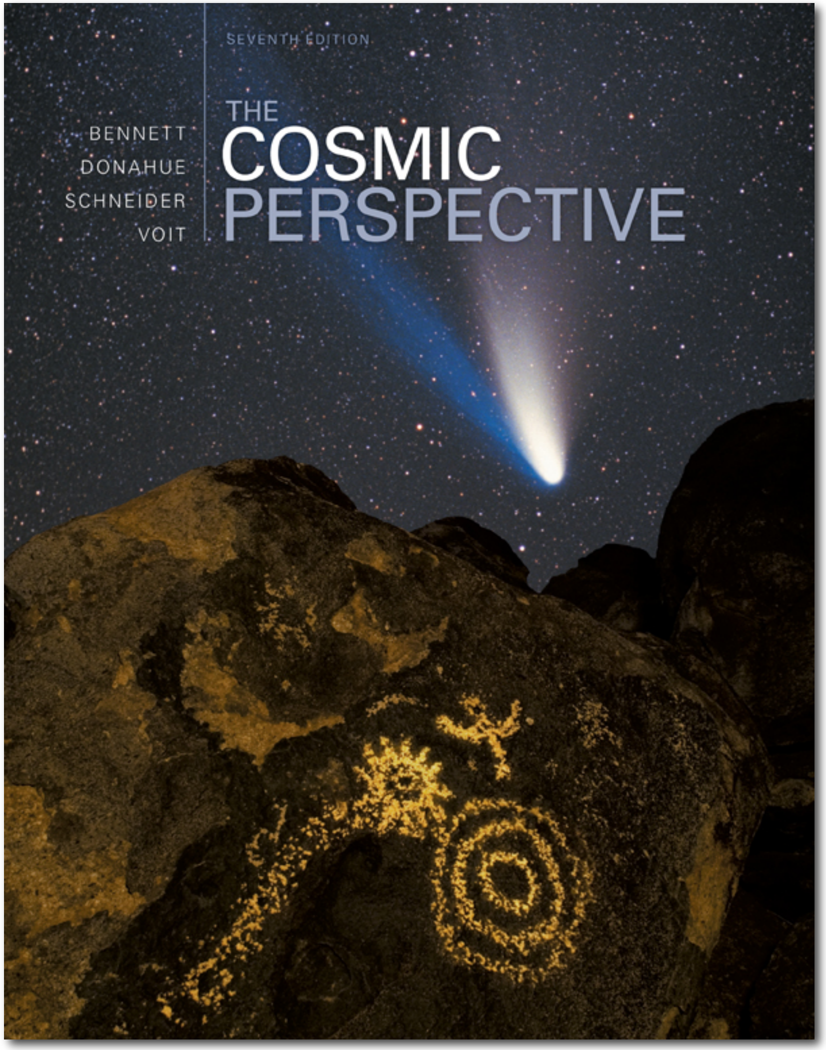
The Cosmic Perspective

Seventh Edition

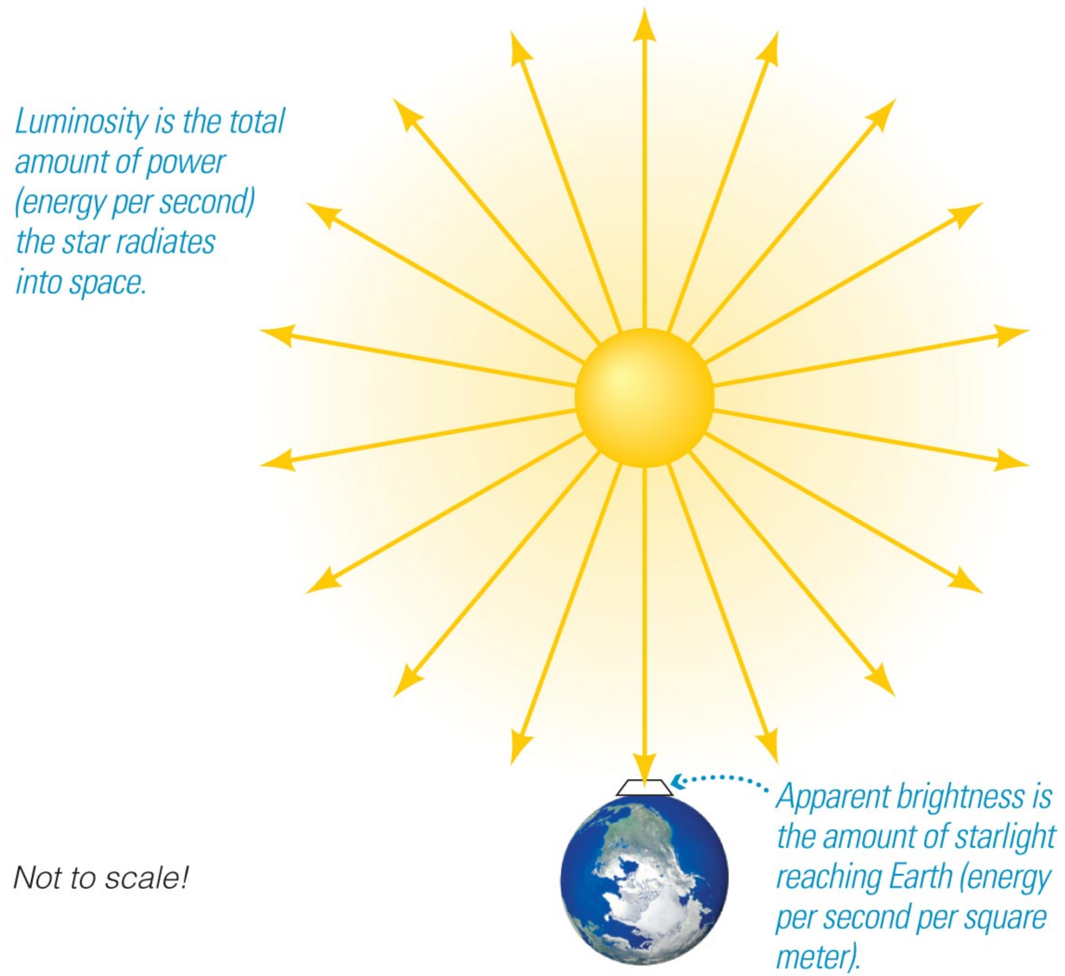


Surveying the Stars

15.1 Properties of Stars

- Our goals for learning:
  - **How do we measure stellar luminosities?**
  - **How do we measure stellar temperatures?**
  - **How do we measure stellar masses?**

How do we measure the luminosities of Stars?



Luminosity:

- Amount of power a star radiates (energy per second = watts)

Apparent brightness:

- Amount of starlight that reaches Earth (energy per second per square meter)

Inverse Square Law

- The relationship between apparent brightness and luminosity depends on distance:

$$\text{Flux} = \text{Apparent Brightness} = \frac{Luminosity}{Area} = \frac{L}{4\pi R^2}$$

- We can determine a star's luminosity if we can measure its distance and apparent brightness:

$$\text{Luminosity} = 4\pi\,(\text{distance})^2 \times \text{Flux}$$

UNITS:
Flux: J s^{-1} m^{-2}
Luminosity: J s^{-1}

Thought Question

How would the apparent brightness of Alpha Centauri change if it were three times farther away?

A. It would be only 1/3 as bright
B. It would be only 1/6 as bright.
C. It would be only 1/9 as bright.
D. It would be three times brighter.

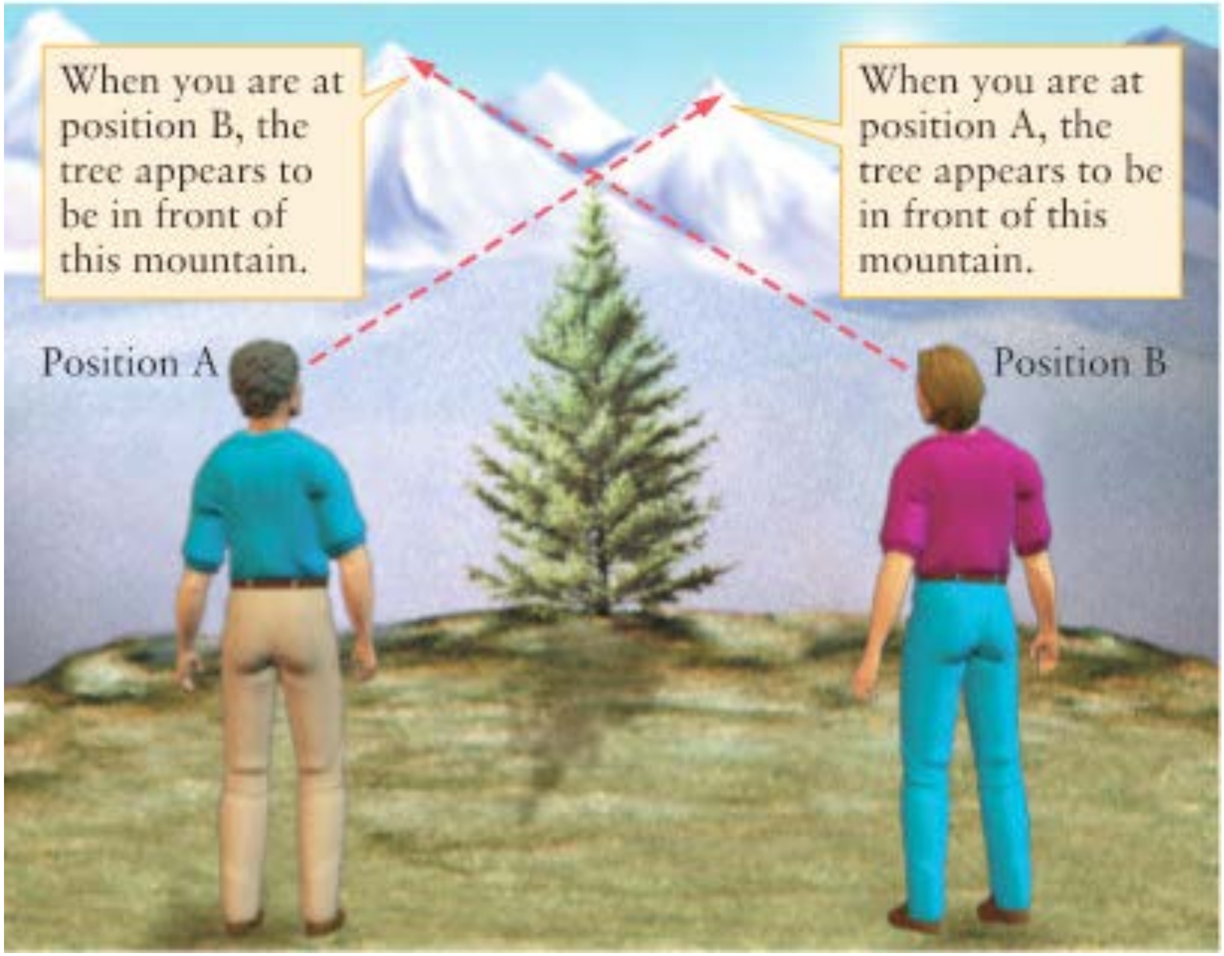
Thought Question

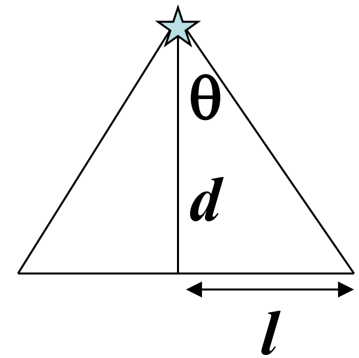
How would the apparent brightness of Alpha Centauri change if it were three times farther away?

A. It would be only 1/3 as bright
B. It would be only 1/6 as bright.
C. It would be only 1/9 as bright.
D. It would be three times brighter.

- So how far away are these stars?

Measuring Distances

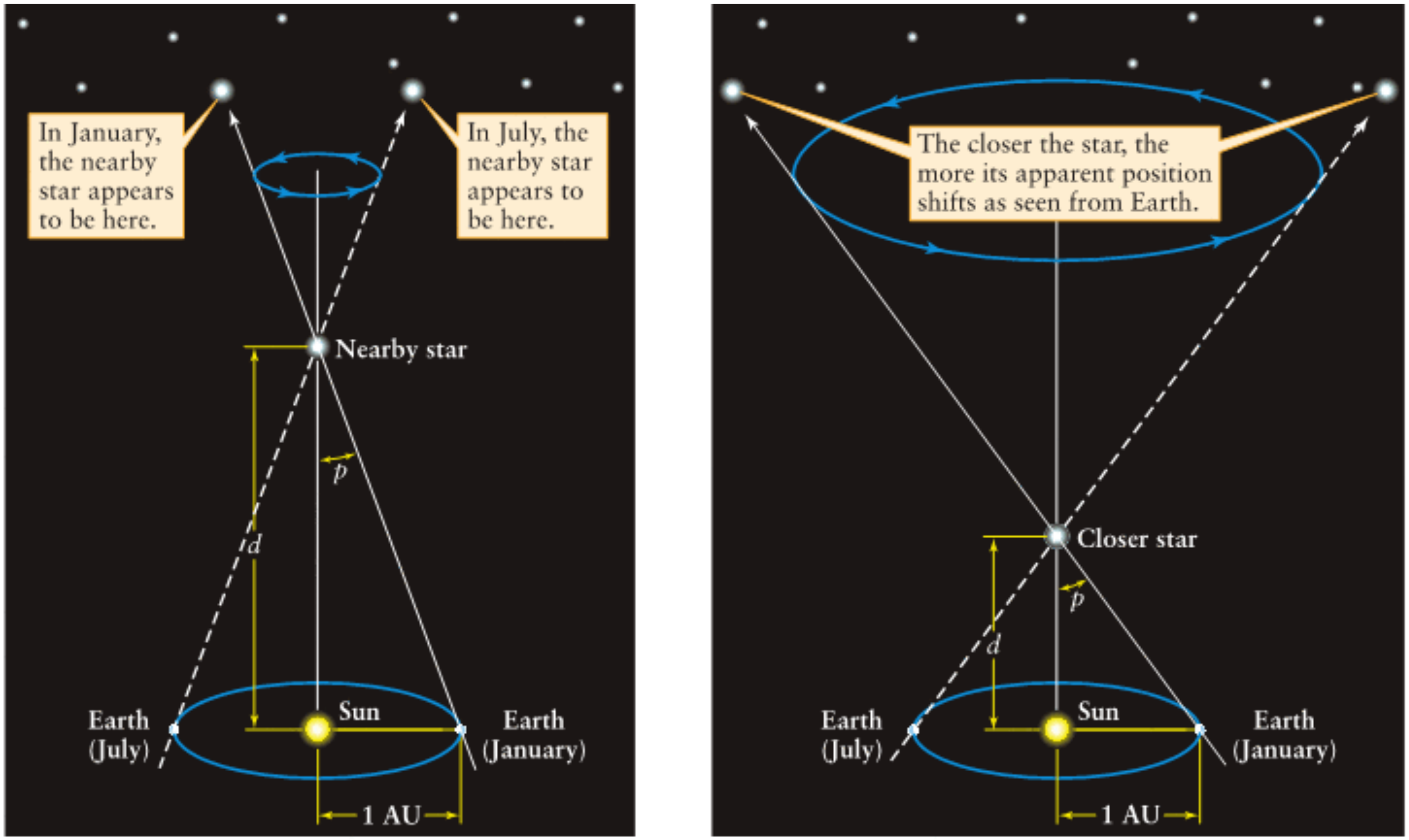




2*l*

tan(θ) = *l*/d → d ~ *l*/θ (θ in radians)

Parallax



(a) Parallax of a nearby star

(b) Parallax of an even closer star

The distance d to the star (in parsecs) is just 1 over the parallax angle p (in arcseconds): **d = 1/p**.

Parallax and Distance

$$p = \text{parallax angle}$$

$$d \text{ (in parsecs)} = \frac{1}{p \text{ (in arcseconds)}}$$

$$d \text{ (in light-years)} = 3.26 \times \frac{1}{p \text{ (in arcseconds)}}$$

HIPPARCOS

The smallest parallax angle that can be measured from the ground is about 0.01 arcsec so the furthest stars that can have distances measured from the ground are at d = 1/0.01 = 100 pc.

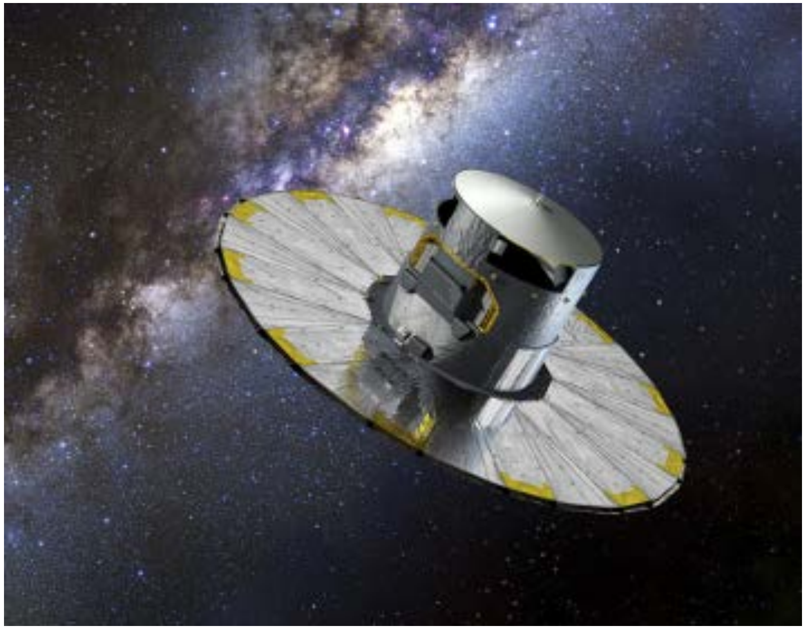
Observations made in space by the **Hipparcos** satellite permit measurements of even smaller parallax angles down to 0.001 arcsec corresponding to distances of 1000 pc.

Hipparcos has measured about 118,000 stars using the parallax method.

GAIA

GAIA is a space observatory of the European Space Agency, launched in 2013. The mission aims to construct a 3D space catalog, totaling ~ 1 billion objects, mainly stars, but also planets, comets, asteroids and quasars among others (see wiki page).

Observations made by GAIA permit measurements of parallax angles down to 200 micro arcsec (at m = 20) corresponding to distances of 5,000 pc.



GAIA

- Most luminous stars (not common):

  $10^6\ L_{Sun}$

- Least luminous stars (common):

  $10^{-4} L_{Sun}$

- (L_{Sun} is luminosity of Sun)

Magnitude Scale: Apparent Magnitude

The **magnitude scale** is a system used to denote the brightness of an astronomical object.

Keep in mind that **the greater the apparent magnitude, the dimmer the star.**

A 5th magnitude star is a factor of 100 times fainter in brightness than a 1 magnitude star

$$m_1 - m_2 = 2.5\log_{10}\left(\frac{F_2}{F_1}\right)$$

$\mathrm{m}_1, \mathrm{m}_2$ = apparent magnitudes of sources 1 and 2, respectively

F_1, F_2 = apparant brightnesses (fluxes) of sources 1 and 2, respectively

Magnitude Scale: Apparent Magnitude

$$m_1 - m_2 = 2.5\log_{10}\left(\frac{F_2}{F_1}\right) \Rightarrow \frac{m_1 - m_2}{2.5} = \log_{10}\left(\frac{F_2}{F_1}\right) \Rightarrow 10^{\frac{m_1 - m_2}{2.5}} = \frac{F_2}{F_1}$$

Example: If the apparent magnitudes of two stars are $m_1 = 15$ and $m_2 = 10$ what is the ratio of the apparent brightnesses (fluxes) of star 2 to star 1 ($F_2/F_1 = ?$)

Solution:

$$\frac{F_2}{F_1} = 10^{\frac{m_1 - m_2}{2.5}} = 10^{\frac{15-10}{2.5}} = 10^{\frac{5}{2.5}} = 10^2 = 100$$

Magnitude Scale: Absolute Magnitude

Absolute magnitude: The apparent magnitude that a star would have if it were at a distance of 10 parsecs from Earth.

The apparent magnitude of the Sun is -26.7. If the Sun were moved to a distance of 10 parsecs from the Earth, it would look fainter and have a magnitude of +4.8.
(remember larger magnitudes means fainter)

The relation between the apparent and absolute magnitudes of an object is:

$$m - M = 5\log d - 5$$

d = distance between the Earth and the object in parsec

m - M is referred to as the distance modulus

Magnitude Scale: Absolute Magnitude

$$m - M = 5\log d - 5$$

d = distance between the Earth and the object in parsec

m - M is referred to as the distance modulus

If a star has an apparent magnitude of m = 15 and an absolute magnitude of M = 5 what is its distance?

