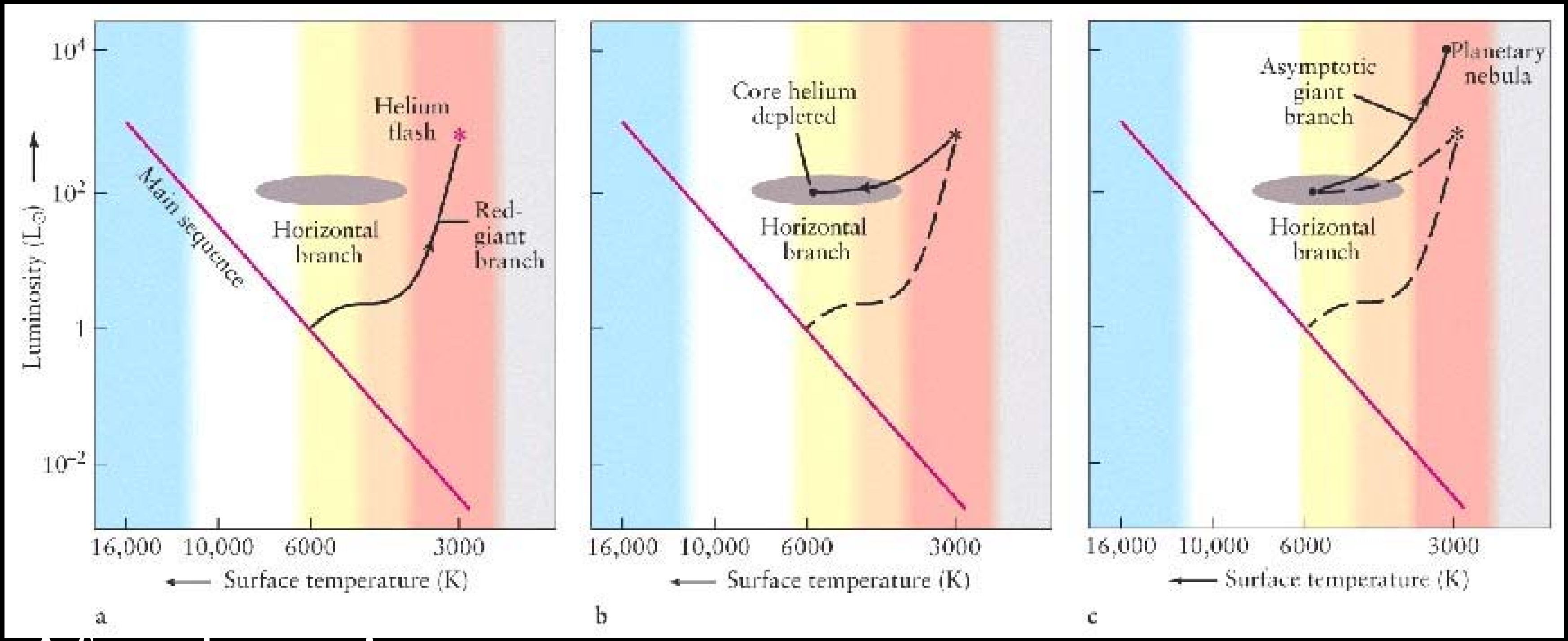


Pulsating variable stars in the *instability strip* that occur when stars are no longer in hydrostatic equilibrium.

- RR Lyrae variables
  - Small stars that have periods less than 24 hrs.
- Cepheid variables
  - Have periods between 1 and 100 days.
- Mira variables
  - Large stars that have periods more than 100 days.

Low-mass stars go through two distinct red-giant stages.