Magnitude Scale: Absolute Magnitude

$m - M = 5\log d - 5$

d = distance between the Earth and the object in parsec

m - M is referred to as the distance modulus

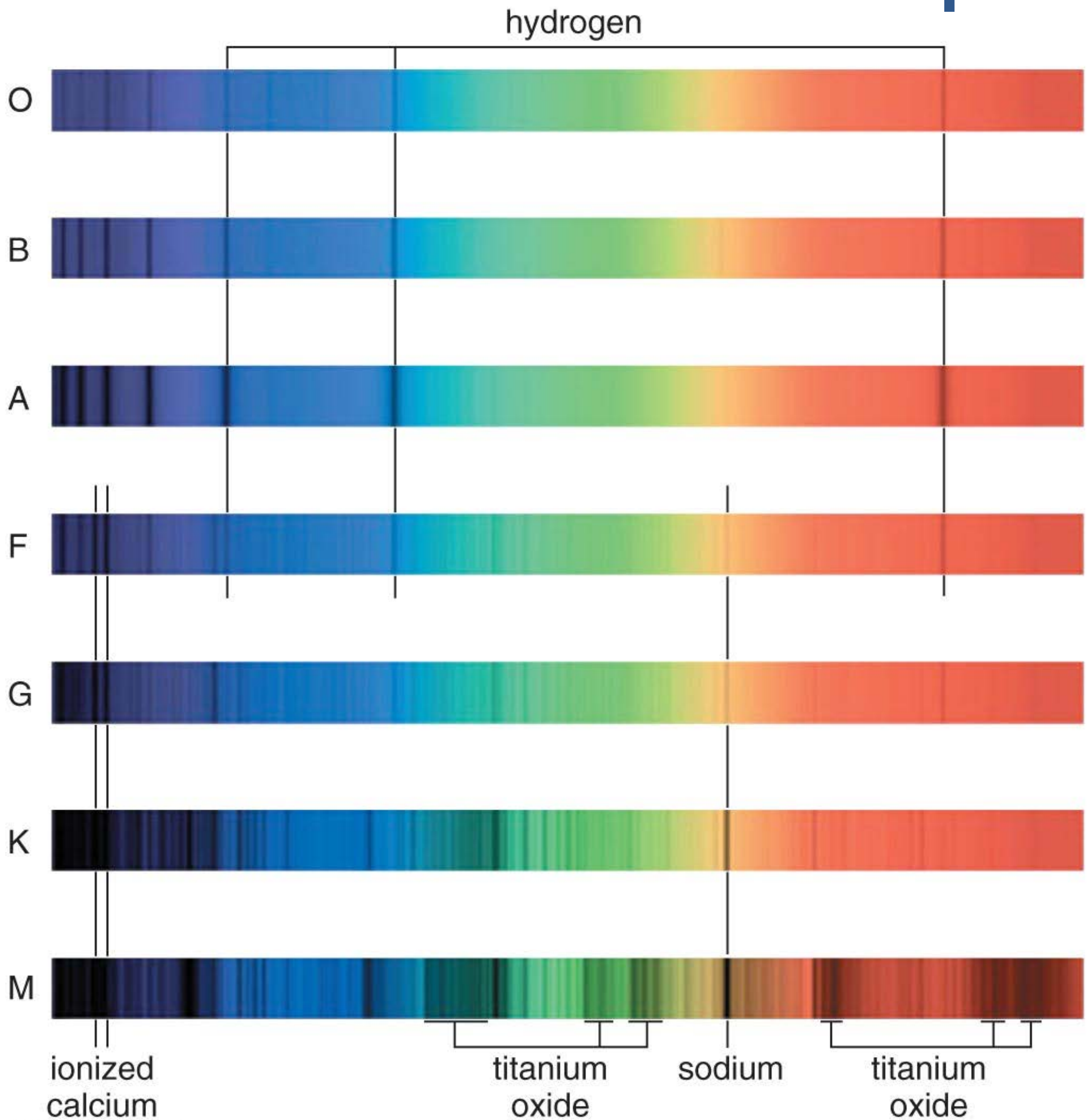
If a star has an apparent magnitude of m = 15 and an absolute magnitude of M = 5 what is its distance?

$$m - M = 5\log d - 5 \rightarrow \log d = \frac{m - M + 5}{5} \rightarrow$$

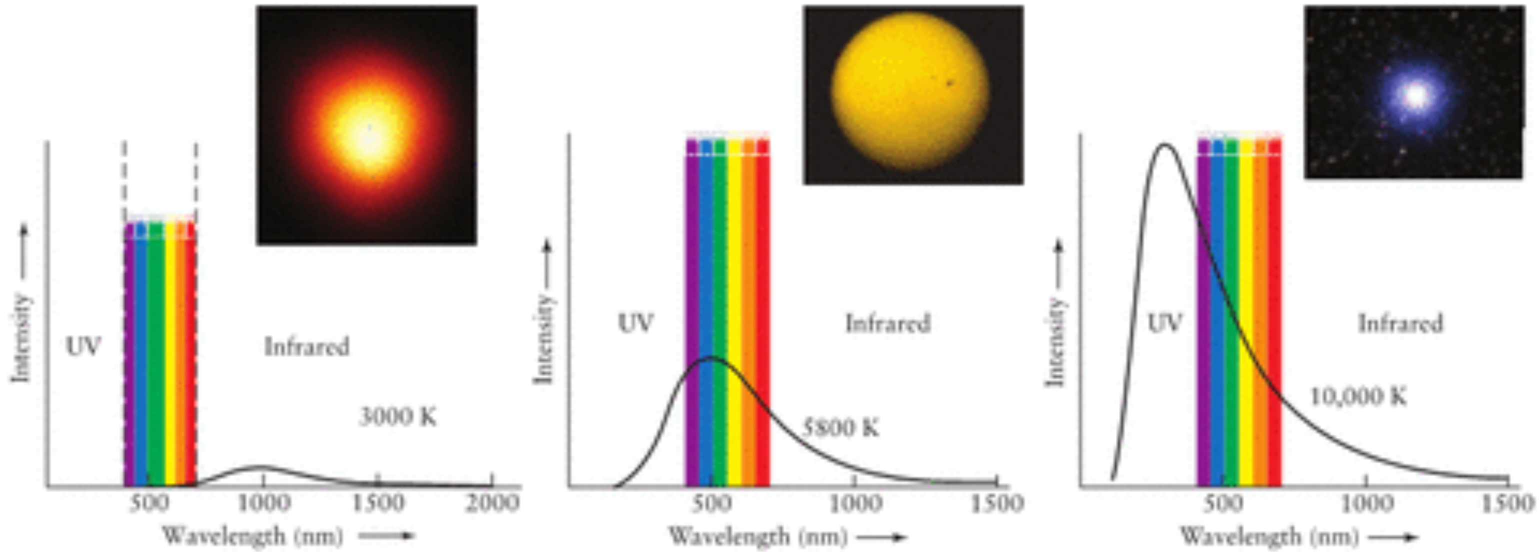
$$d = 10^{\frac{m-M+5}{5}} pc$$

For m-M =10 we obtain: $d = 10^{\frac{15}{5}} pc = 10^3 pc$

How do we measure stellar temperatures?



Colors and Temperature



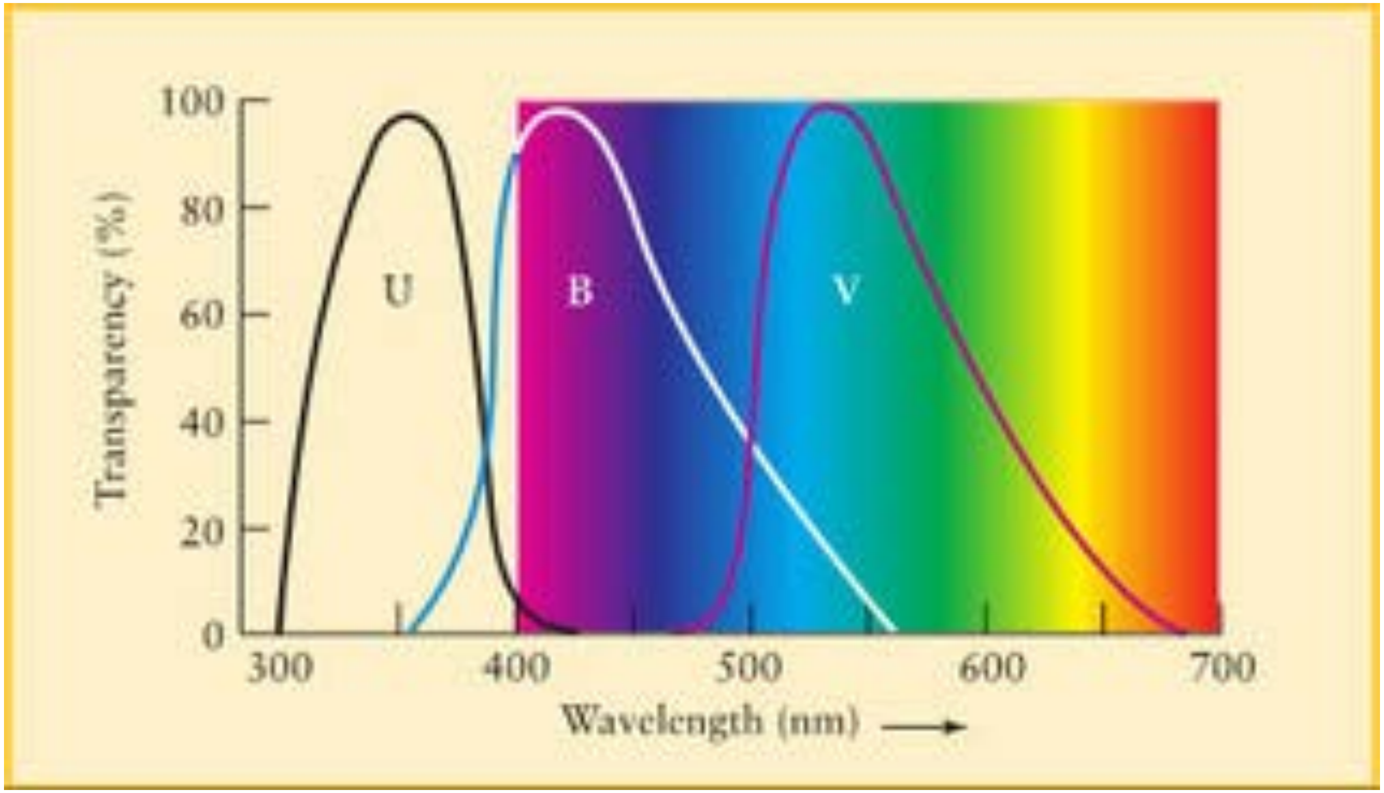
(a) A **cool star** with surface temperature 3000 K emits much more red light than blue light, and so appears red.

(b) A **warmer star** with surface temperature 5800 K (like the Sun) emits roughly equal amounts of all visible wavelengths, and so appears yellow-white.

(c) A **hot star** with surface temperature 10,000 K emits much more blue light than red light, and so appears blue.

A star's temperature is related to its color. Red stars a relatively cold and blue stars are relatively hot.

Measuring Temperatures with Filters



A filter is transparent to a certain wavelength band.
A **U filter** is more transparent in the ultraviolet band a **B filter** if more transparent in the blue and a **V filter** is more transparent in the yellow-green.

Measuring Temperatures with Filters

Method: First measure a stars brightness through each of the U, B and V filters. This gives the fluxes of b_U, b_B and b_V.

Then compare the relative fluxes by taking the ratios b_V/b_B and b_B/b_U. These ratios indicate the temperature of the stars surface.

Spectra of Stars

Absorption spectra in stars are produced in the following way:

A star produces a **continuum spectrum** from hot (T_{gas}) dense gas in its atmosphere. This spectrum is very close to that of a **blackbody spectrum** with a temperature of T_{gas}.

The stars continuum radiation goes through cooler less dense parts of its upper atmosphere where **photons of only certain wavelengths are absorbed.**

The **wavelengths** of the absorption lines are **characteristic of the elements and the ionization level** of the stars absorbing gas.

Stellar Classification

To bring some order in the zoo of stellar spectra astronomers have grouped stars according to the appearance of their spectra. These **classifications of stars according to the appearance of their spectra** are called **spectral classes**.

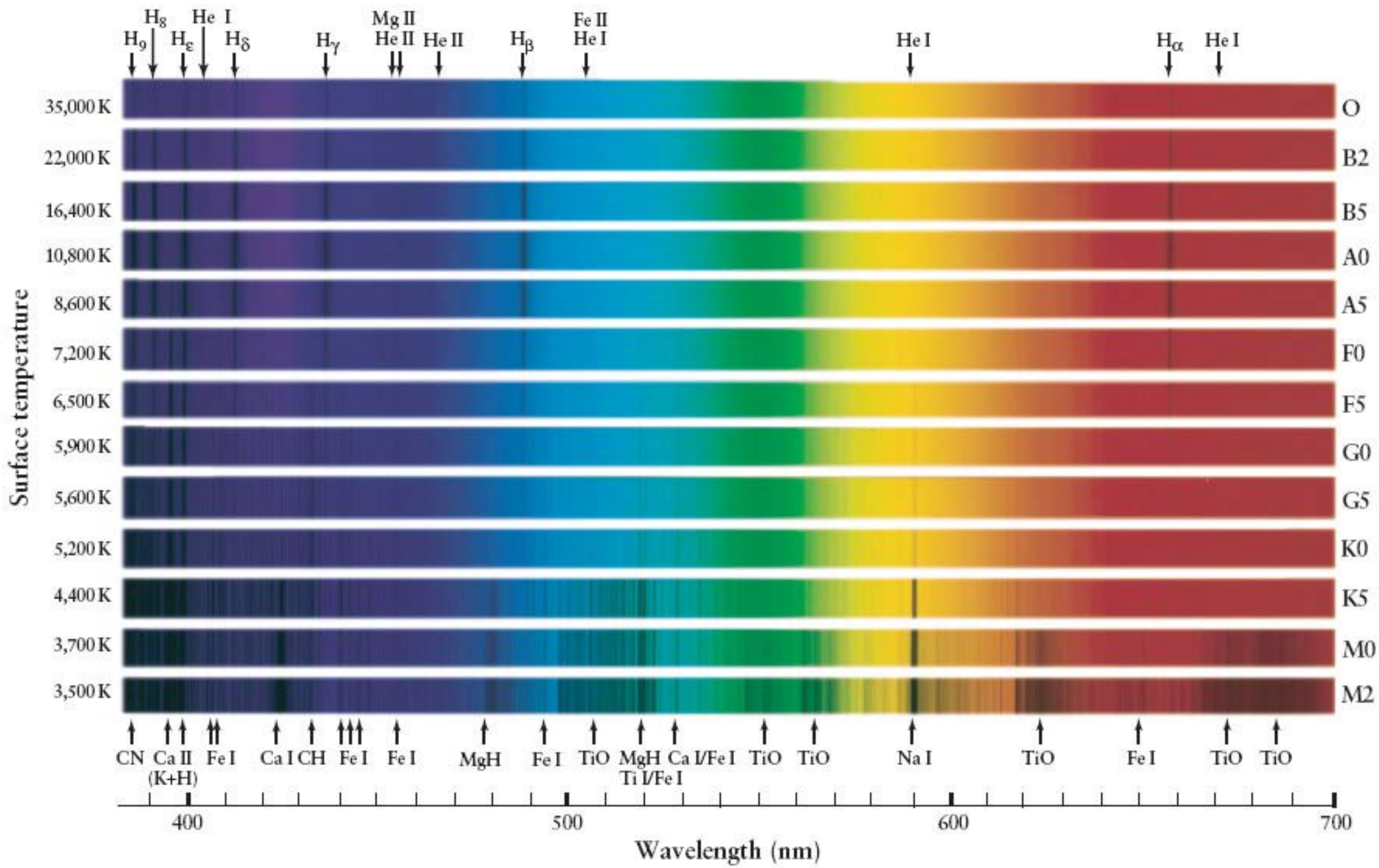
The **spectral classes** are labeled:

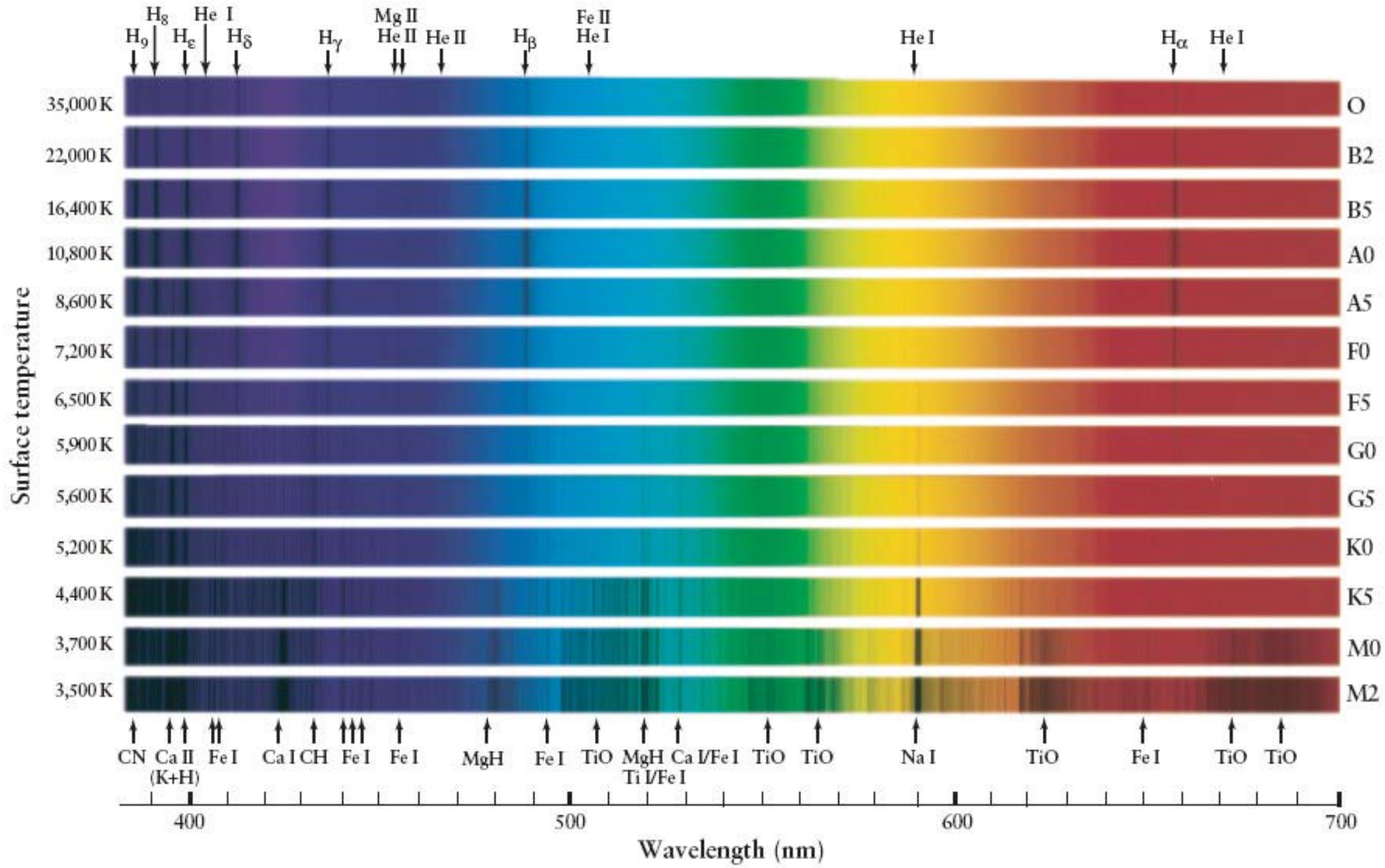
O B A F G K M L T

A refined scheme adds a number ranging from 0 to 9 to each letter. This subdivision of the spectral class is called **spectral type**.

In the late 1800's a team of women at the Harvard College Observatory undertook the task of classifying the spectra of hundreds of thousands of stellar spectra.

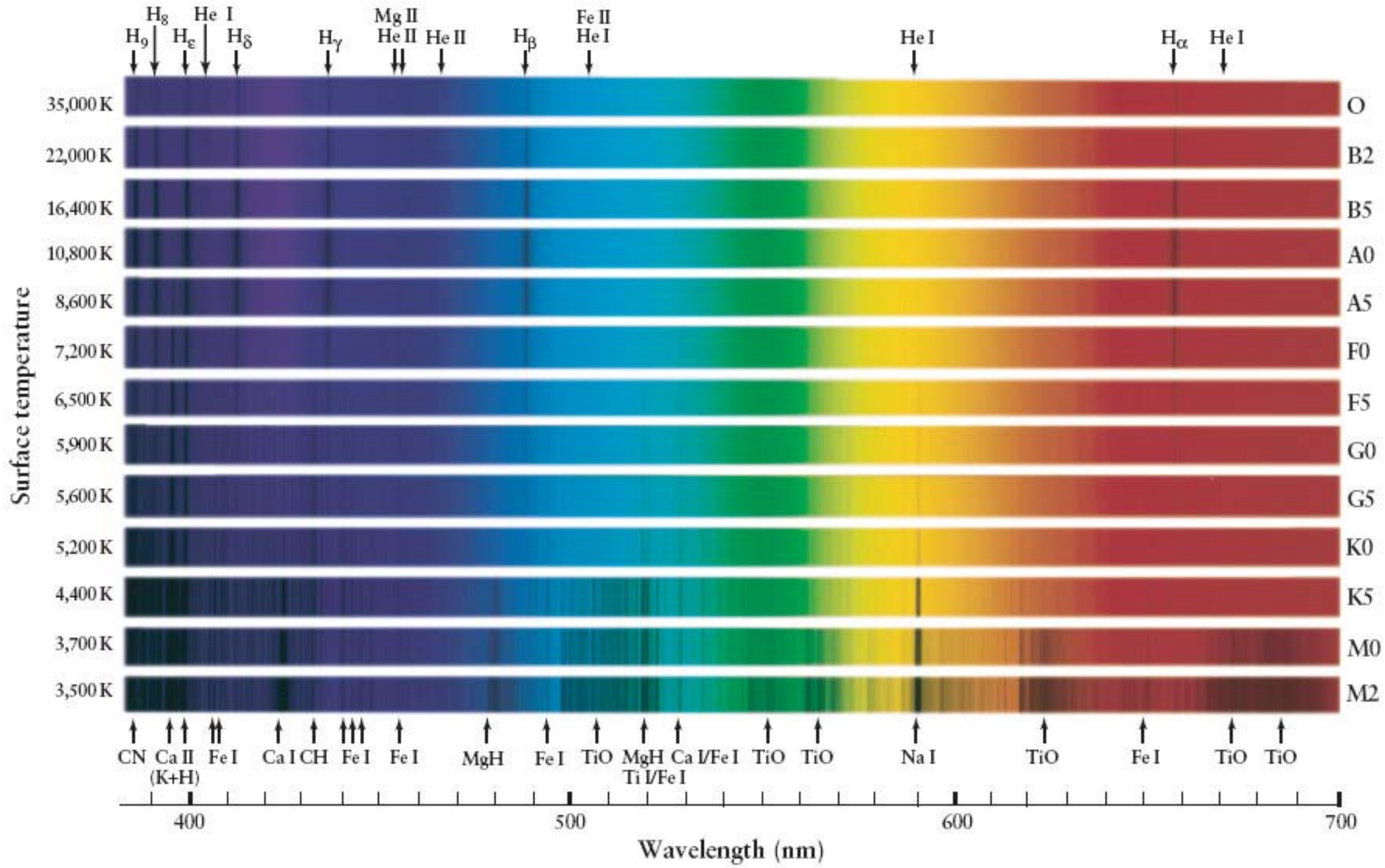
Stellar Spectra and Temperature





- Absorption lines in a star's spectrum tell us its ionization level and its temperature.

- (Hottest) O B A F G K M L T (Coolest)



For T > 20,000 K most H atoms are ionized so the Balmer lines are very weak in very hot stars.

For T < 4,000 K most H atoms have electrons in the n = 1 level and the Balmer lines are very weak in very cool stars.

Thought Question

Which kind of star is hottest?

A. M star
B. F star
C. A star
D. K star

Thought Question

Which kind of star is hottest?

A. M star
B. F star
C. A star
D. K star

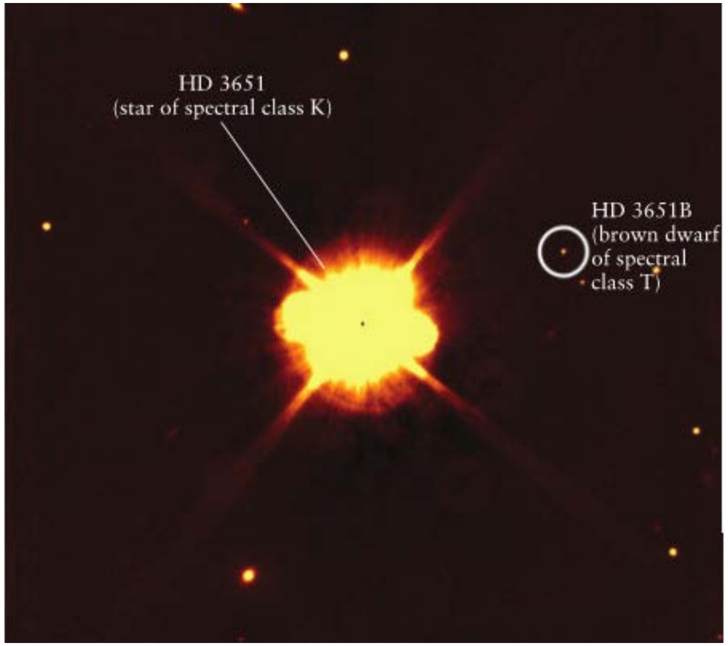
Brown Dwarfs

Brown Dwarfs are starlike objects that are not massive enough ($M < 0.08\ M_{\odot}$) to sustain hydrogen fusion in their core.
They have temperatures lower than those of spectral class M stars.

They are primary heated by Kelvin-Helmoltz contraction.

Since they are so cool **their spectra peak in the infrared**.

Brown Dwarf spectra have a rich variety of **absorption lines produced by molecules**.



Infrared image of brown dwarf HD3561B. The star HD 3561 is of spectral class K, with a surface temperature of about 5200 K. HD 3651 is orbited by a brown dwarf with a surface temperature between 800 and 900 K and a luminosity just 1/300,000 that of the Sun.

Stellar Radii

Stefan - Boltzmann Law : $F = \sigma T^4$

Inverse Square Law : $F = \dfrac{L}{4\pi R^2}$

F = flux at the stars surface in W m^{-2}

L = stars luminosity in W

R = radius of stars emitting surface in meters

T = temperature of stars surface in kelvins

σ = Stefan - Boltzmann contant = 5.67×10^{-8} W m^{-2} K^{-4}

Stellar Radii

$L = 4\pi R^2 \sigma T^4$ Equation (1)

$L_\odot = 4\pi R_\odot^2 \sigma T_\odot^4$ Equation (2)

Dividing equation 1 by equation 2 we have:

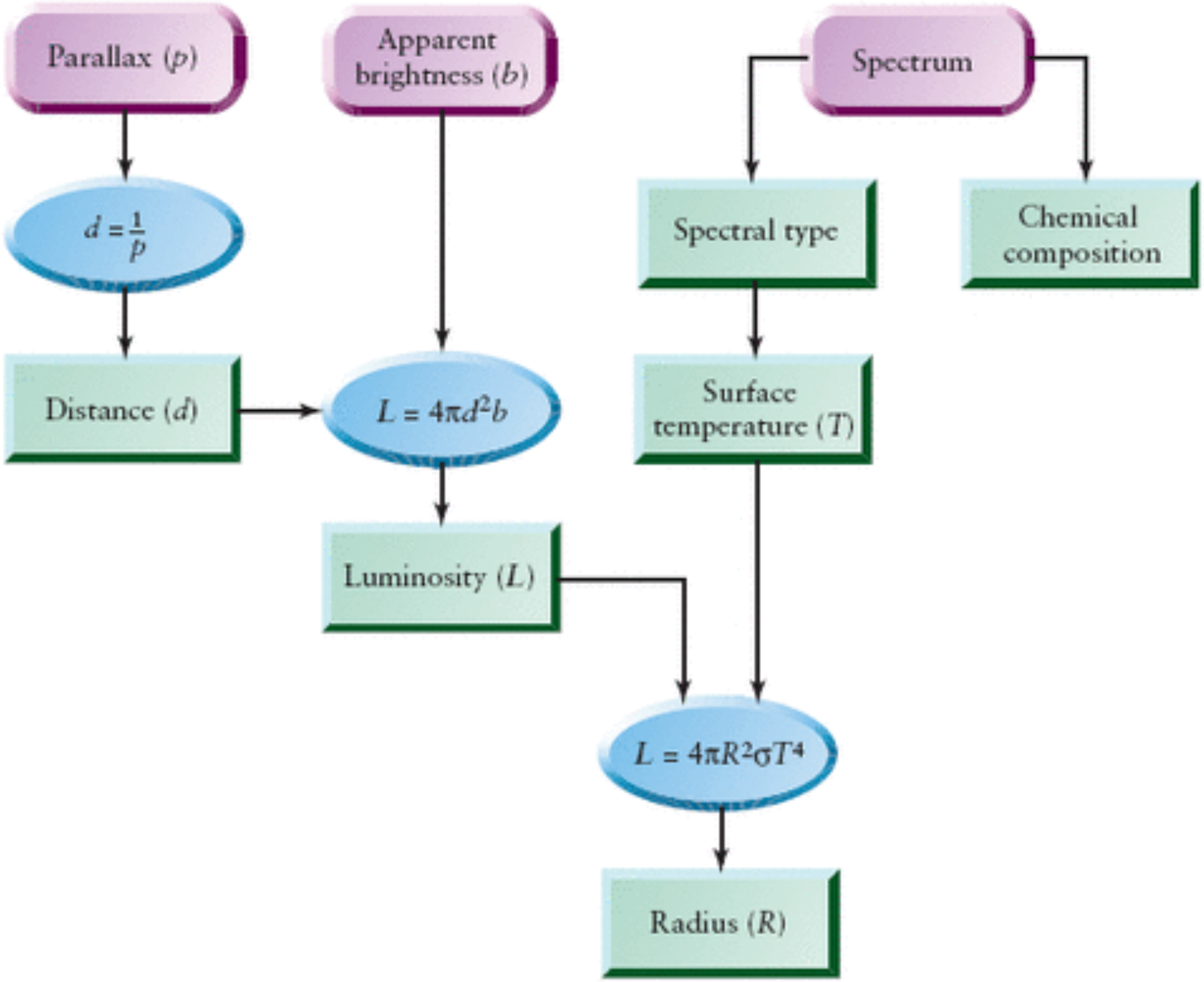
$L/L_\odot = (R/R_\odot)^2 (T/T_\odot)^4$ Equation (3)

Solving for $R/R_\odot$ we have:

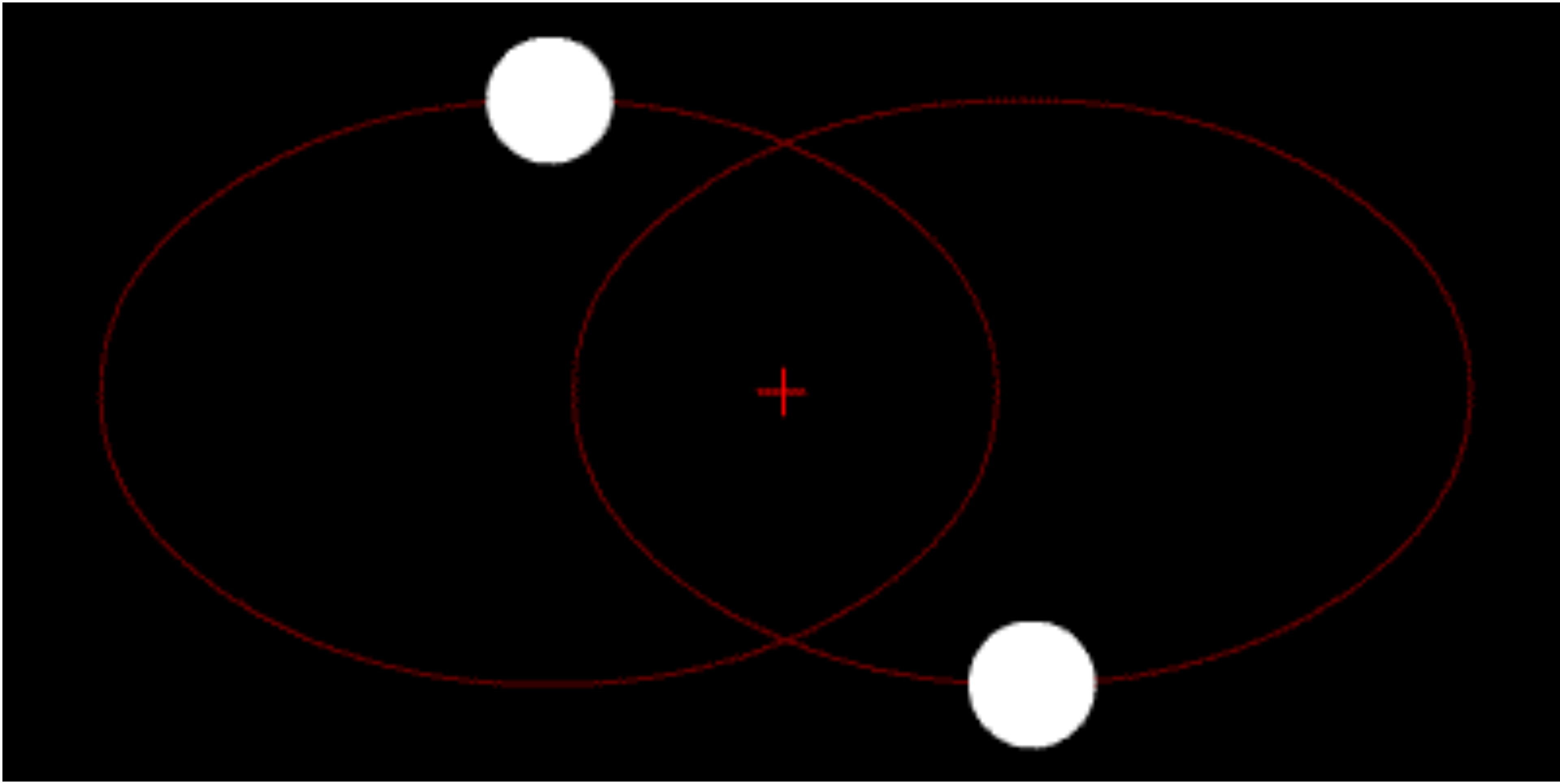
$R/R_\odot = \sqrt{L/L_\odot}(T_\odot/T)^2$

Example: The bright reddish star Betelgeuse in the constellation Orion is 60,000 times more luminous than the Sun and has a surface temperature of 3500 K. How much larger is Betelgeuse's radius from the Sun's radius ? ($T_\odot$=5,800 K)

Measuring the Properties of Stars



Binary Star Systems

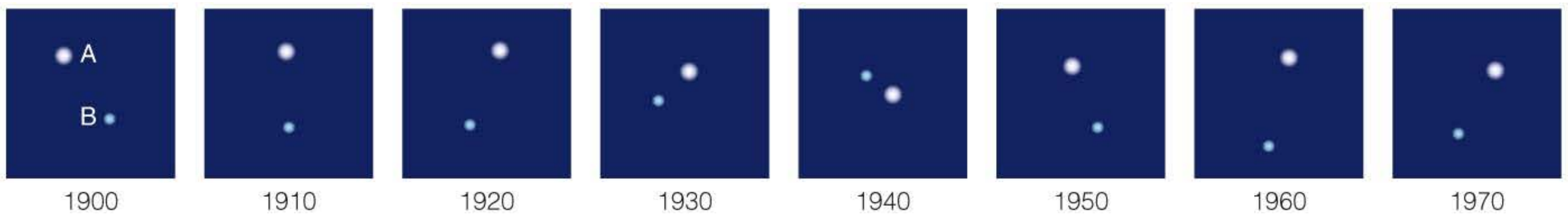


Types of Binary Star Systems

- Visual binary
- Spectroscopic binary
- Eclipsing binary

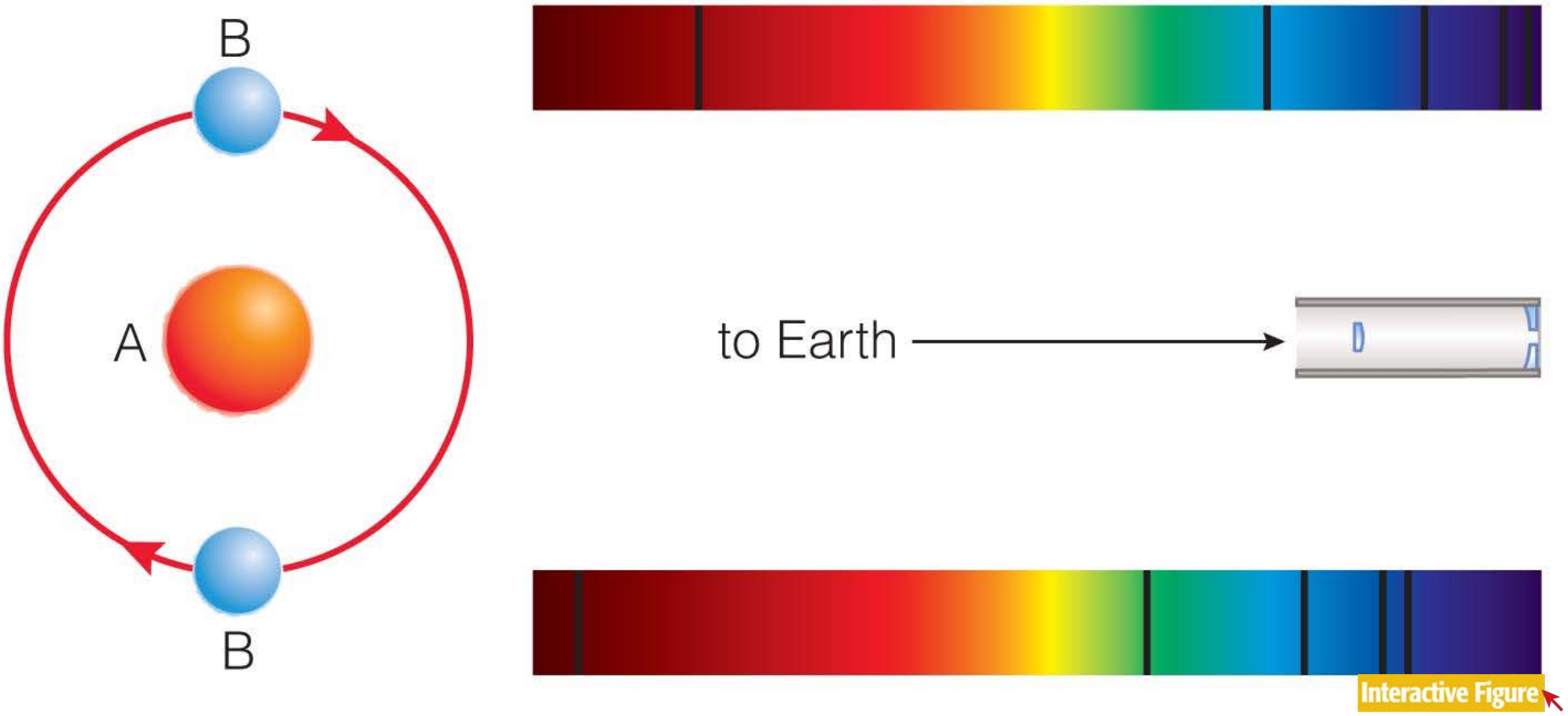
About half of all stars are in binary systems.

Visual Binary



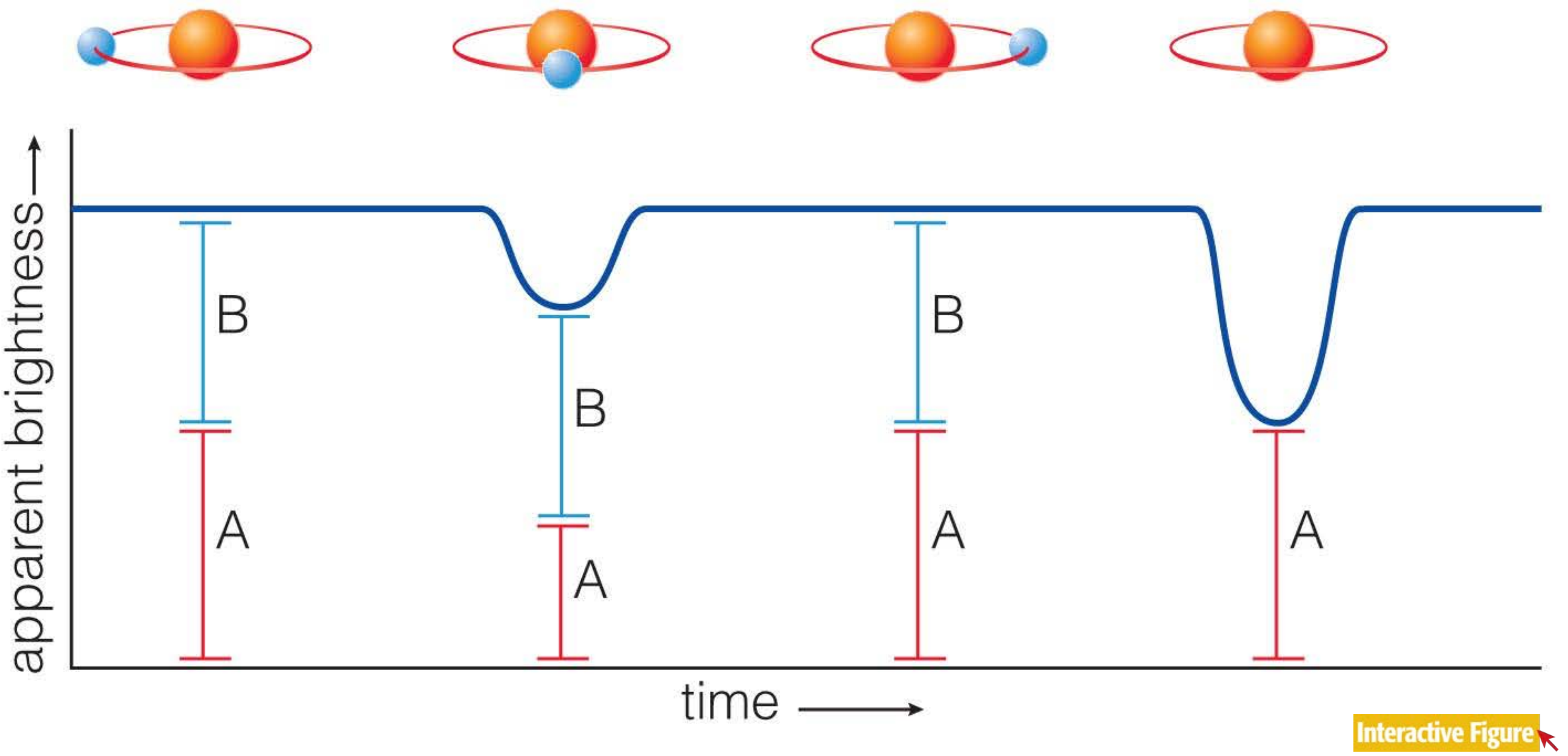
- We can directly observe the orbital motions of these stars.

Spectroscopic Binary



- We determine the orbit by measuring Doppler shifts.

Eclipsing Binary

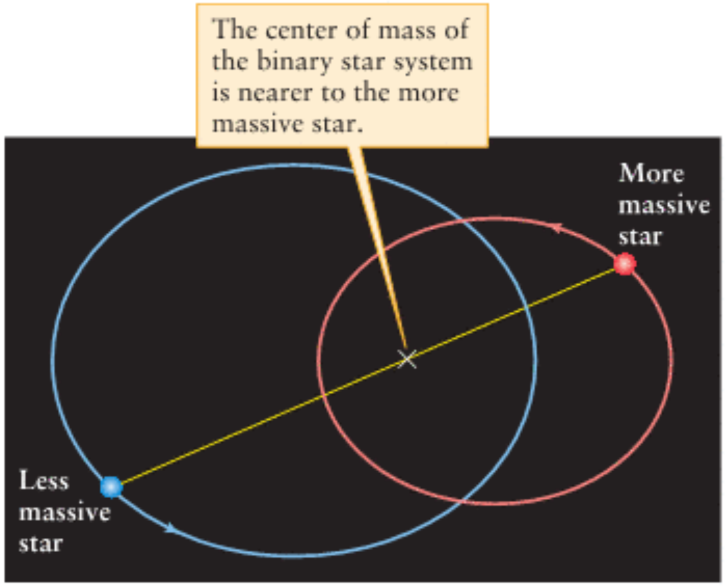


- We can measure periodic eclipses.

Masses of Stars in Binary Systems

$$M_1 + M_2 = \frac{a^3}{P^2}$$

$$\frac{M_1}{M_2} = \frac{v_2}{v_1} = \frac{a_2}{a_1}$$



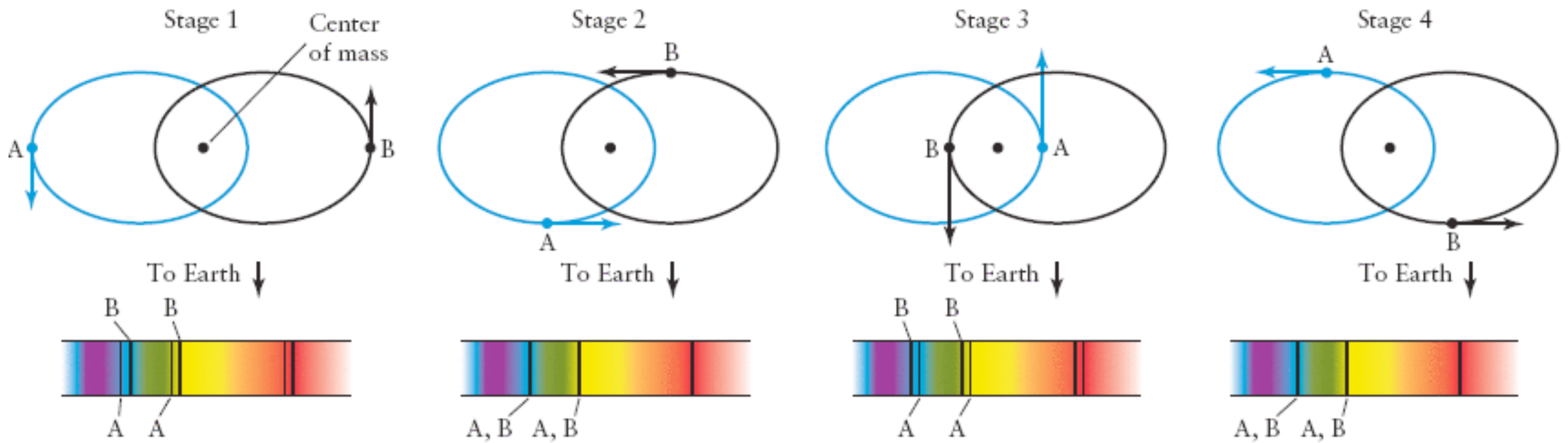
(b) A binary star system

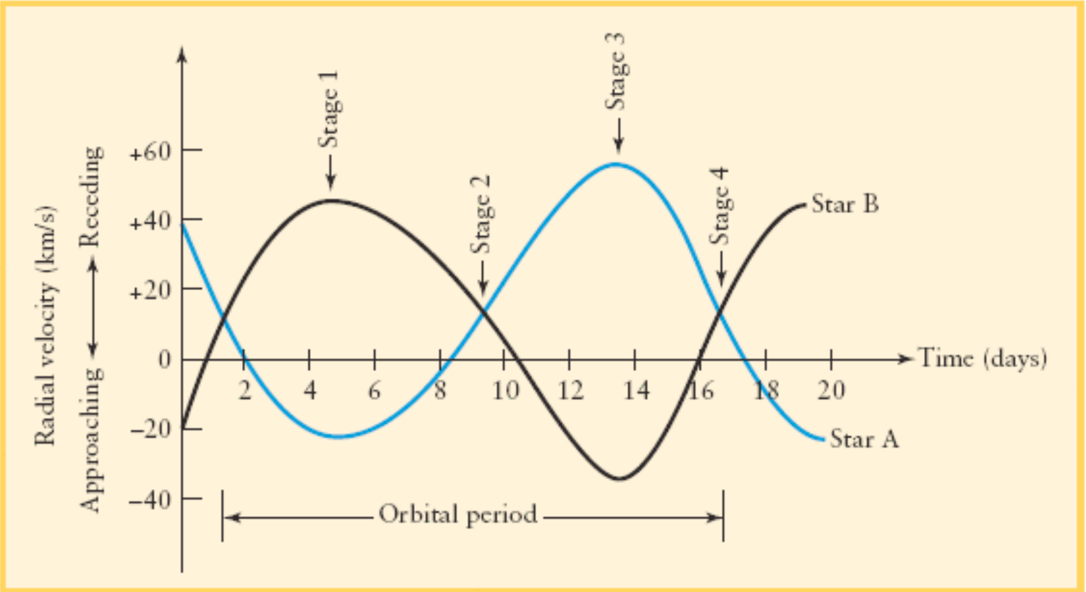
P = period of orbit, in years

$a = a_1 + a_2$, in AU (a_1,a_2 are the semimajor axes of the orbits of M_1, M_2 , respectively