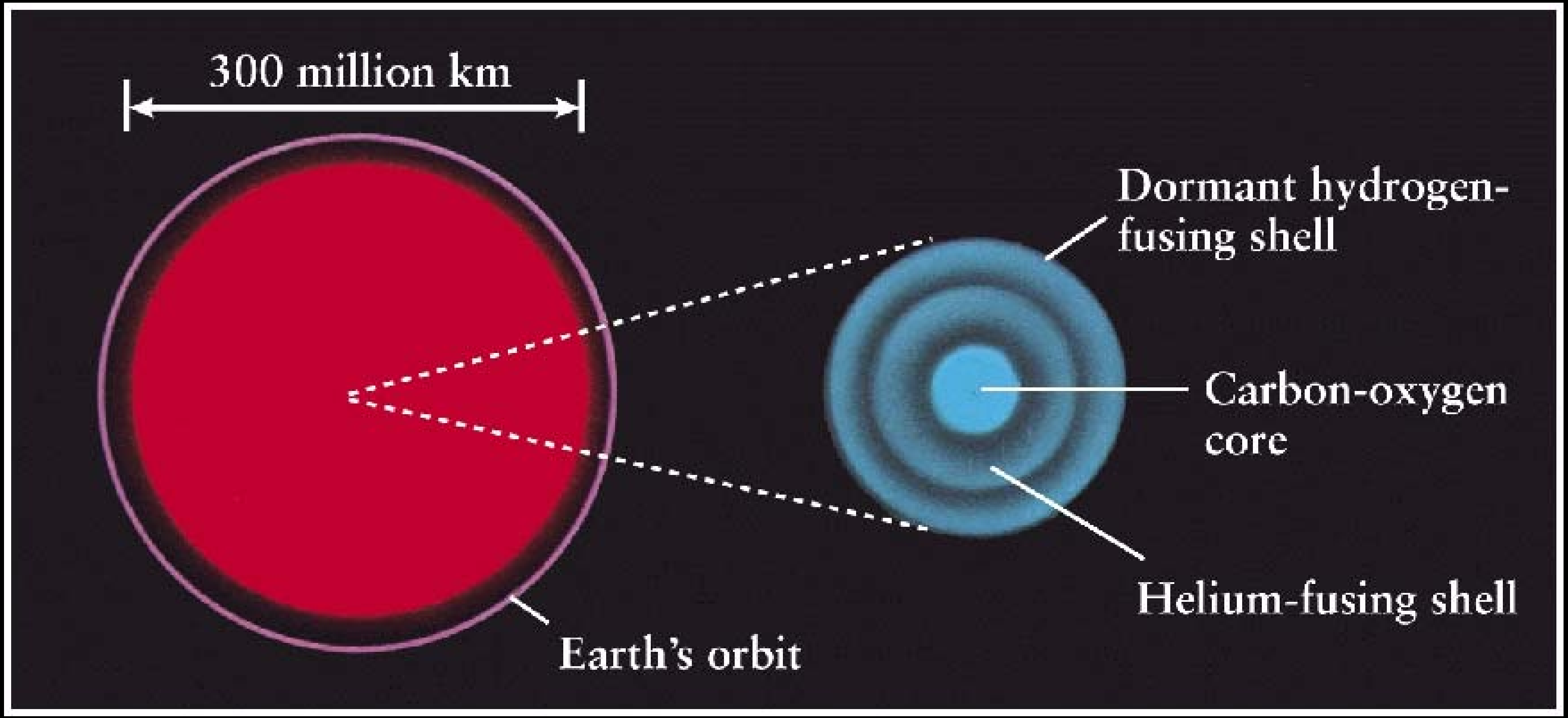
After the main-sequence

•Red-giant phase

Then stabilize in the horizontal branch

•Asymptotic giant branch (AGB phase)