M_1, M_2 = mass of stars, in solar masses

Spectroscopic Binaries



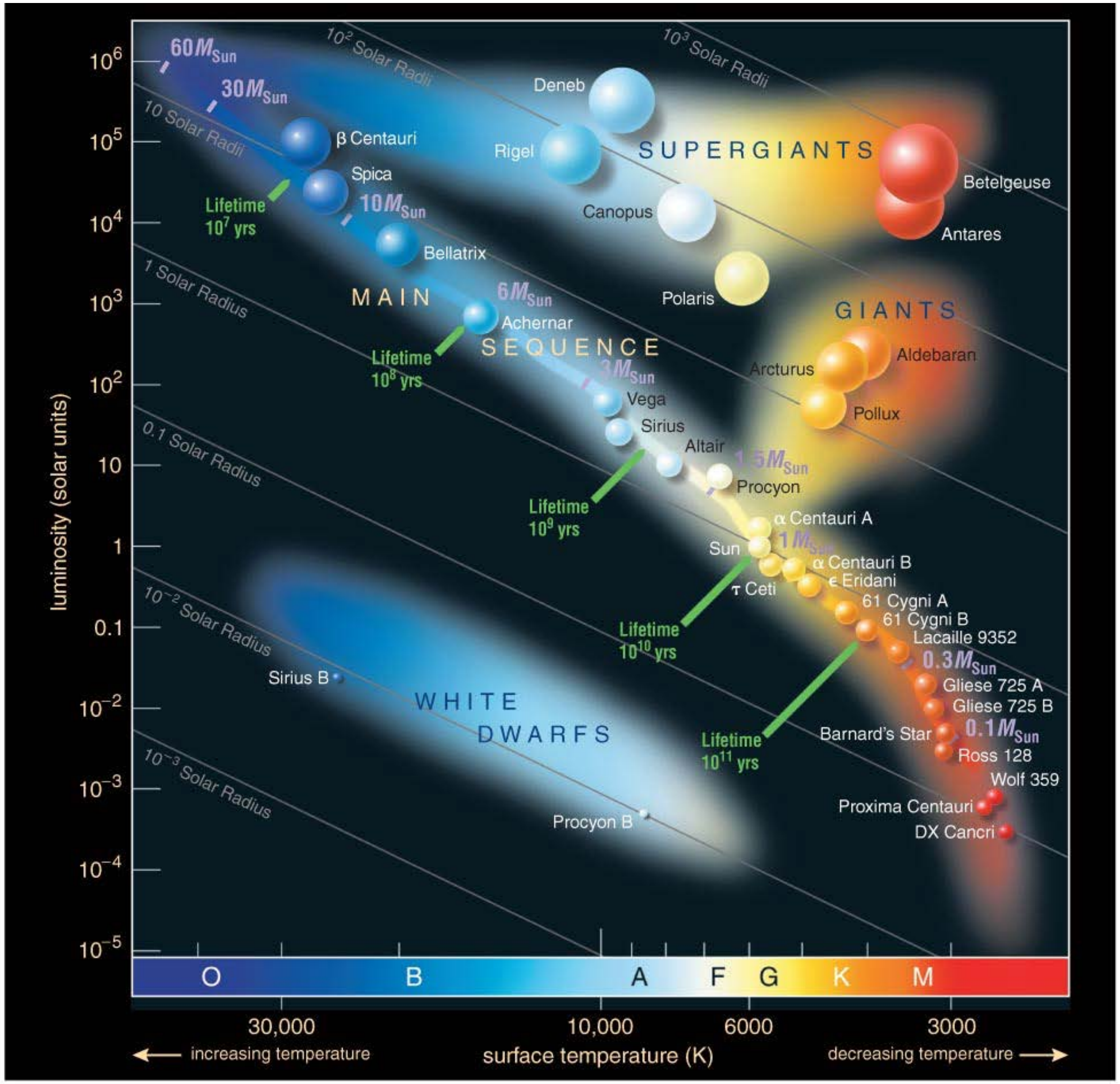


Radial Velocity Curves of Spectroscopic binary system HD 171978

15.2 Patterns Among Stars

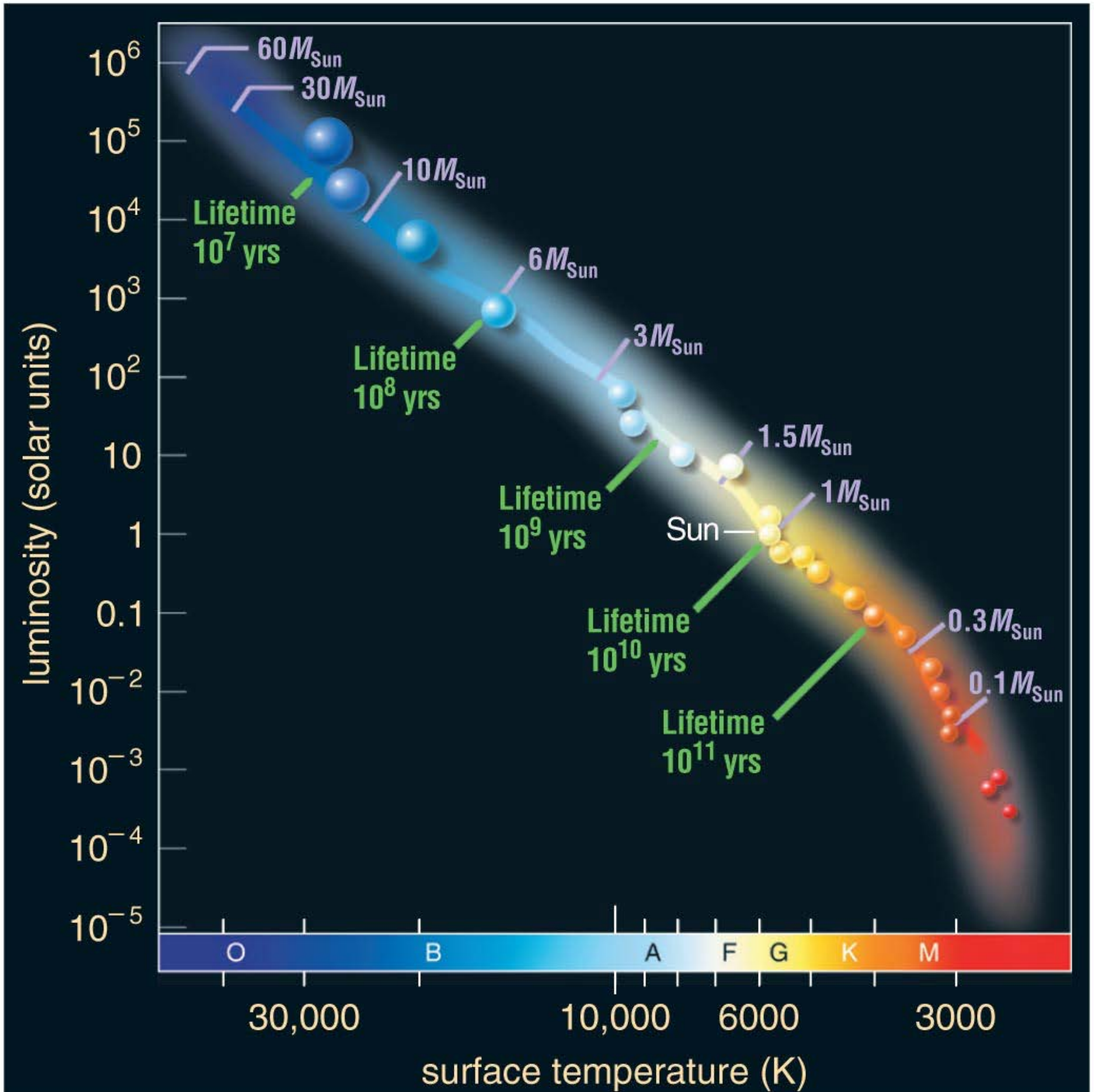
- Our goals for learning:
  - **What is a Hertzsprung-Russell diagram?**
  - **What is the significance of the main sequence?**
  - **What are giants, supergiants, and white dwarfs?**
  - **Why do the properties of some stars vary?**

Luminosity

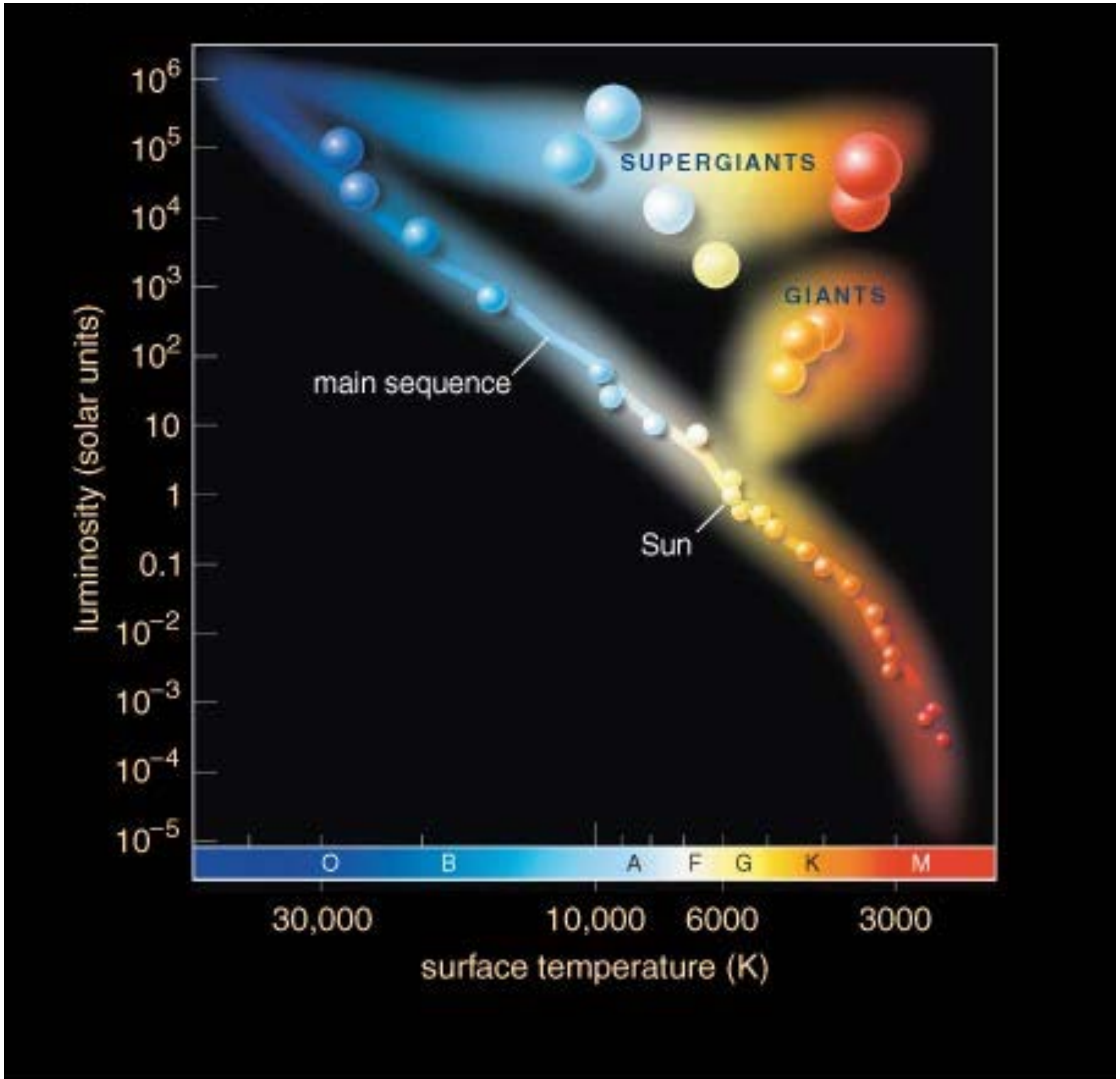


- An H-R diagram plots the luminosity and temperature of stars.

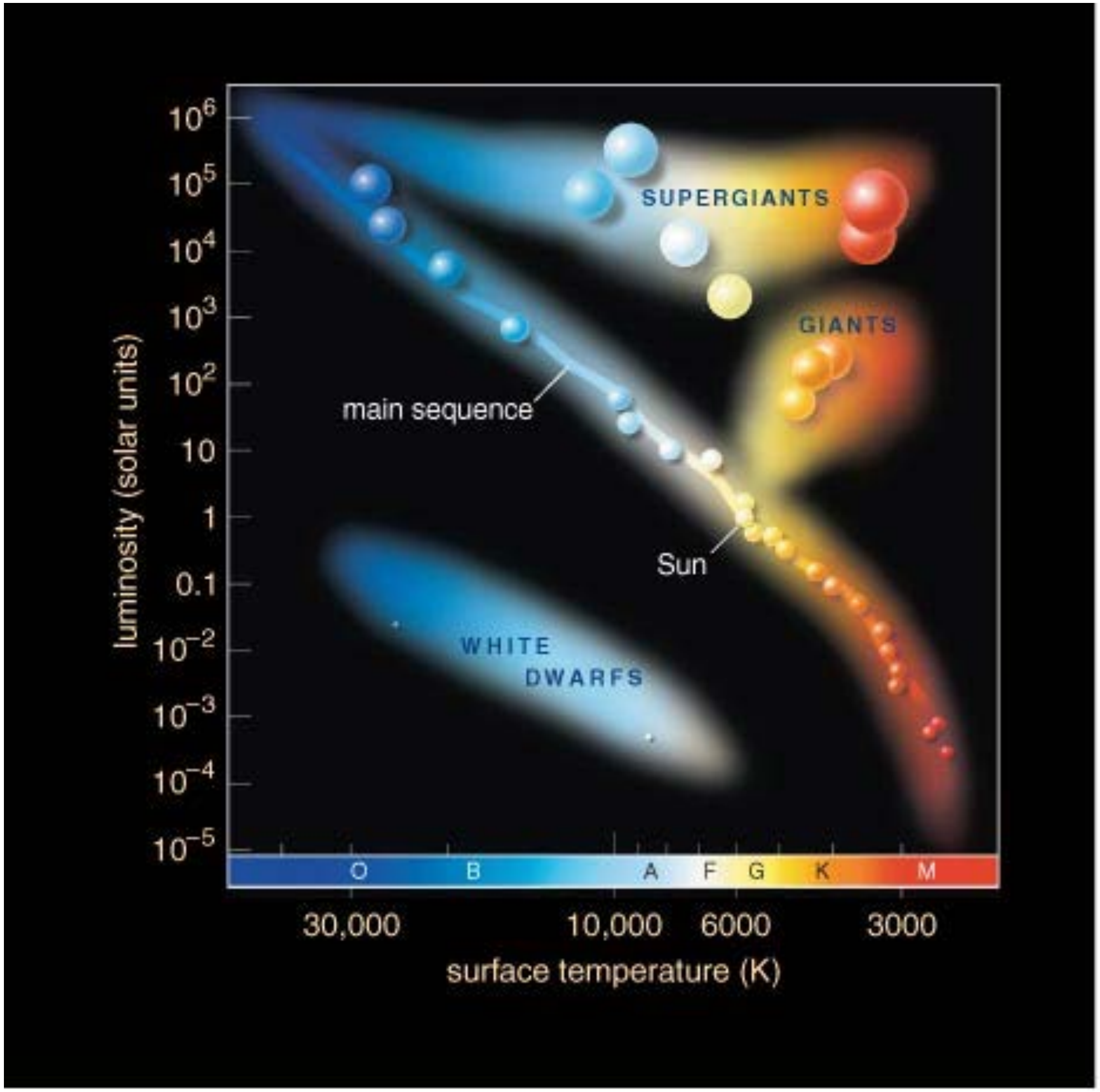
Temperature



- Most stars fall somewhere on the ***main sequence*** of the H-R diagram.



- Stars with lower *T* and higher *L* than main-sequence stars have larger radii. These stars are called ***giants*** and ***supergiants***.



- Stars with higher *T* and lower *L* than main-sequence stars have smaller radii. These stars are called ***white dwarfs***.

Categories of Stars

Main-sequence stars: hydrogen fusion is taking place in their cores. About 90% of the stars (including the Sun) in the night sky lie along the main sequence.

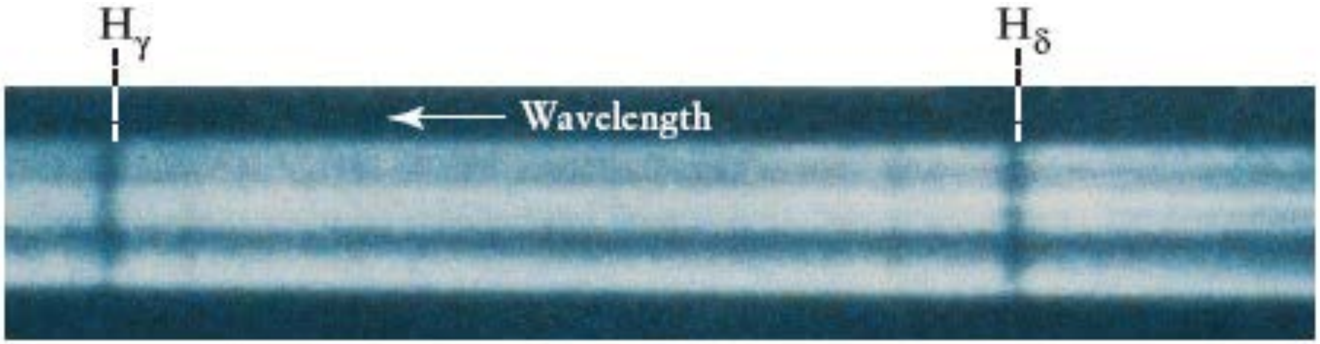
Giant stars: luminosities of 100–1000 $L_\odot$ and temperatures of 3000–6000 K. Red giants have T : 3000–5000 K.

Supergiant stars: considerably bigger and brighter than typical red giants, with radii of up to 1000 $R_\odot$.

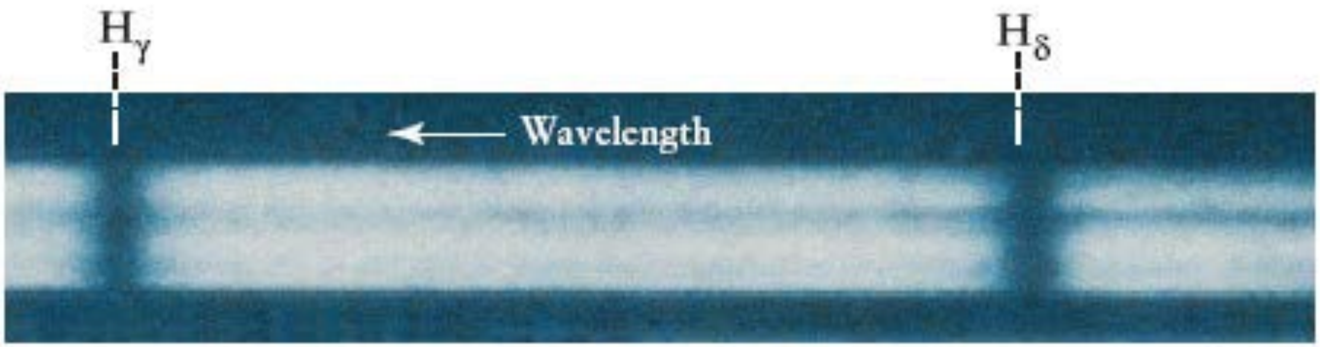
White Dwarfs: A low-mass star that has exhausted all its thermonuclear fuel and contracted to a size roughly equal to the size of the Earth (*has-been star*).

Brown Dwarfs: Starlike ($M < 0.08M_\odot$) objects that are not massive enough to sustain hydrogen fusion in their core (*never-will-be star*).

Absorption Line Widths of Stars



(a) A supergiant star has a low-density, low-pressure atmosphere: its spectrum has narrow absorption lines



(b) A main-sequence star has a denser, higher-pressure atmosphere: its spectrum has broad absorption lines

Absorption Line Widths of Stars

The widths of the absorption lines in stellar spectra depends **on the density and pressure of the gas** causing the absorption.

The widths of the absorption lines (especially the H lines) indicate the category (ie. main sequence, giant, supergiant) the star belongs to.

In the 1930s W. W. Morgan and P. C. Keenan of the Yerkes Observatory of the University of Chicago classified stars into **luminosity classes** depending on the widths of their lines.

Luminosity Classes: V (Main sequence), IV (Subgiant), III (Giant), II (Bright giant), Ib(Less luminous supergiant) and Ia(Most Luminous supergiant)

Stellar Luminosity Classes

- A star's full classification includes spectral type (line identities) and luminosity class (line shapes, related to the size of the star):

  I - supergiant
  II - bright giant
  III - giant
  IV - subgiant
  V - main sequence

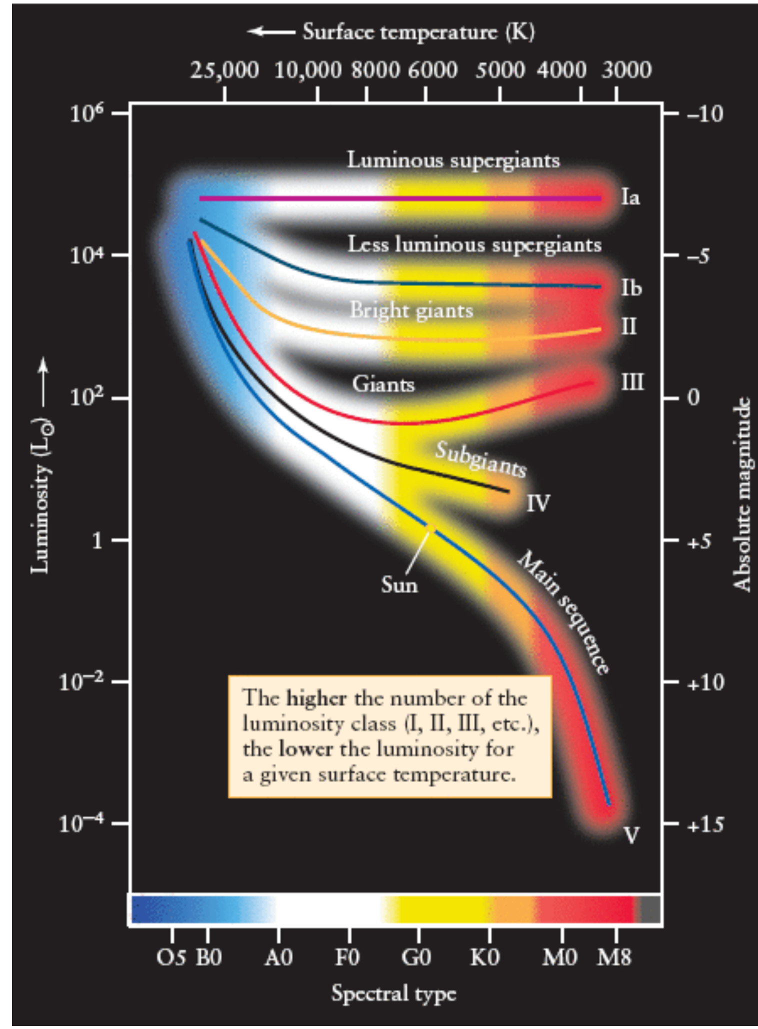
  Examples: Sun - G2 V
  Sirius - A1 V
  Proxima Centauri - M5.5 V
  Betelgeuse - M2 I

Stellar Spectral Type and Luminosity Class

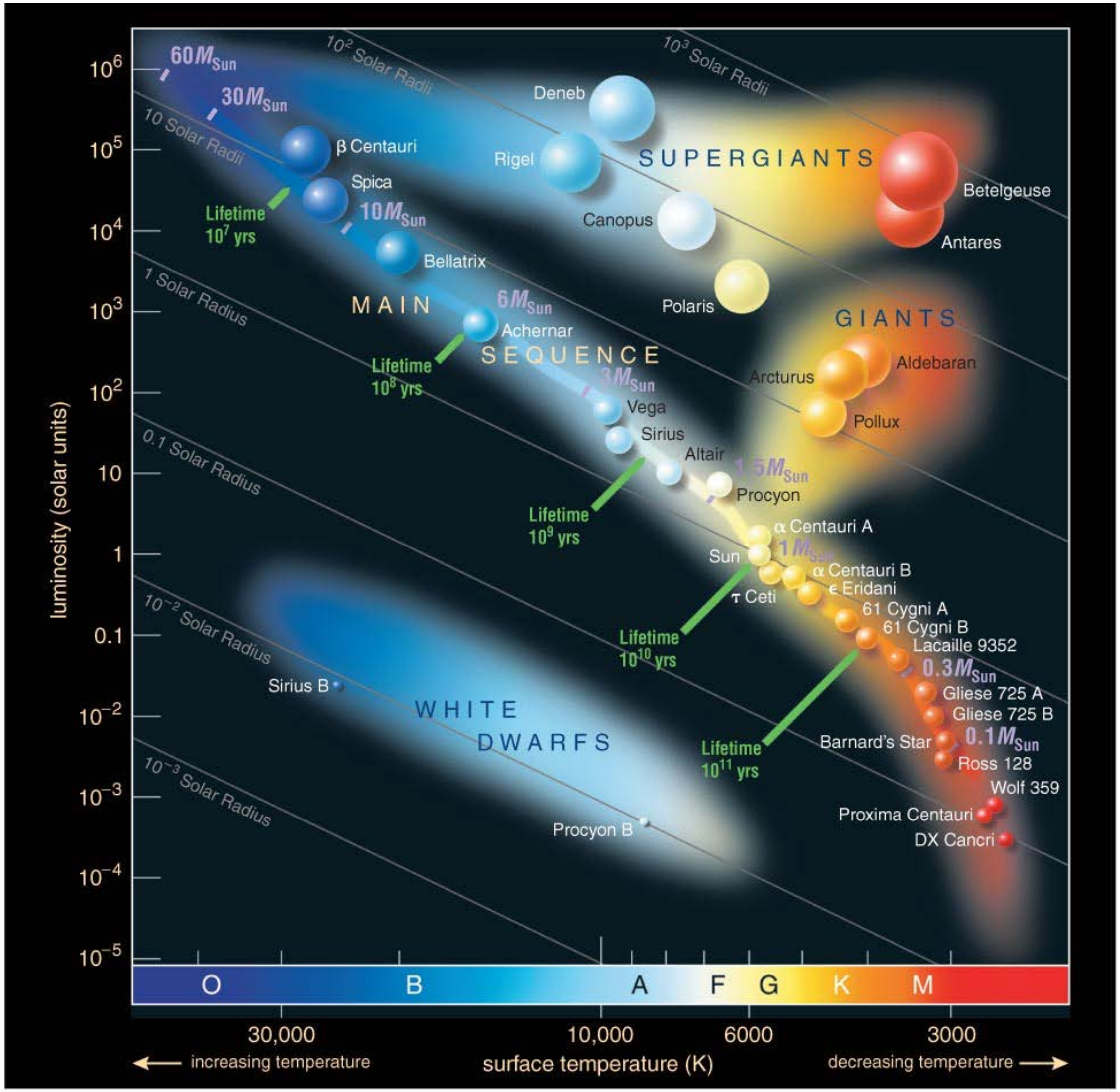
Combining the **spectral type** (which gives the stars temperature) with the **luminosity class** (which indicates on what branch of the H-R diagram the star lies one can estimate the stars luminosity.