Structure of an Old, Low-Mass AGB Star



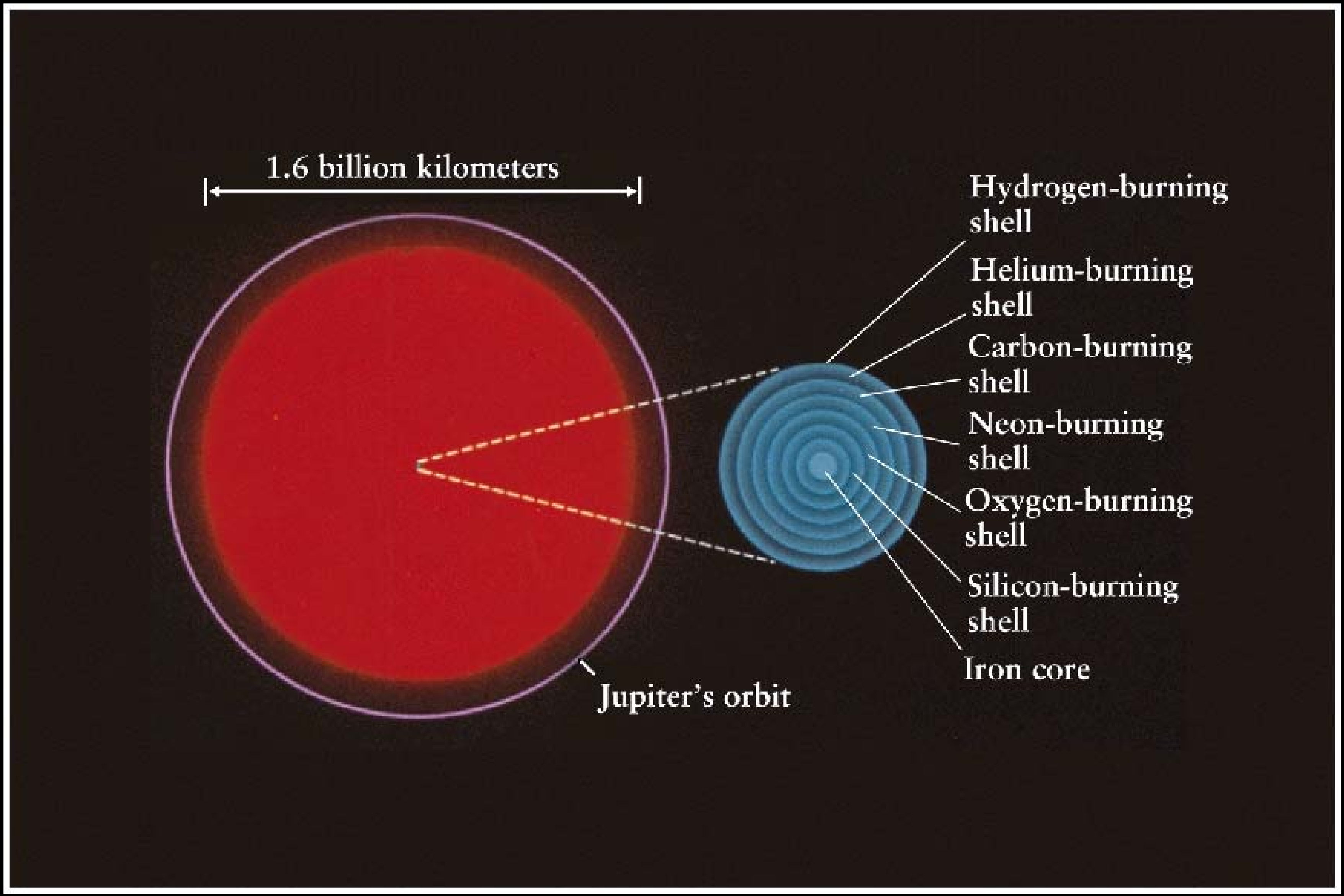
Low-mass stars die by gently ejecting their outer layers, creating planetary nebulae.

The aging AGB star first ejects a doughnut-shaped cloud of gas and dust.