Examples: What is the luminosity of

-a G2 V star ?
-a M0 II star ?
-a B0 Ia star ?



H-R diagram with Luminosity Classes..



Luminosity ⟶

⟵ Temperature

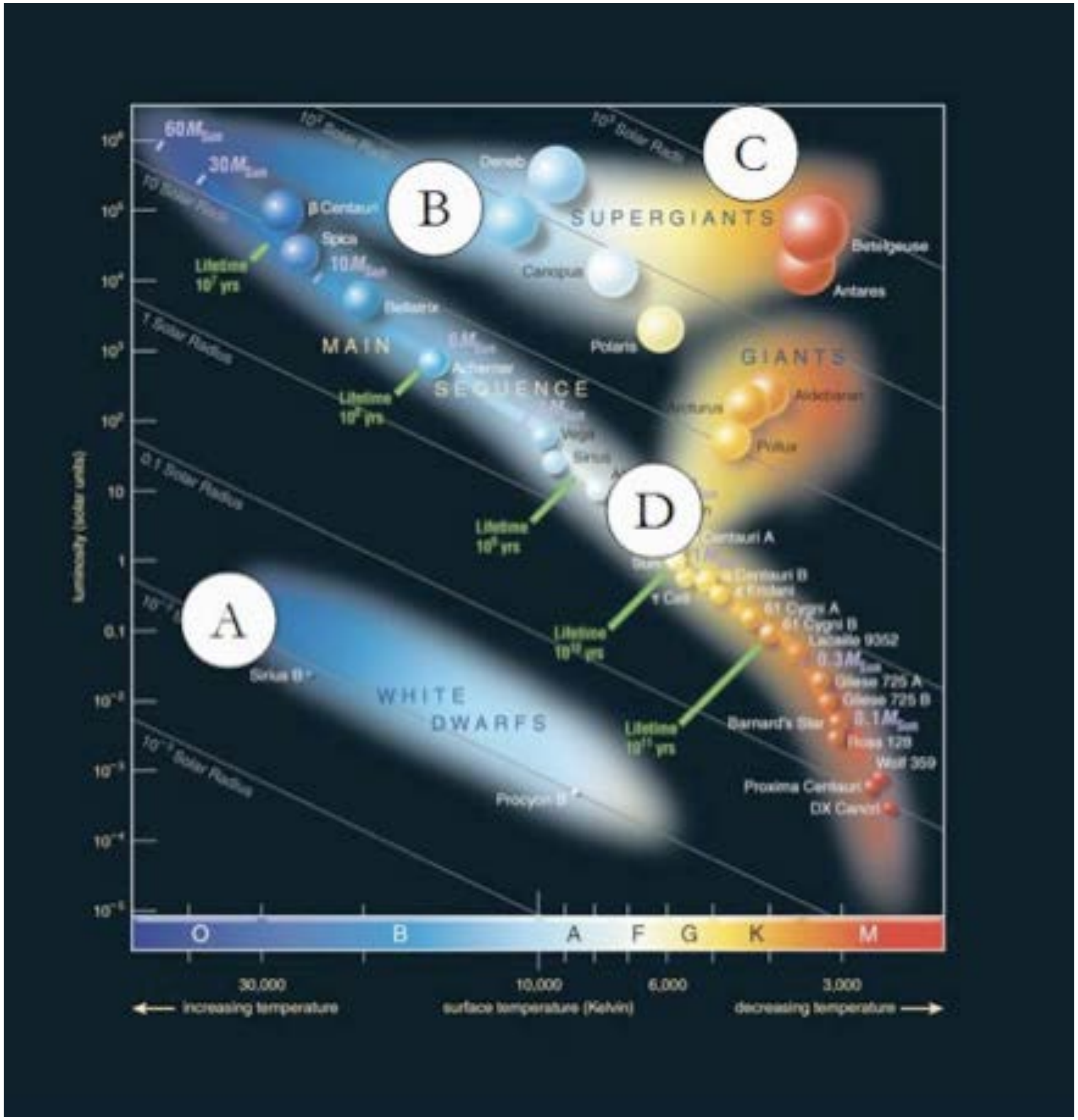
- H-R diagram depicts:

  Temperature

  Luminosity

  Luminosity Class

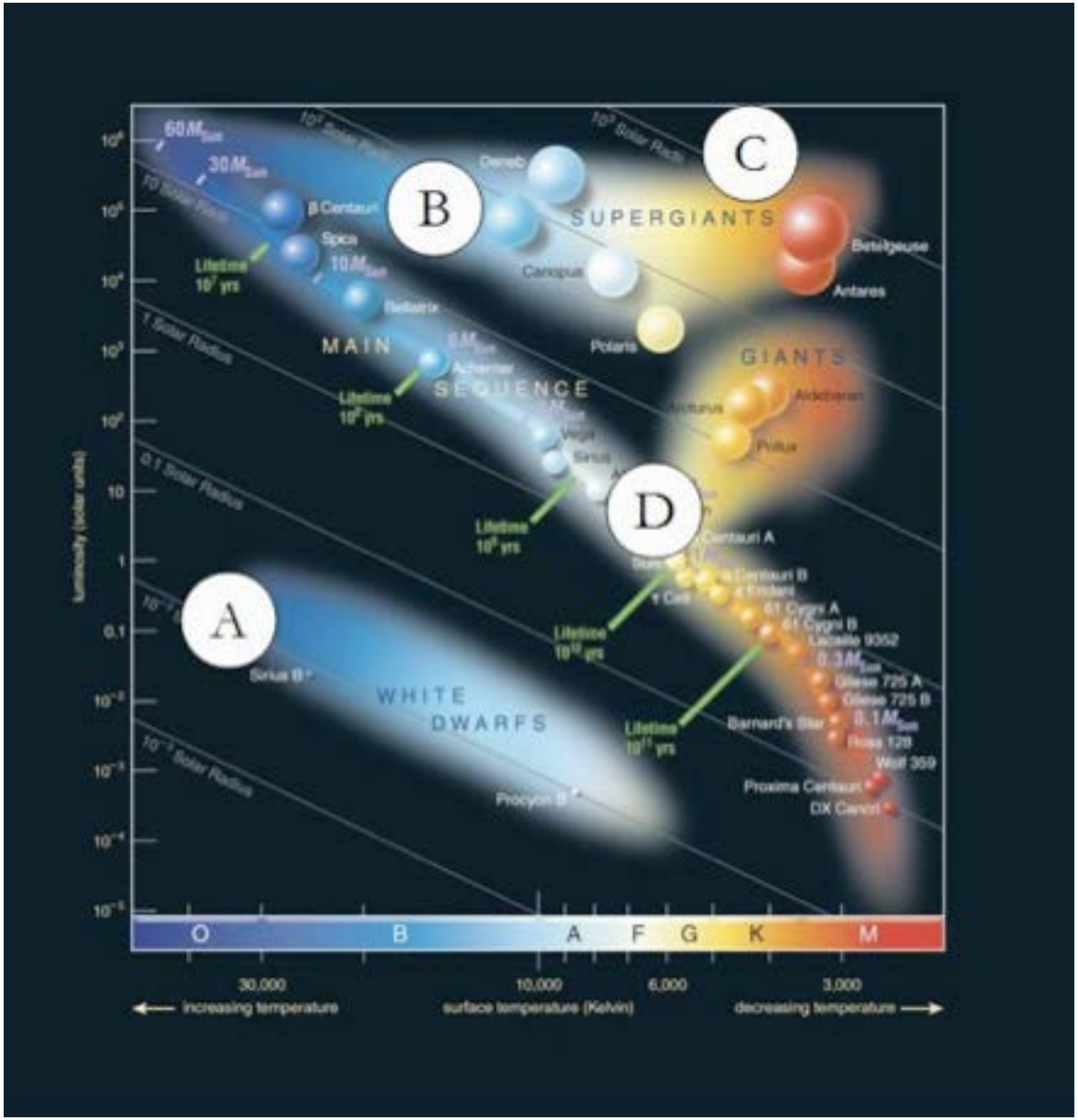
  Radius



Luminosity

Temperature

- Which star is the hottest?

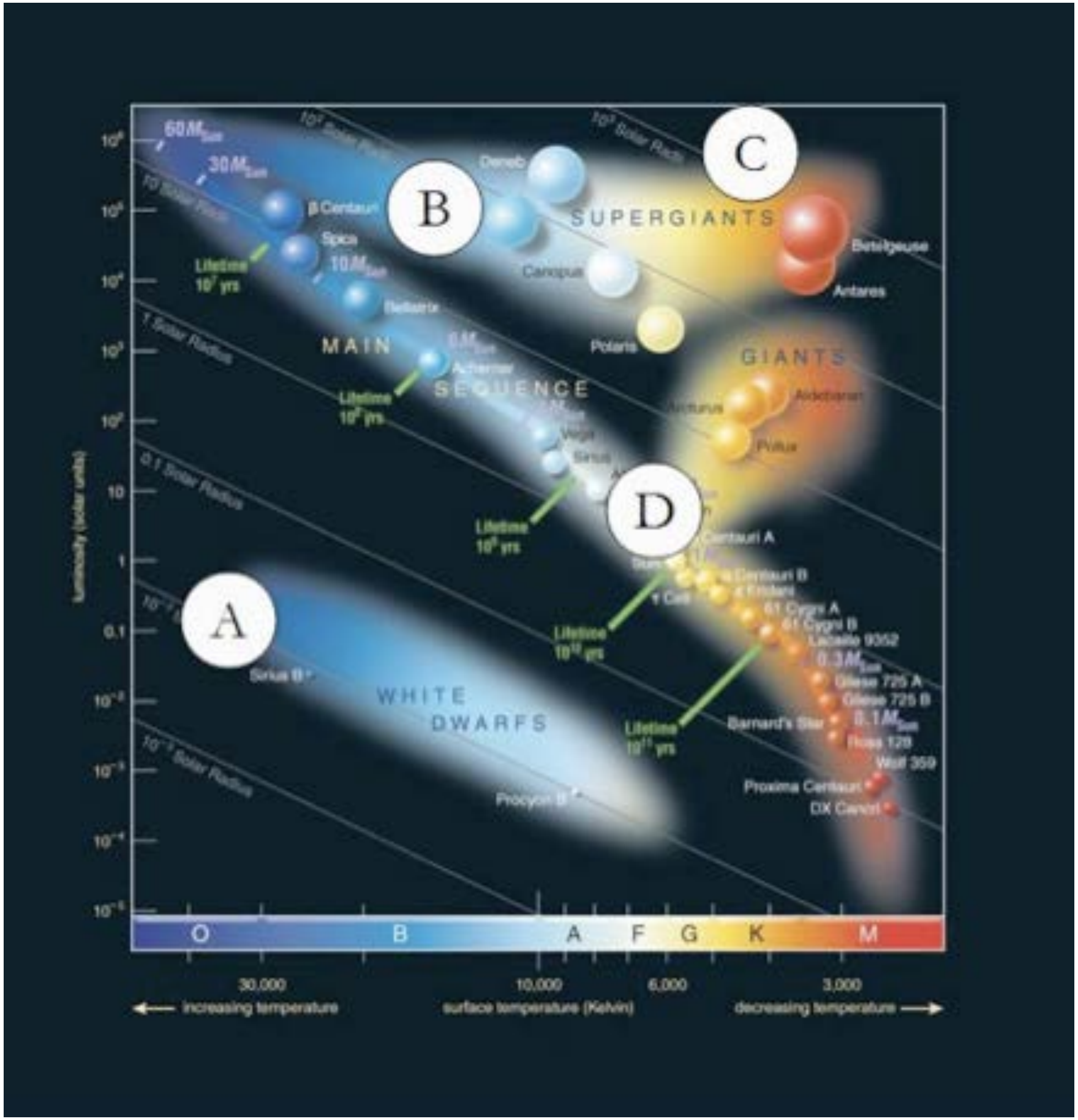


Luminosity

Temperature

- Which star is the hottest?

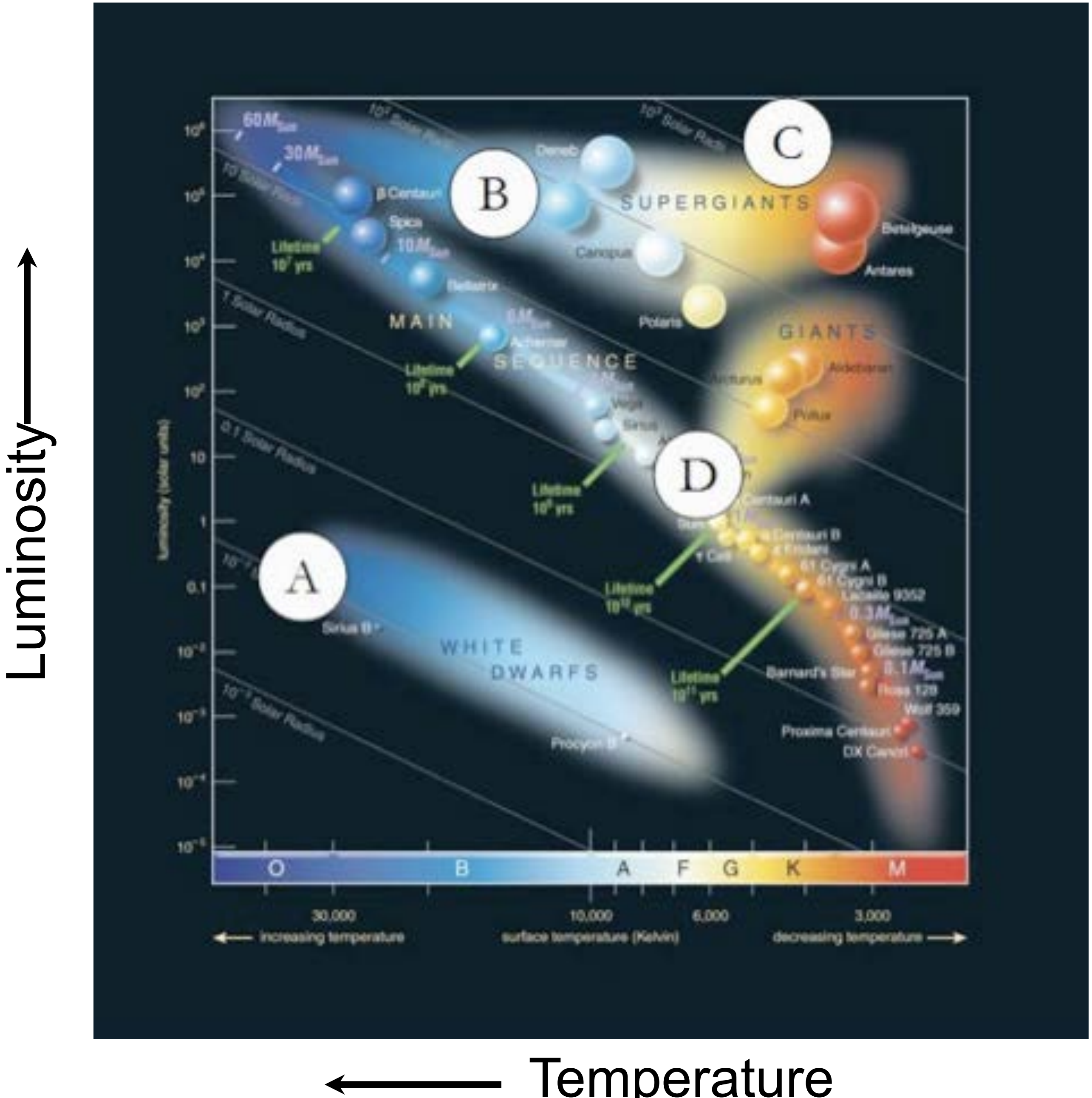
A



Luminosity

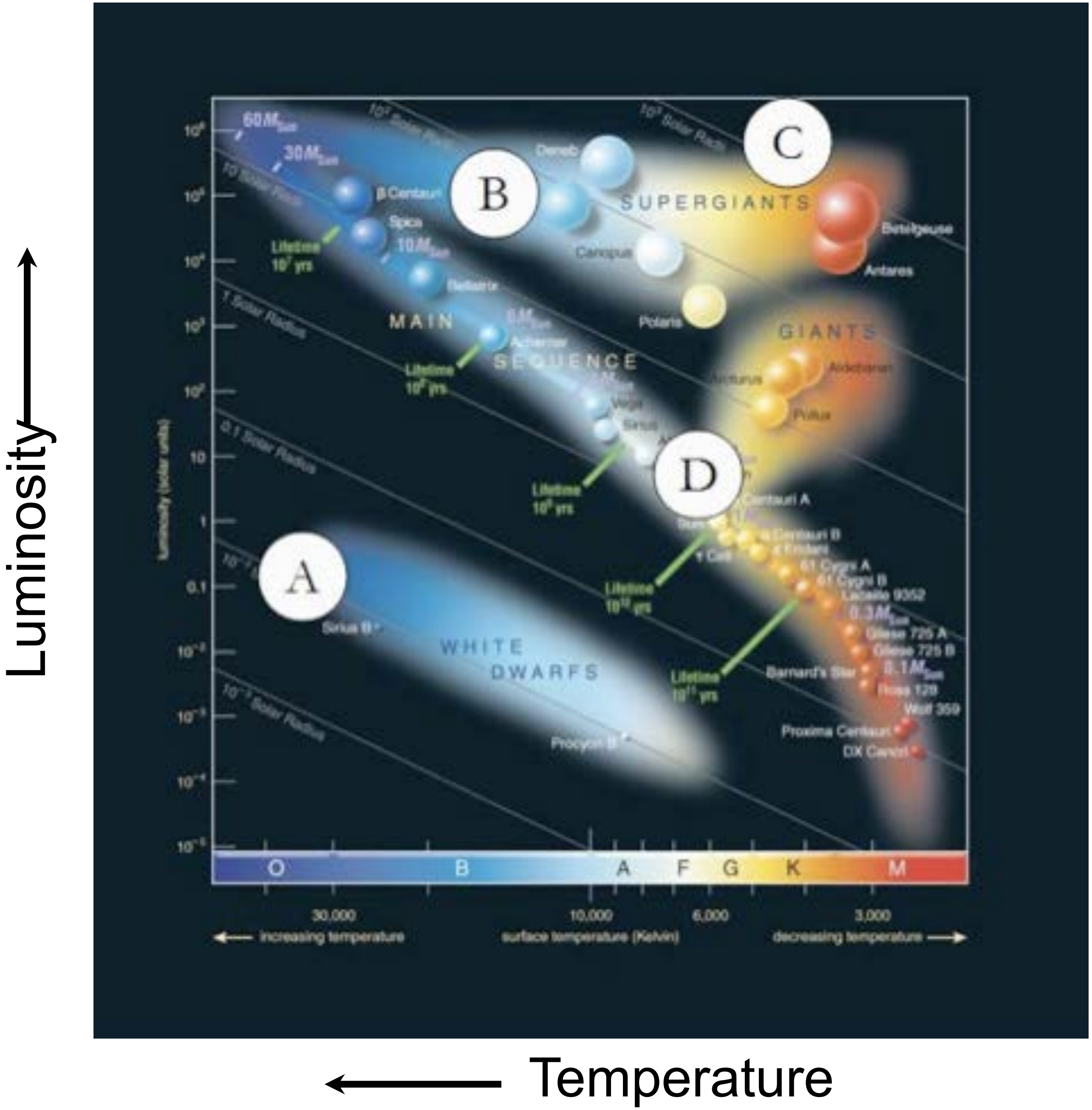
Temperature

- Which star is the most luminous?