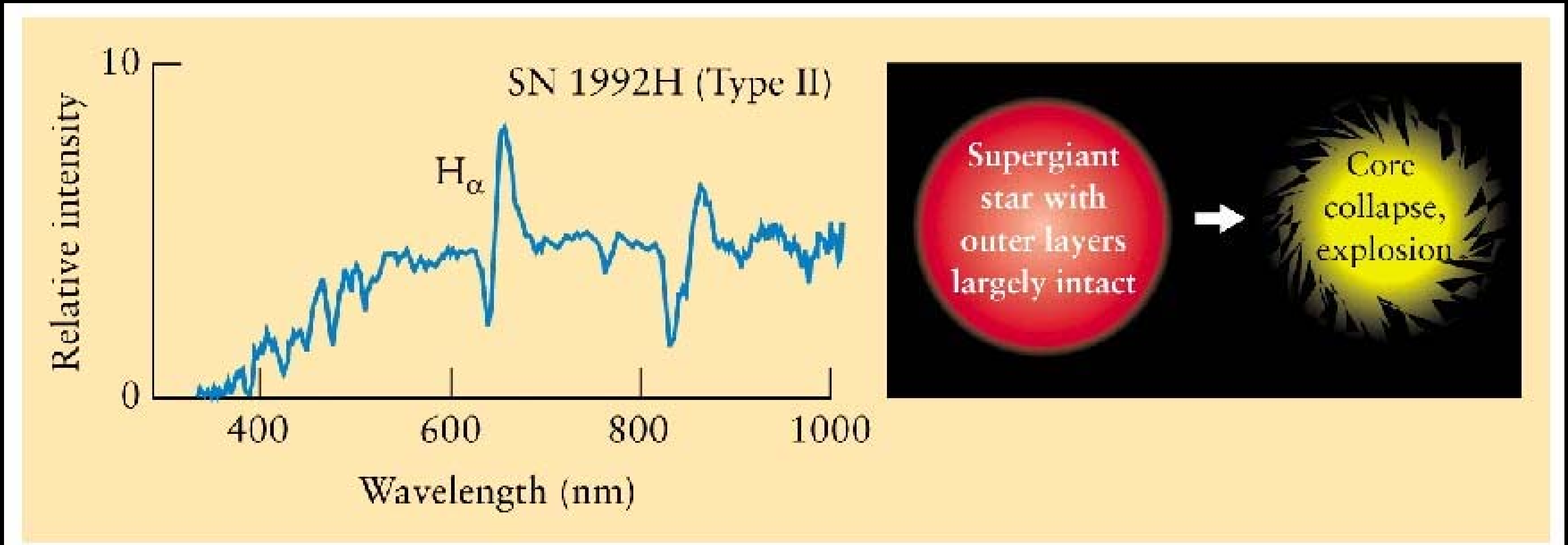
The star then ejects gas from its entire surface, but the doughnut blocks this outflow and channels it into two opposite directions.

The old stellar core remains in the center.

High-mass stars create heavy elements in their cores.



When iron builds up in the core, thermonuclear fusion ceases, the star implodes, and high-mass stars violently blow apart in supernova explosions.



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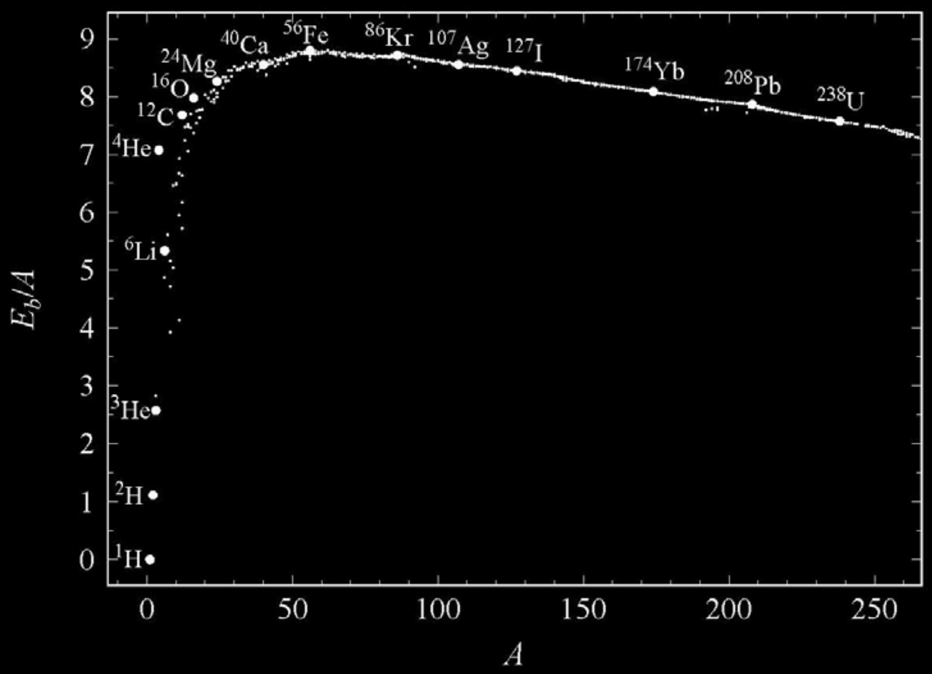
When a single star goes supernova, it is called a type II supernova.