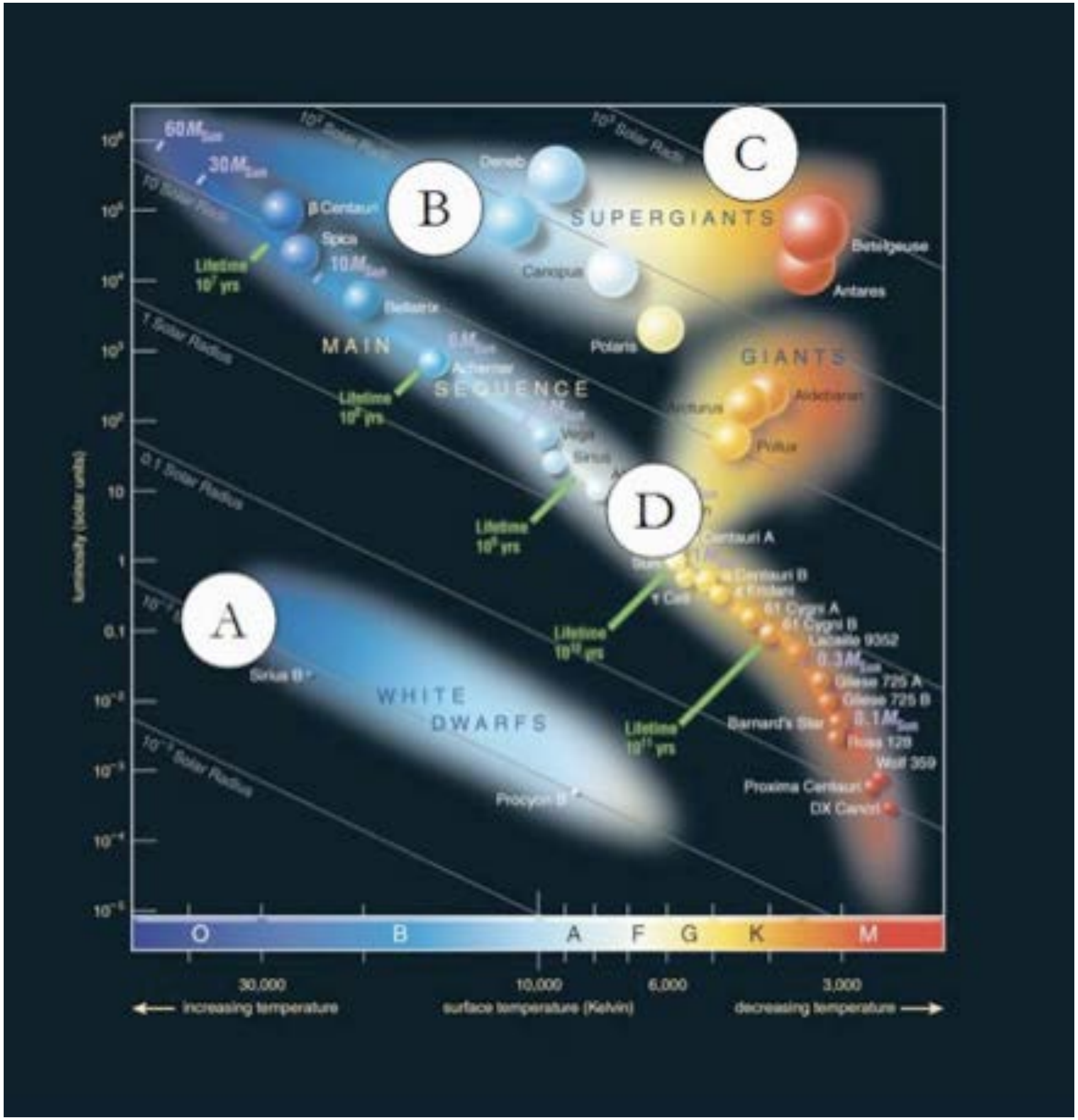


- Which star is the most luminous?

C



- Which star is a main-sequence star?



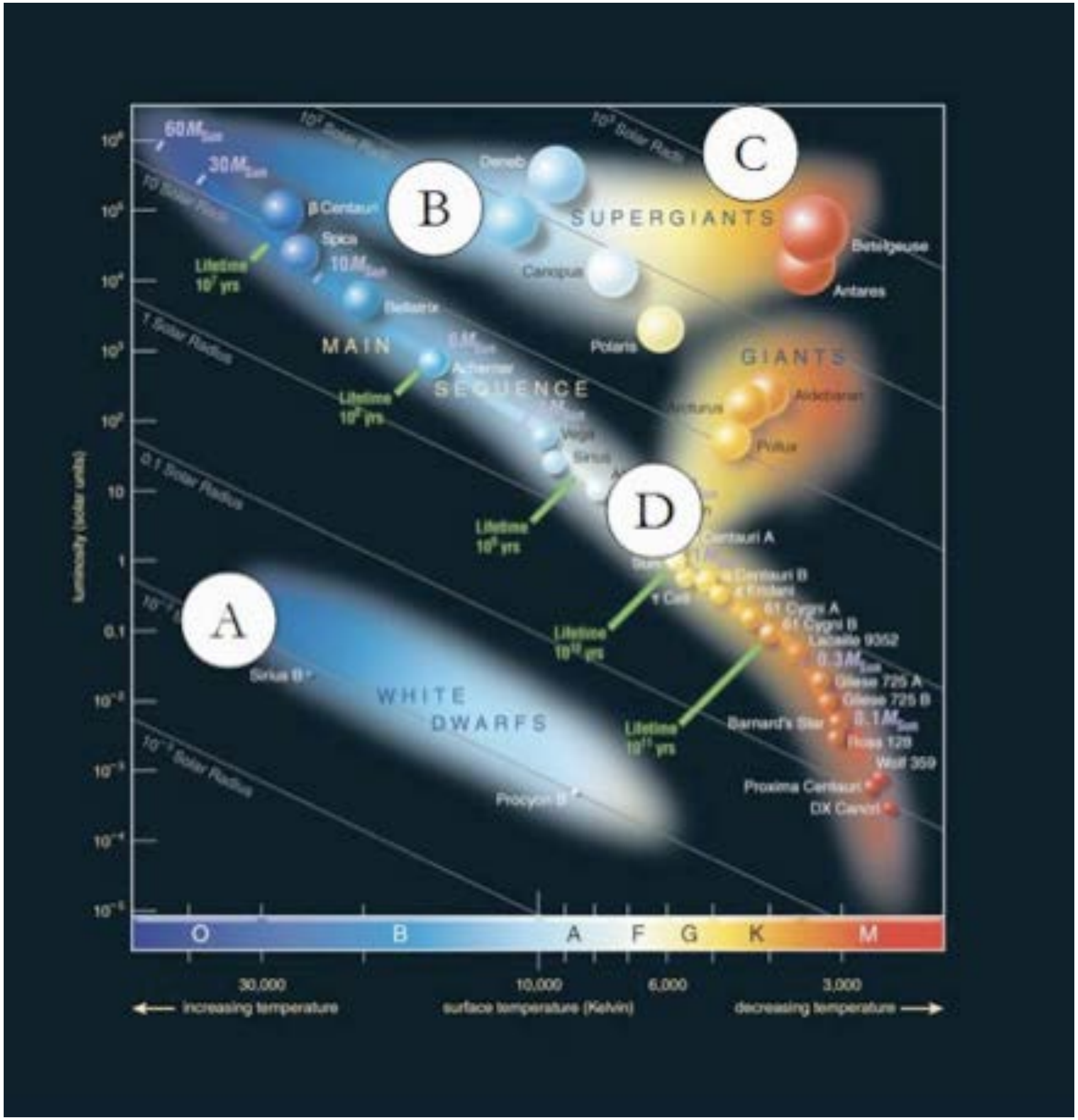
Luminosity

Temperature

- Which star is a main-sequence star?

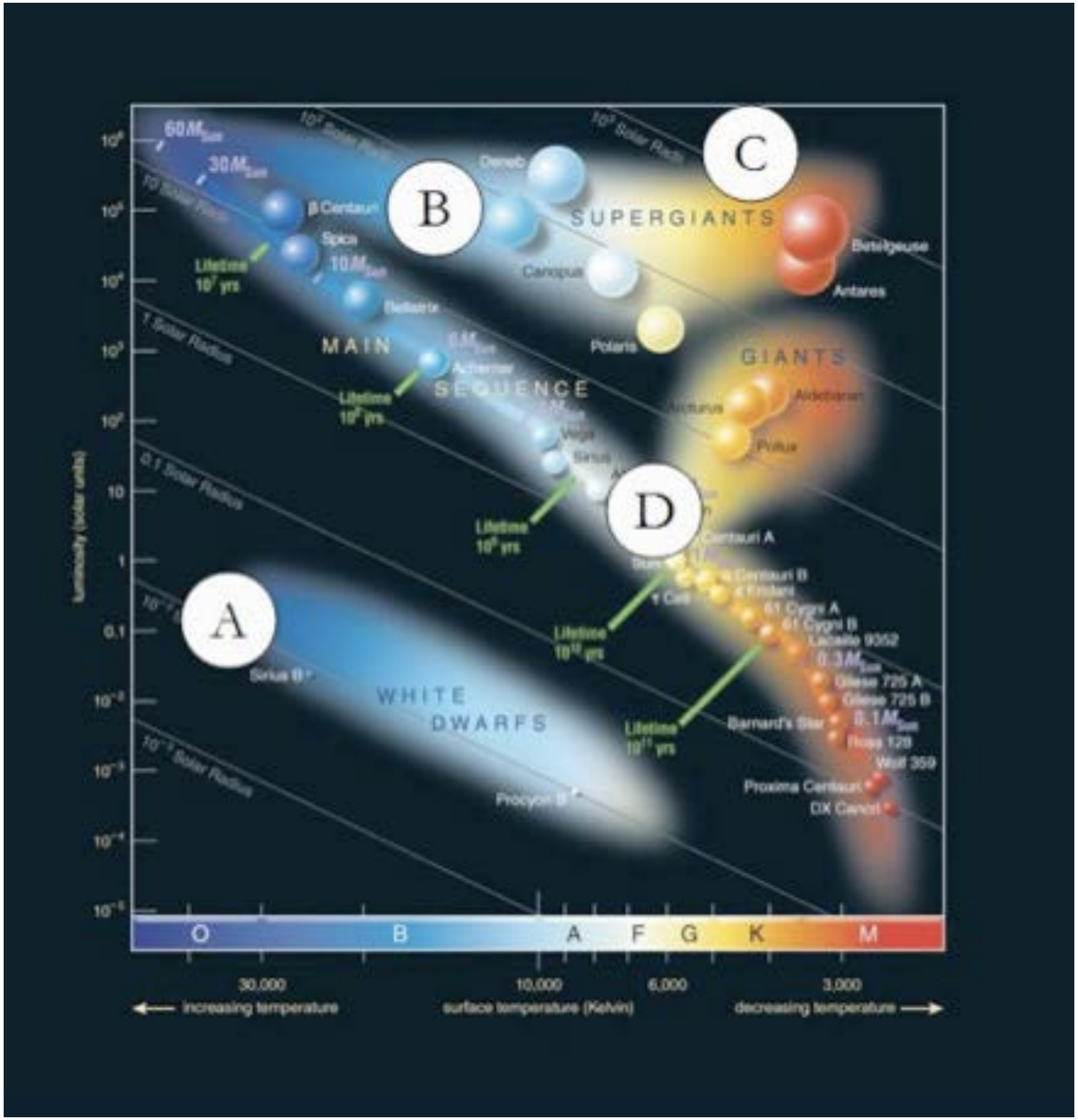
D

Luminosity



Temperature

- Which star has the largest radius?



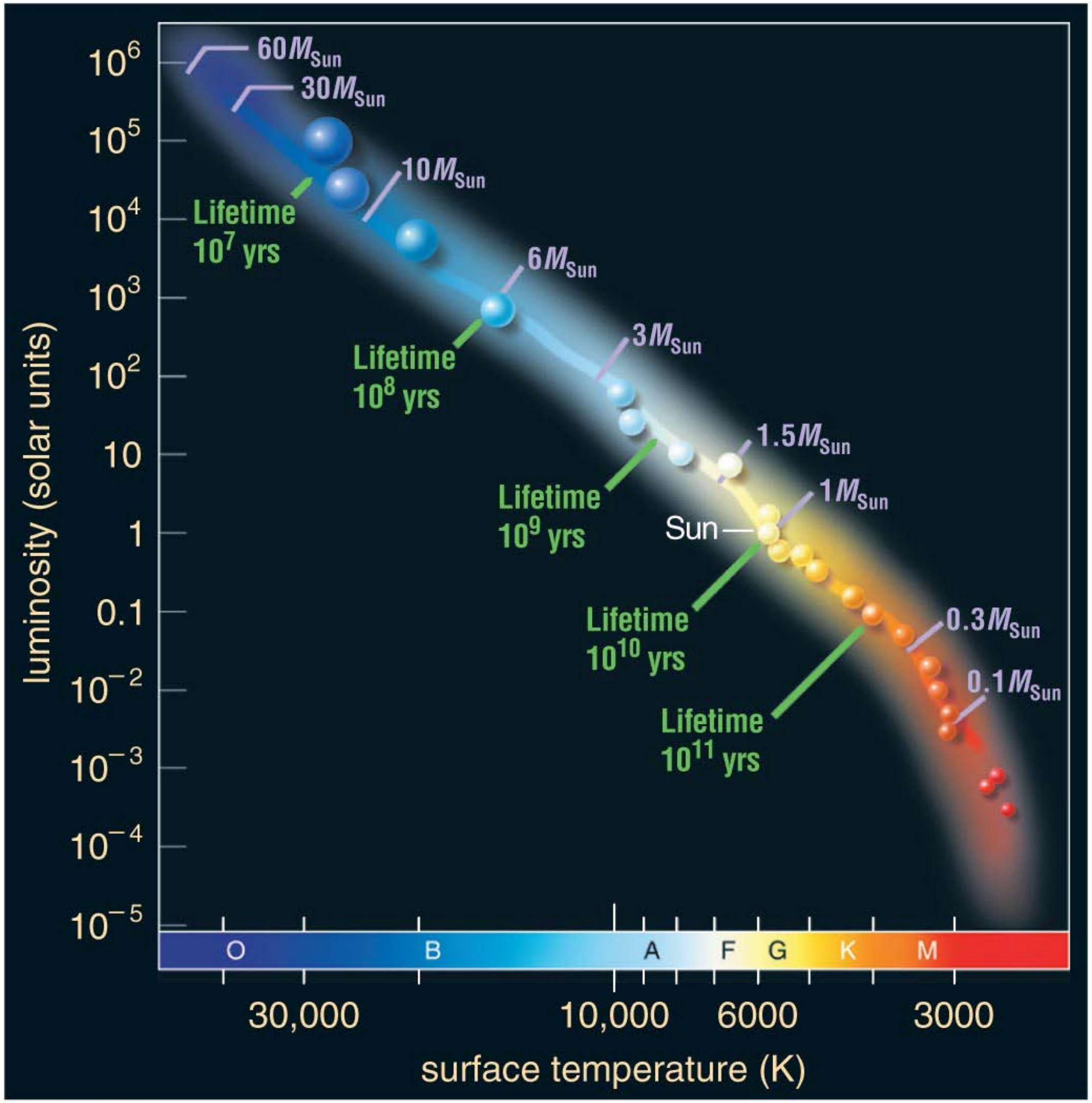
Luminosity

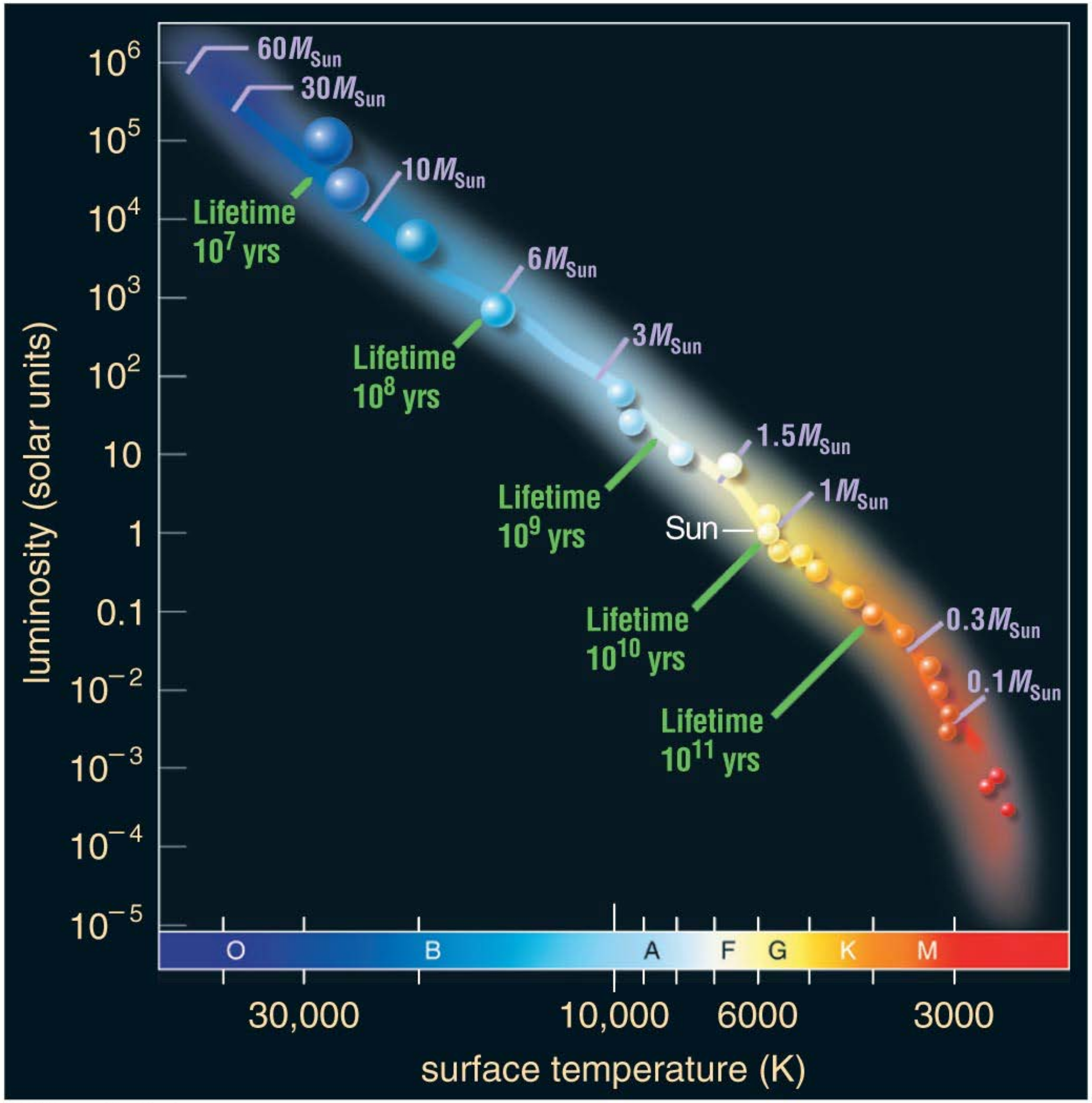
Temperature

- Which star has the largest radius?

C

What is the significance of the main sequence?

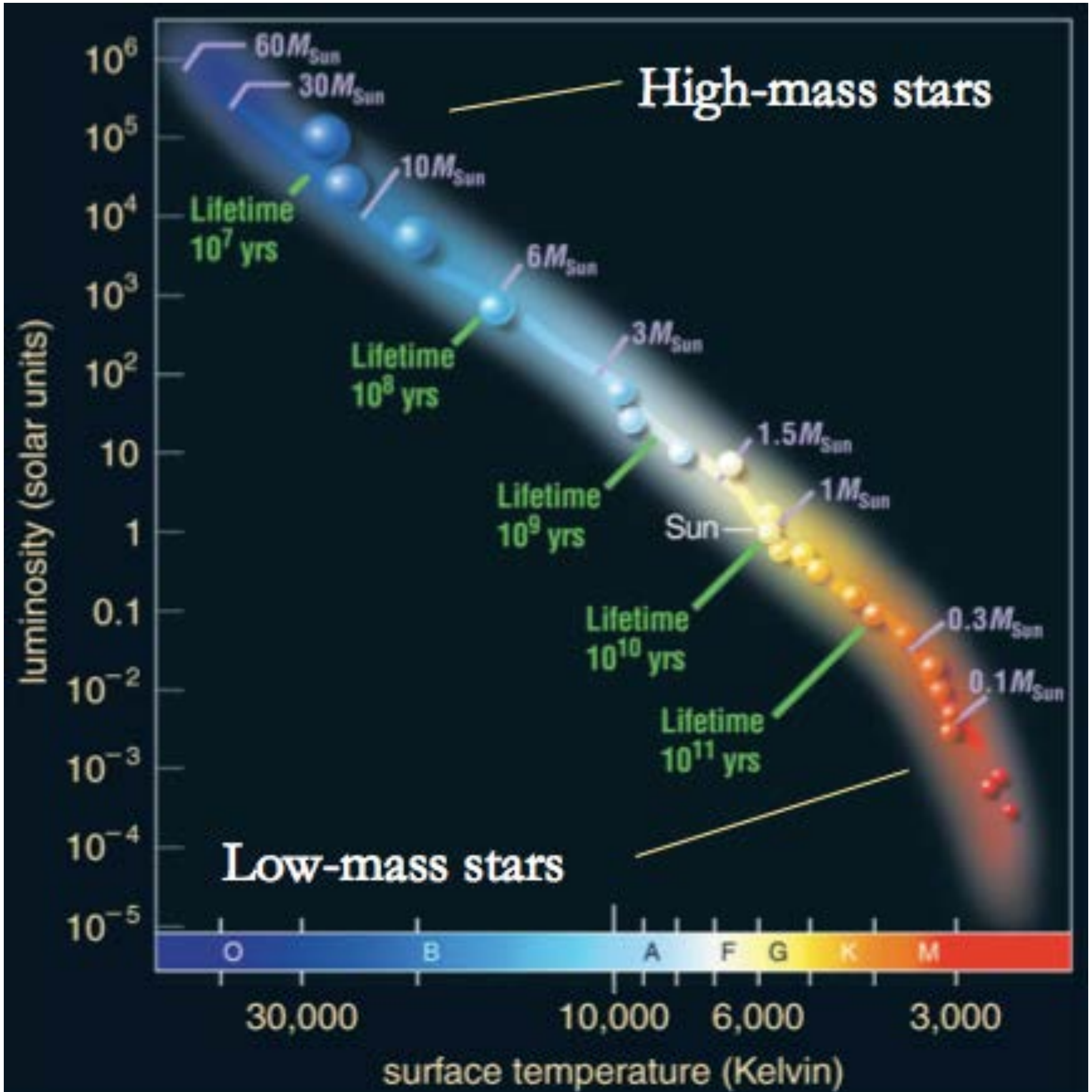




- ***Main-sequence stars*** are fusing hydrogen into helium in their cores like the Sun.

- Luminous main-sequence stars are hot (blue).

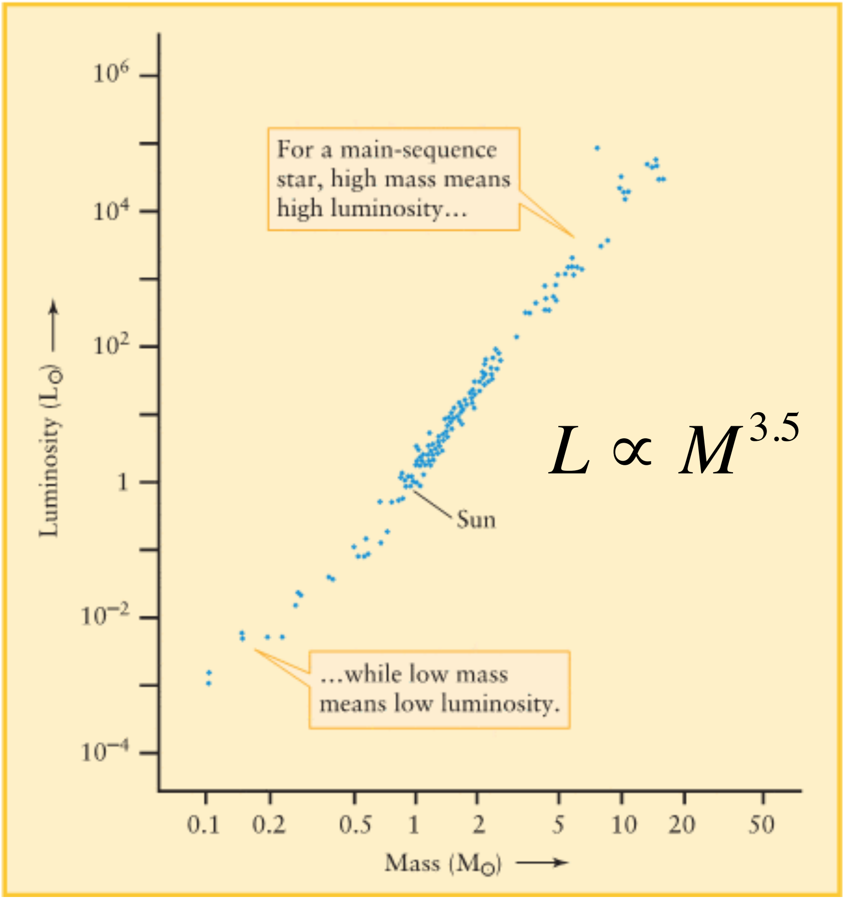
- Less luminous ones are cooler (yellow or red).



- Mass measurements of main-sequence stars show that the hot, blue stars are much more massive than the cool, red ones.

Mass-Luminosity Relation for Main Sequence Stars

Explaining the M-L correlation: The more massive a star the larger the pressure, density and temperature in its core in order to balance gravity. This leads to a larger fusion reaction rate and thus a larger luminosity.



$$L \propto M^{3.5}$$

Stellar Properties Review

- ***Luminosity:*** from apparent brightness and distance

  (0.08M_{Sun}) $10^{-4}L_{Sun}$–$10^{6}L_{Sun}$ **(100M_{Sun})**

- ***Temperature:*** from color and spectral type

  (0.08M_{Sun}) 3000 K–50,000 K **(100M_{Sun})**

- ***Mass:*** from period (p) and average separation (a) of binary star orbit

  $0.08M_{Sun}$–$100M_{Sun}$

Mass and Lifetime

- ***Sun's life expectancy ~*** 12 billion years

How long will a star remain on the main sequence?

$E = fMc^2$, where f is the fraction of the star's mass that's converted into energy

$$L = \frac{E}{t} \Rightarrow t = \frac{E}{L} = \frac{fMc^2}{L} \propto \frac{M}{M^{3.5}} = \frac{1}{M^{2.5}}$$

$$t_{star} = t_{solar}\left(\frac{M_{solar}}{M_{star}}\right)^{2.5}, \quad t_{solar} = 1.2 \times 10^{10}\,\text{years}$$

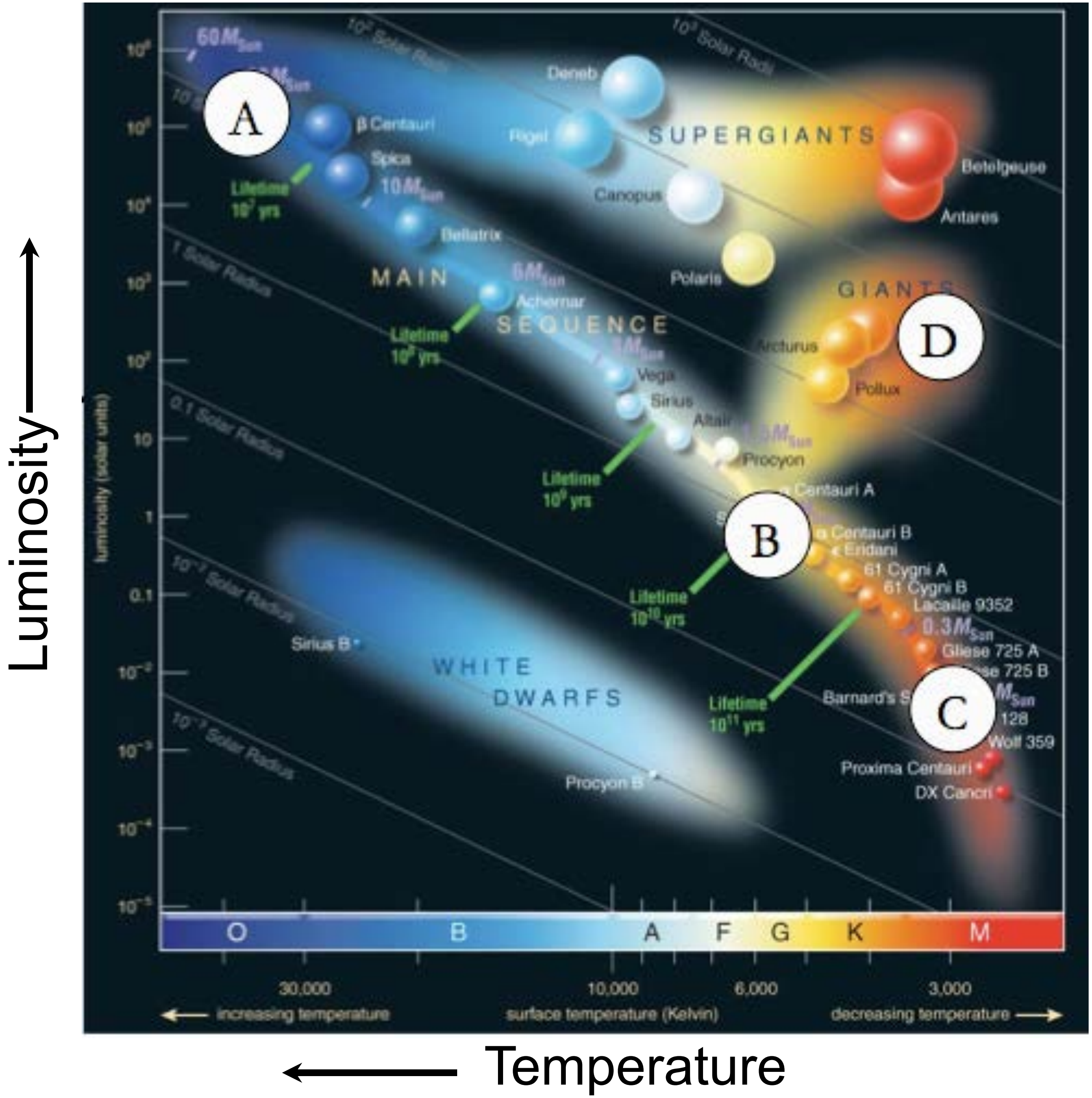
What are giants, supergiants, and white dwarfs?

Off the Main Sequence

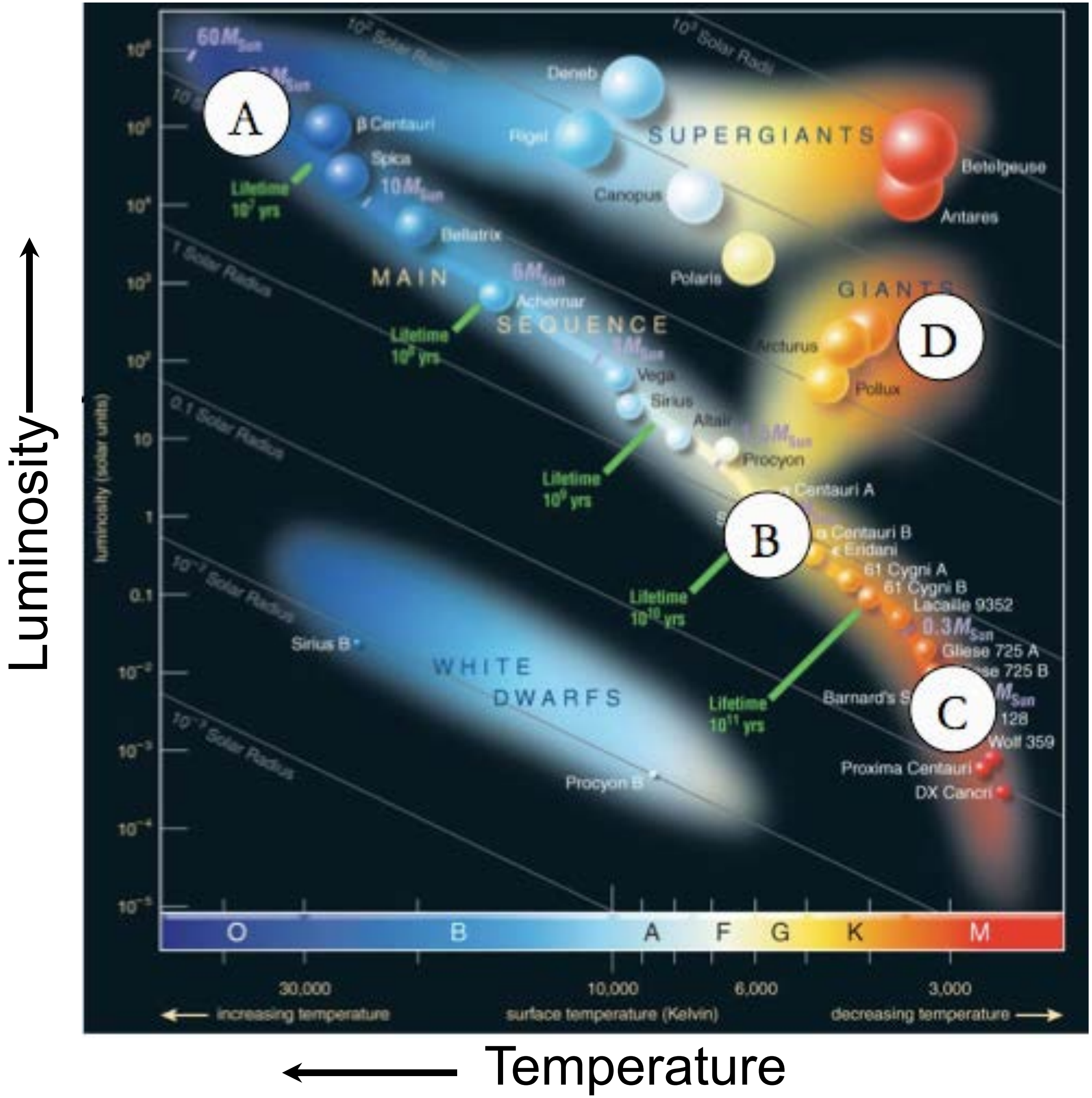
- Stellar properties depend on both mass and age: Those that have finished fusing H to He in their cores are no longer on the main sequence.

- All stars become larger and redder after exhausting their core hydrogen: **giants** and **supergiants.**

- Most low mass stars end up small and white after fusion has ceased: **white dwarfs.**

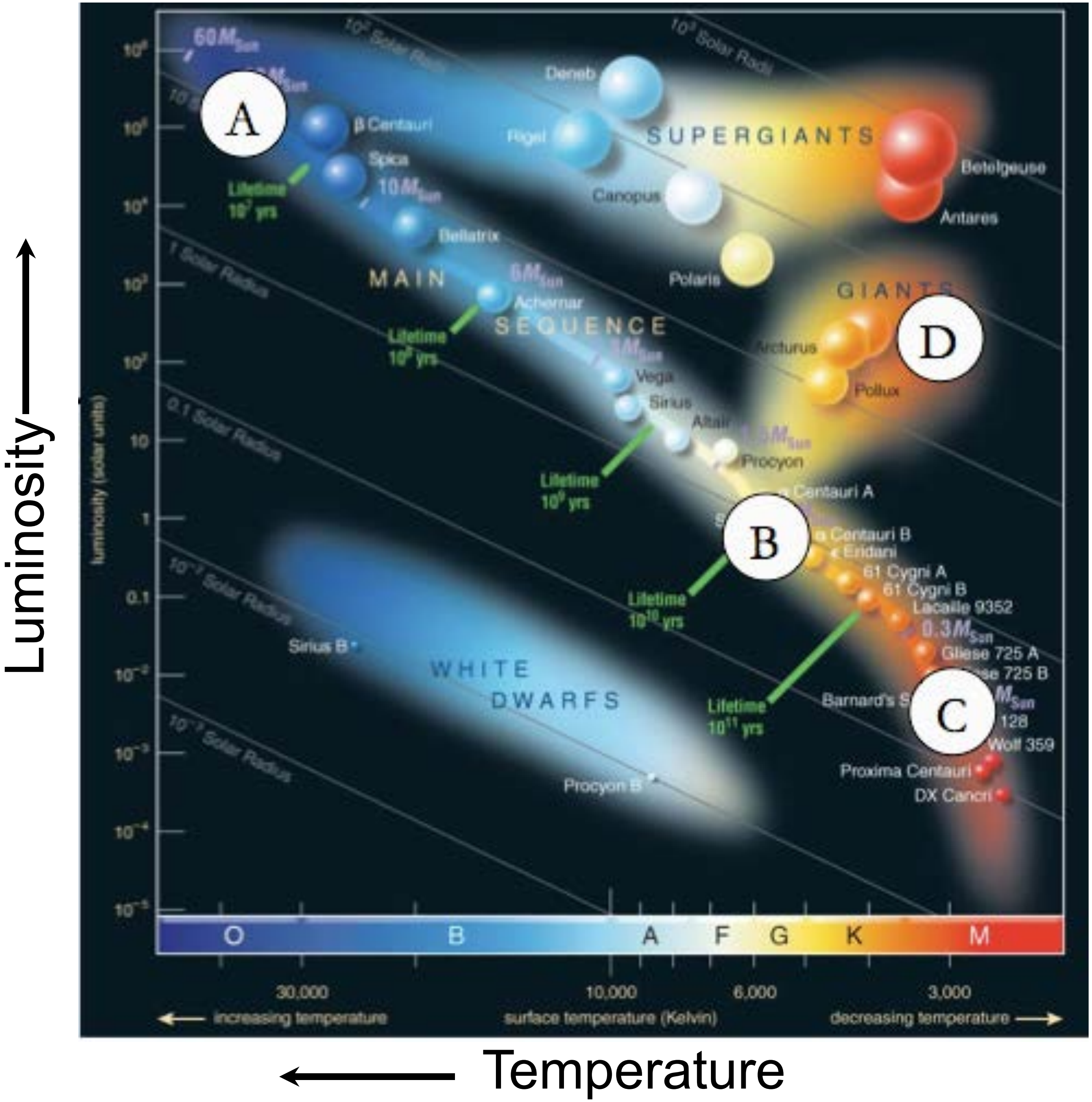


- Which star is most like our Sun?

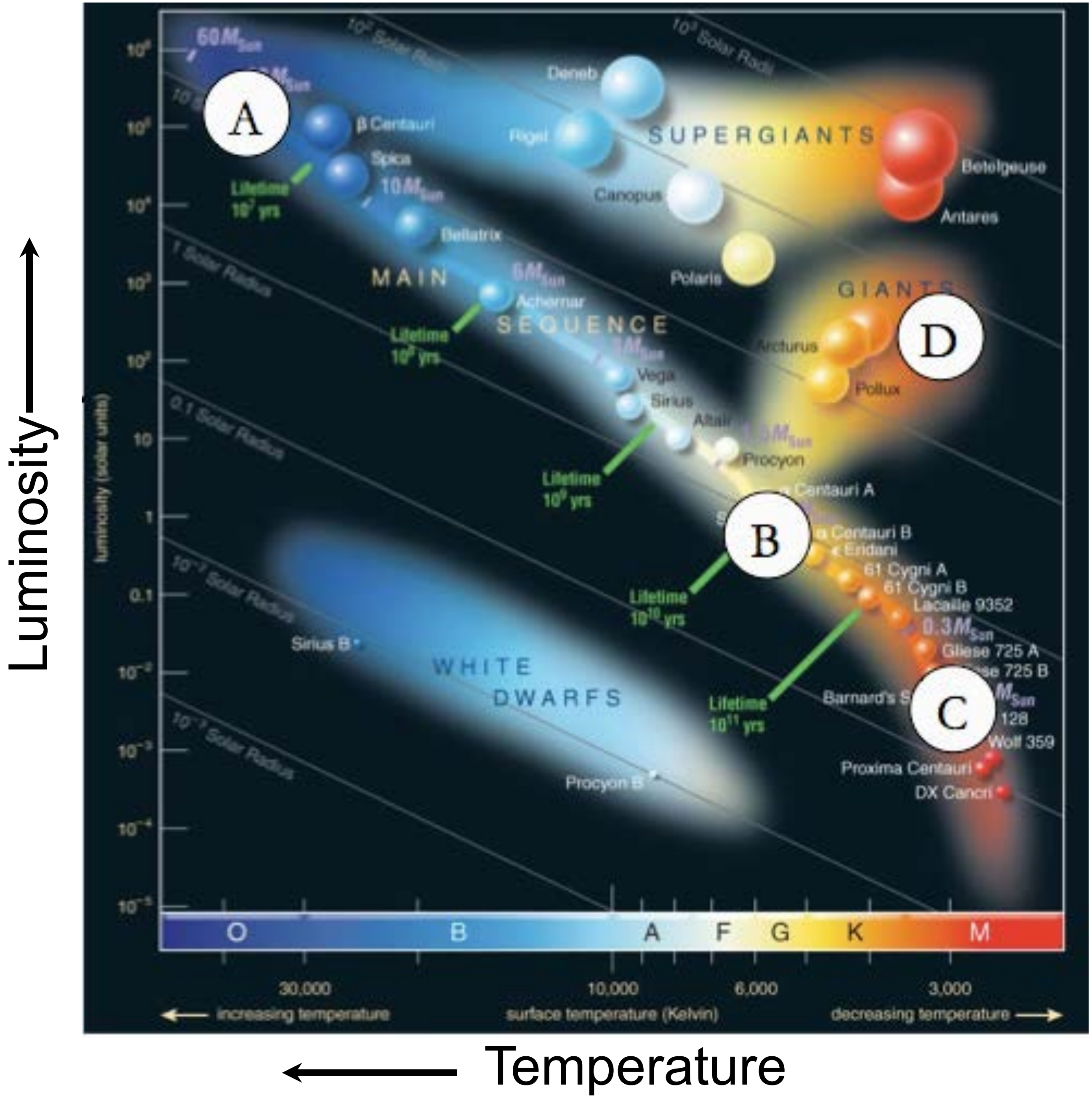


- Which star is most like our Sun?

B

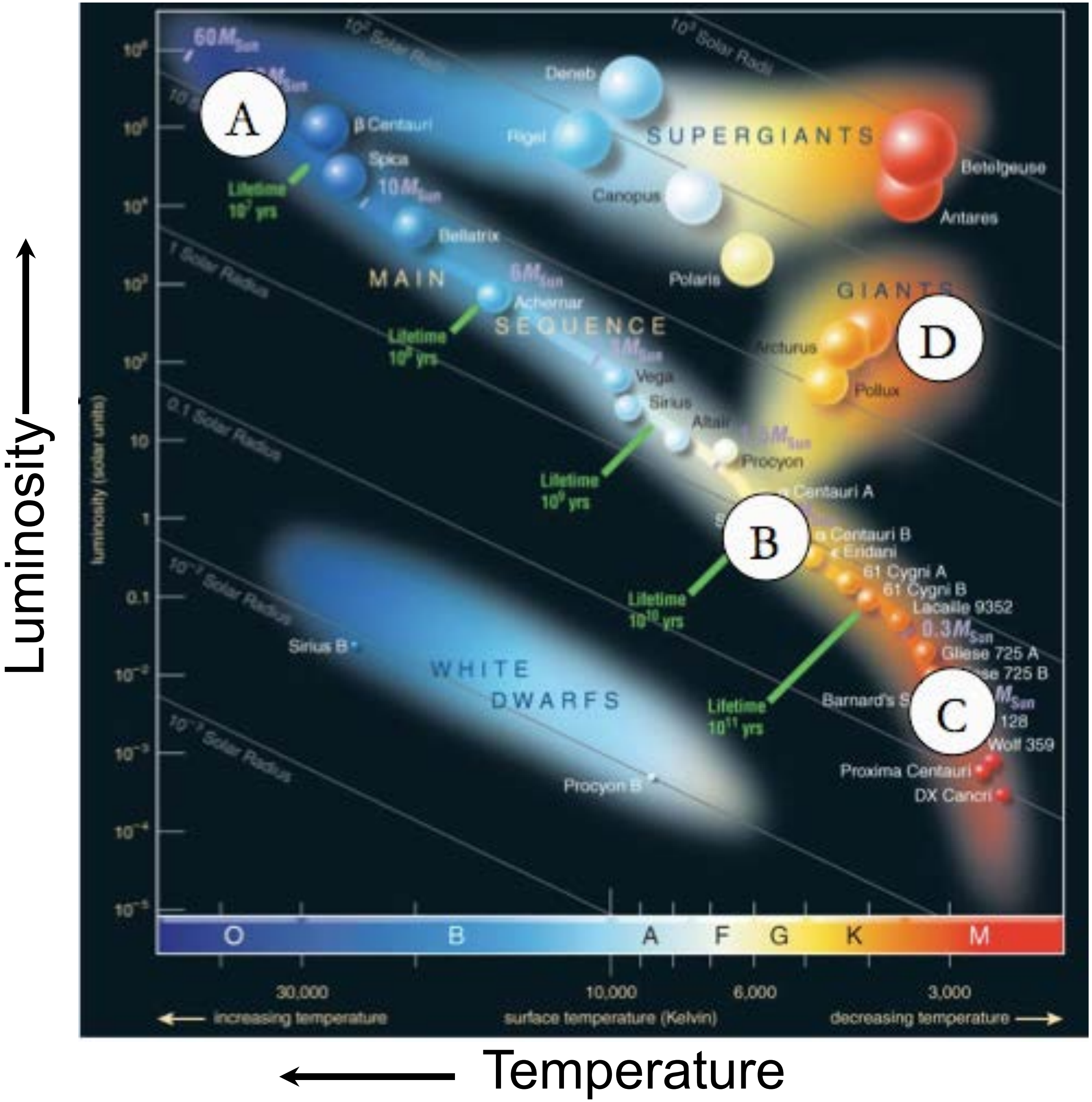


- Which of these stars will have changed the least 10 billion years from now?