Timescales

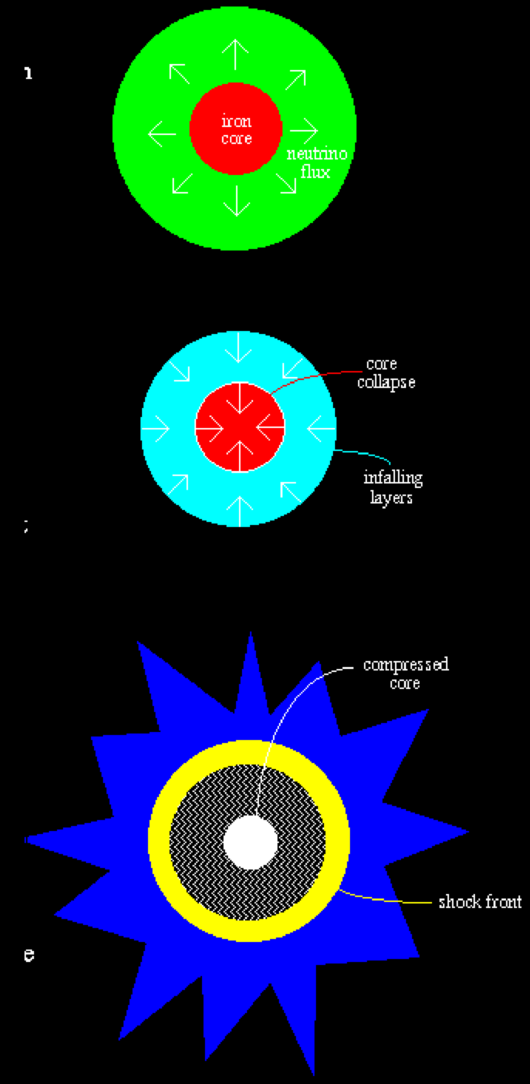
- As the iron peak is approached, the energy released per unit mass of reactant decreases. Thus the timescale becomes shorter and shorter

Core burning	**Lifetime**
H	10 million years
He	1 million years
C	300 years
O	200 days
Si	2 days



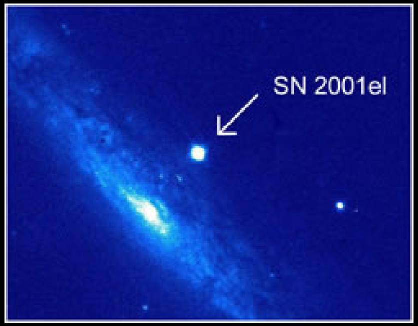
Core collapse

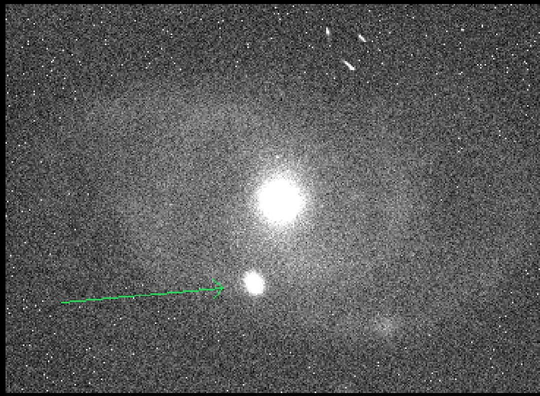
- The inner core collapses, leaving the surrounding material suspended above it, and in supersonic free-fall at velocities of ~100,000 km/s.
- The core density increases to 3x the density of an atomic nucleus and becomes supported by *neutron degeneracy pressure*.
- The core rebounds somewhat, sending pressure waves into the infalling material

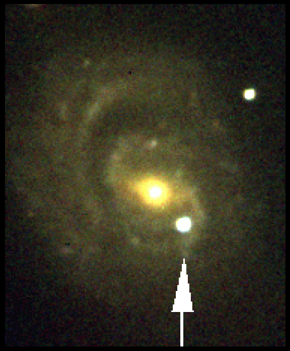


Explosion

- As the shock moves toward the surface, it drives the hydrogen-rich envelope in front of it.
- When the expanding shell becomes optically thin, the radiation can escape, in a burst of luminosity that peaks at about 10^{36} W

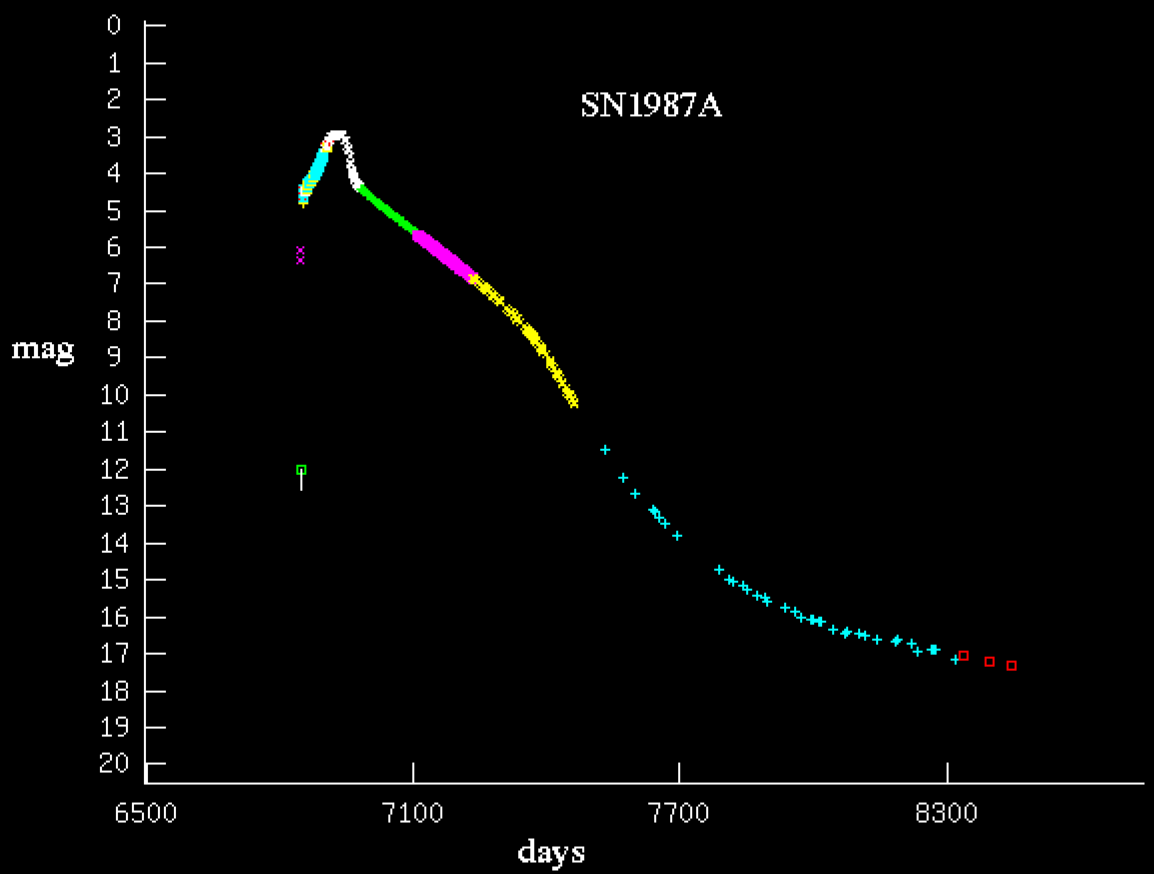






Light curves

- After the initial burst of luminosity, the supernova slowly fades away over a period of several hundred days. This fading is due to the radioactive decay of elements (typically nickel and cobalt) produced during the explosion.

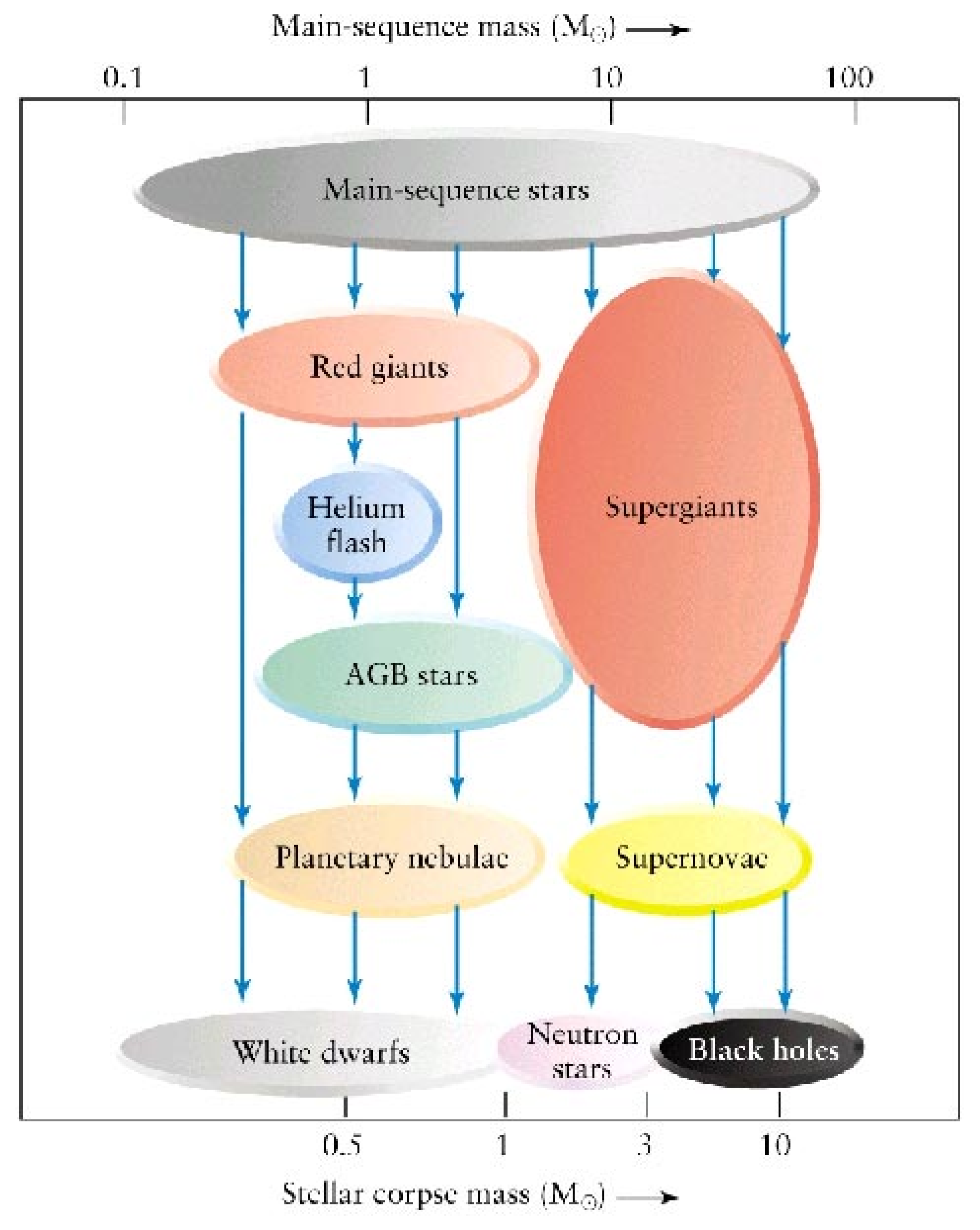


- As the shock wave propagates through the star, it creates a large amount of heavy, radioactive elements.
- Each species decays exponentially with a unique timescale
- The shape of the light curve is due to the superposition of the decay of each species.

Type 1a supernovae

- Type 1a supernovae are very important because their peak luminosity is very uniform – “standard bomb”.
- Probably arise from an accreting C-O white dwarf in a close binary system.

- At maximum light, the peak blue magnitude is m_B=-19.6±0.2.
  - Since they are so bright, they are excellent distance indicators for the Universe.



Main-sequence mass ($M_\odot$)
0.1
1
10
100
Main-sequence stars
Red giants
Helium flash
AGB stars
Supergiants
Planetary nebulae
Supernovae
White dwarfs
Neutron stars
Black holes
0.5
1
3
10
Stellar corpse mass ($M_\odot$)