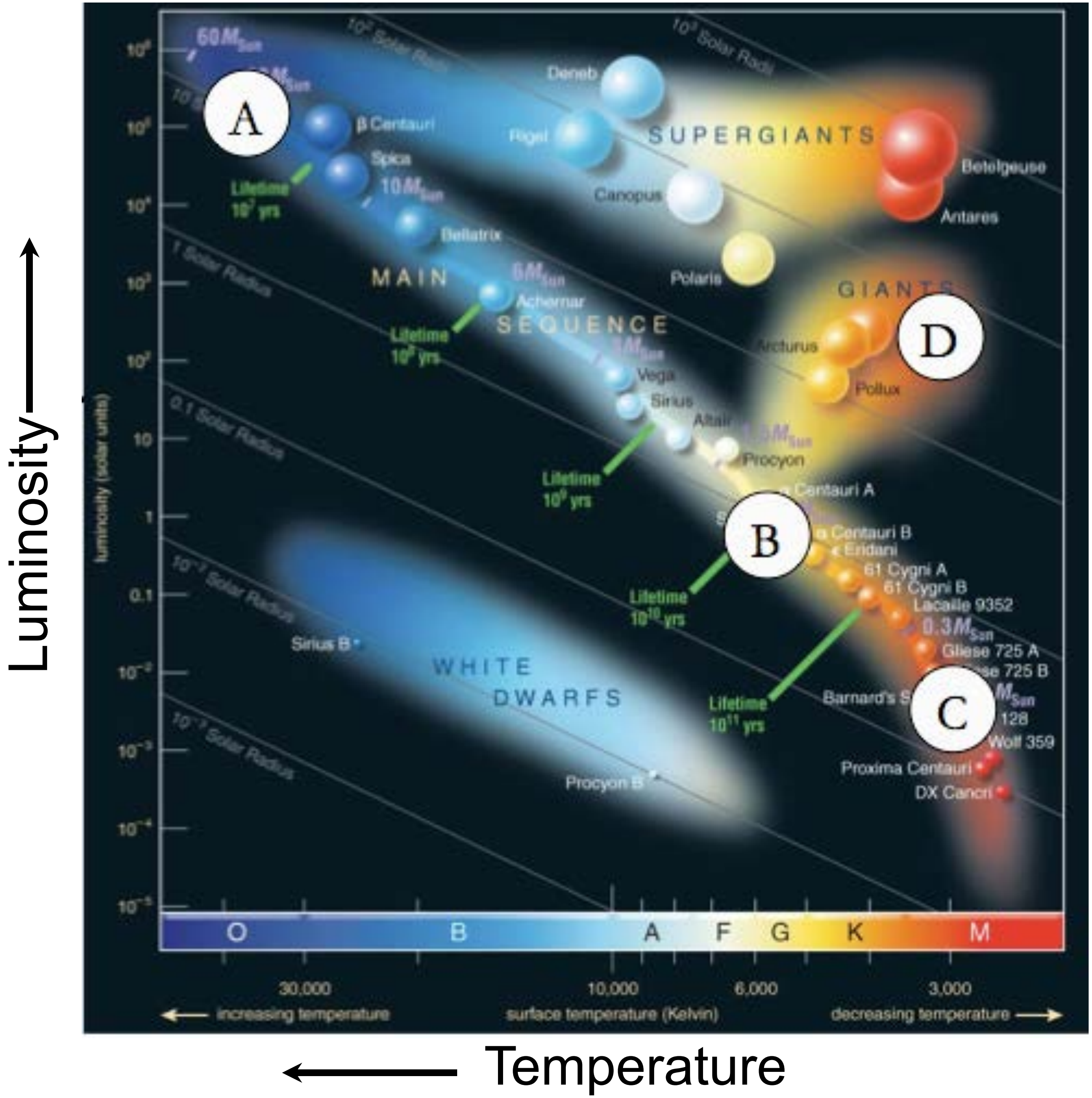


- Which of these stars will have changed the least 10 billion years from now?

C



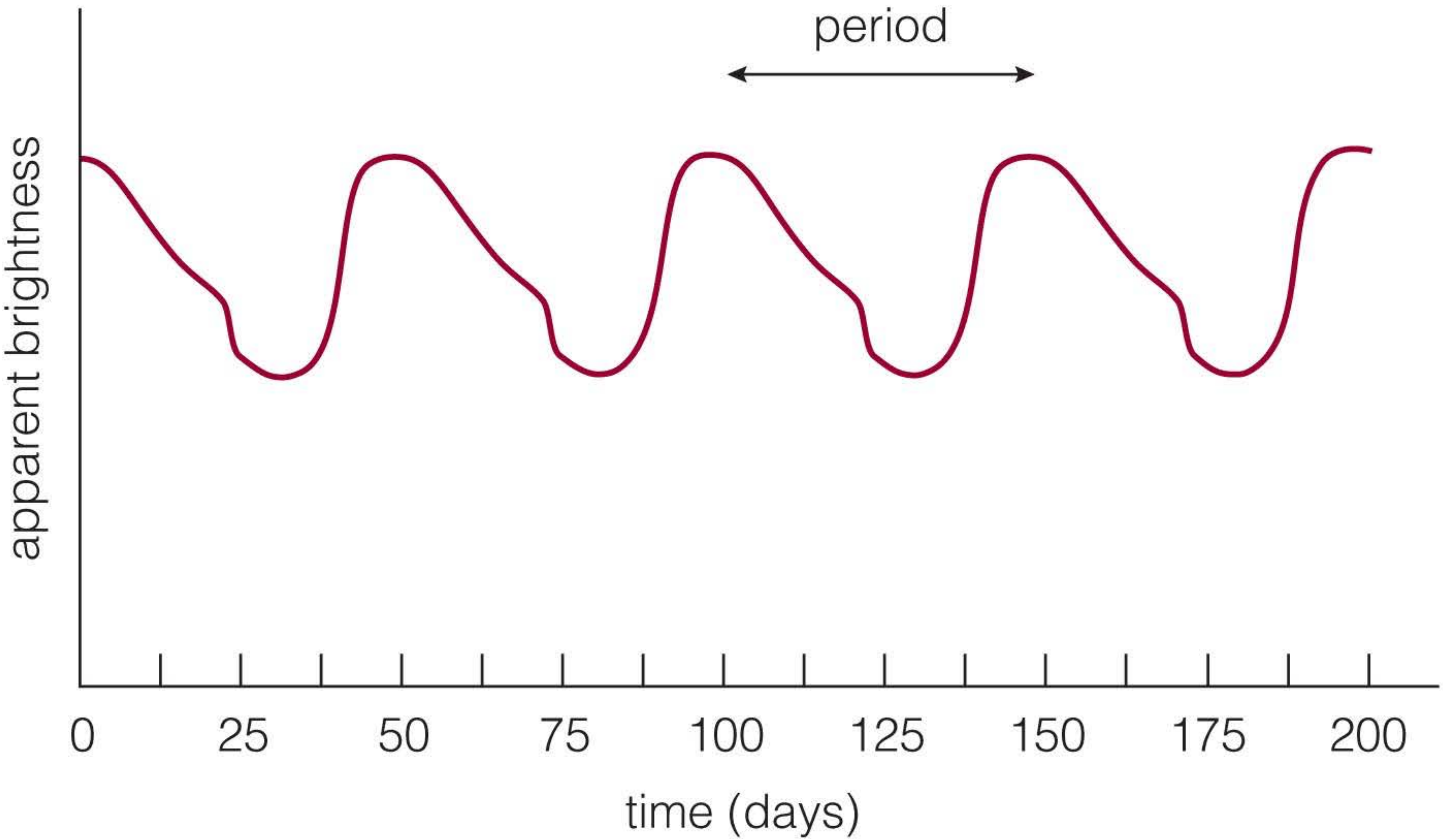
- Which of these stars can be no more than 10 million years old?



- Which of these stars can be no more than 10 million years old?

A

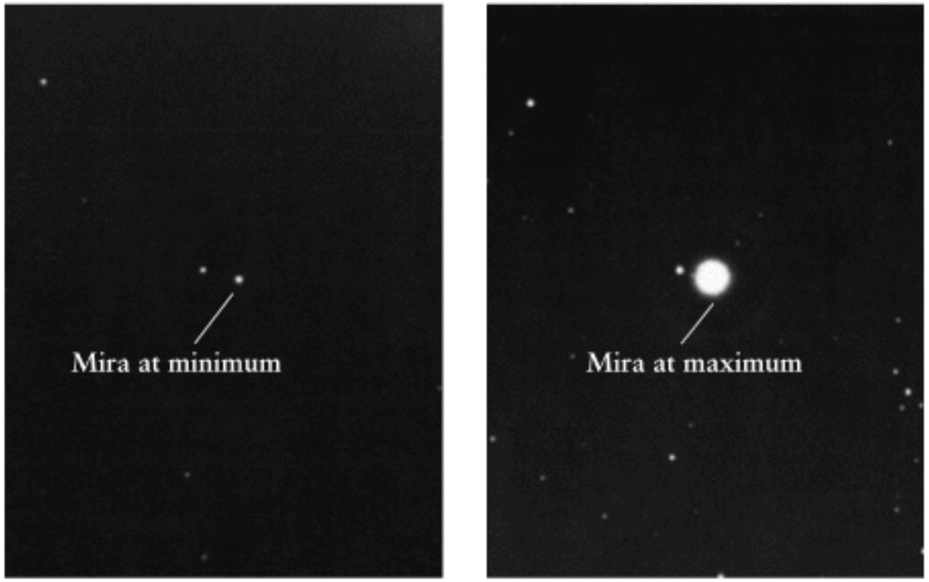
Variable Stars



Variable Stars: Long-Period Variables

Many stars are found to pulsate in size and brightness. These stars are called **pulsating variable stars**.

Long-period variables are **pulsating cool red giants** that vary in brightness by a factor of 100 over a period of months to years. Typical surface temperatures of long-period variables are ~3,500K and luminosities of 10-10,000 L_{solar}.



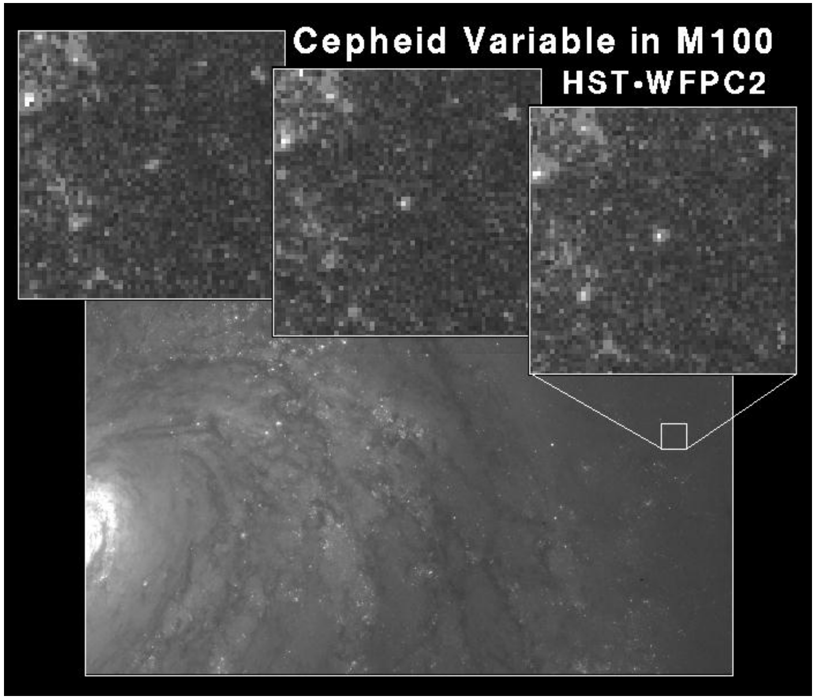
(a) (b)

The first **long-period variable** star discovered was Mira (Period ~ 332 days).

Variable Stars: Cepheid Variables

Pulsating supergiant stars that exhibit rapid brightening followed by gradual dimming with periods ranging from a few to a hundred days **are called Cepheid variables**.

The first Cepheid variable discovered was δ Cephei.



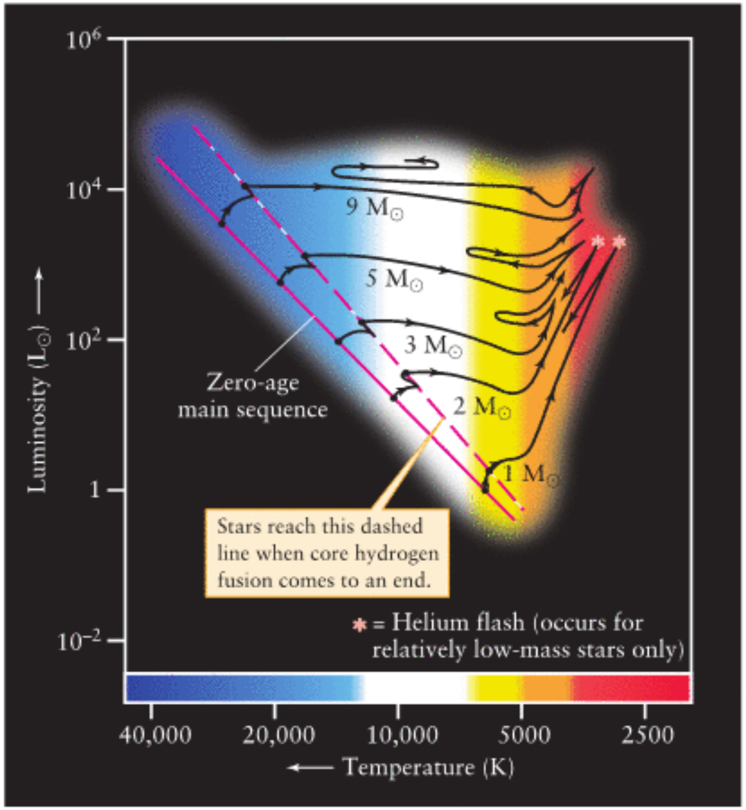
Variable Stars: RR Lyrae Stars

RR Lyrae variables are pulsating horizontal branch stars of spectral class A (and rarely F), with a mass of around half the Sun's. Their periods are less than one day and they are **commonly found in globular clusters**.

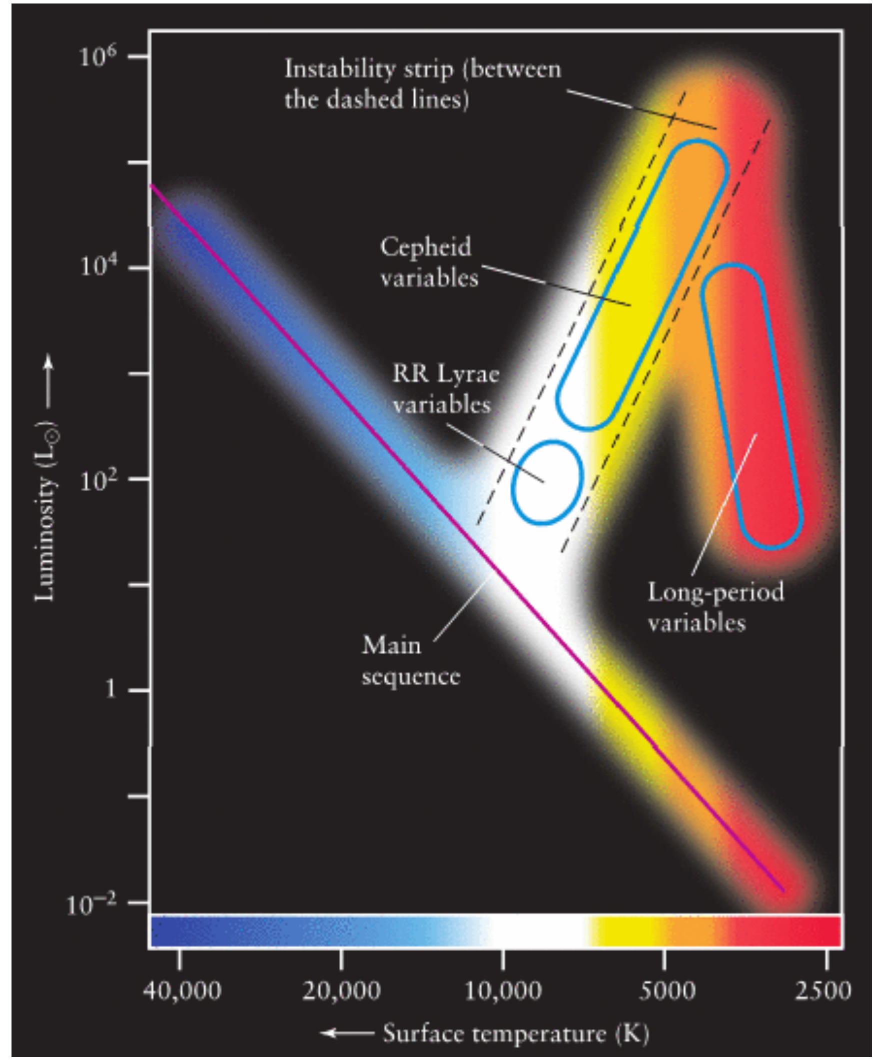
RR Lyrae stars are old, relatively low mass, metal-poor "Population II" stars.

RR Lyrae stars are named for their prototype RR Lyrae in the constellation Lyra.

Variable Stars



(a) Post-main-sequence evolutionary tracks of five stars with different mass



After He fusion begins stars move across an instability strip near the middle of the H-R diagram where they begin to pulsate.

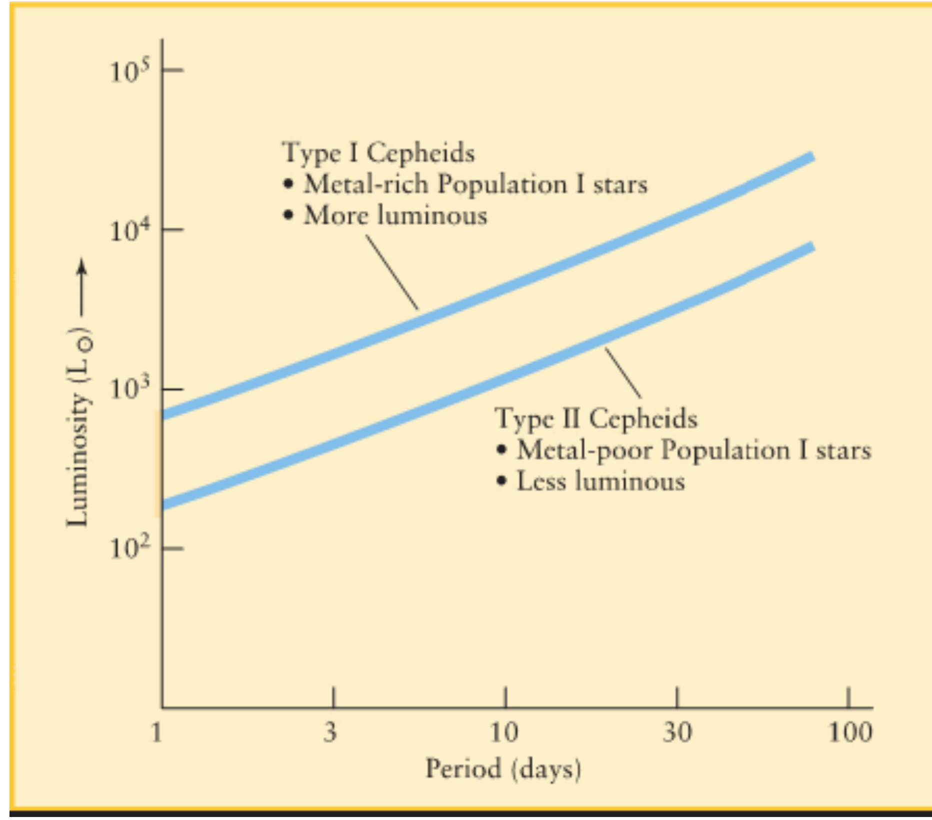
Cepheid Variables: Period-Luminosity Relation

The **P-L relation** together with the brightness of a Cepheid are **used to infer its distance.**

The abundance of metals in a Cepheid's outer layers plays a significant role on how it pulsates.

Metal rich Cepheids are called **Type I Cepheids.**

Metal poor Cepheids are called **Type II Cepheids.**



The period of a Cepheid's pulsations is correlated to its **average luminosity**.

What have we learned?

- **What is a Hertzsprung-Russell diagram?**
  - An H-R diagram plots stellar luminosity of stars versus surface temperature (or color or spectral type).
- **What is the significance of the main sequence?**
  - Normal stars that fuse H to He in their cores fall on the main sequence of an H-R diagram.
  - A star's mass determines its position along the main sequence (high-mass: luminous and blue; low-mass: faint and red).

What have we learned?

- **What are giants, supergiants, and white dwarfs?**
  - All stars become larger and redder after core hydrogen burning is exhausted: **giants** and **supergiants**.
  - Most stars end up as tiny **white dwarfs** after fusion has ceased.
- **Why does the brightness of some stars vary?**
  - Some stars fail to achieve balance between power generated in the core and power radiated from the surface.

15.3 Star Clusters

- Our goals for learning:
  - **What are the two types of star clusters?**
  - **How do we measure the age of a star cluster?**

What are the two types of star clusters?

Star Clusters

Large cold and dense clouds of gas and dust can collapse to form groups of stars referred to as **star clusters**.

There are two main types of star clusters: open and globular clusters.

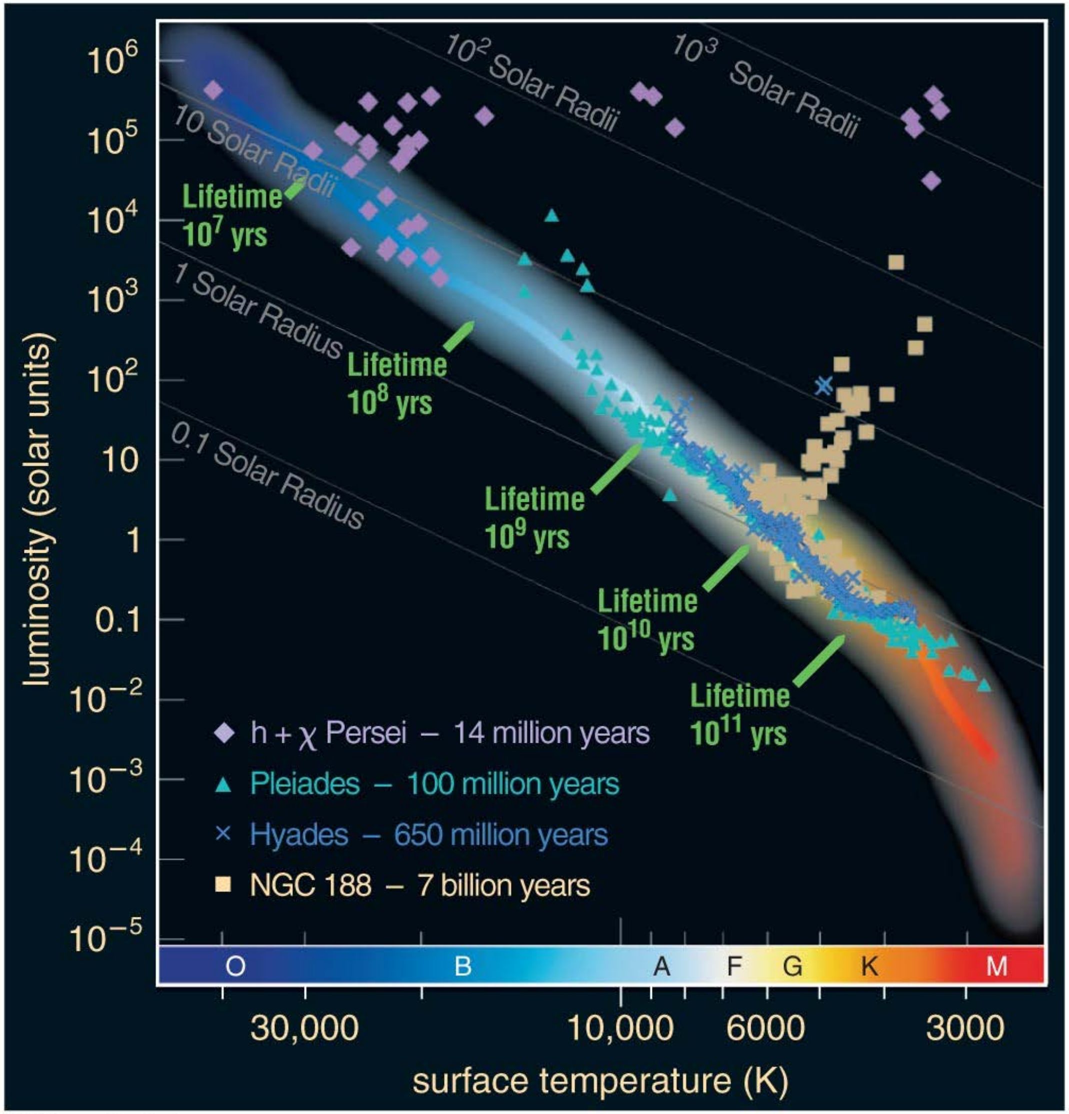
Because the stars in a star cluster were all born at roughly the same time, the different **properties of all the stars in a cluster are a function only of mass.** By studying star clusters we see how stars of different mass evolve differently.

Over time, radiation pressure from the cluster will disperse the molecular cloud. Typically, ~ **10% of the mass of a gas cloud will coalesce into stars** before radiation pressure drives the rest away.

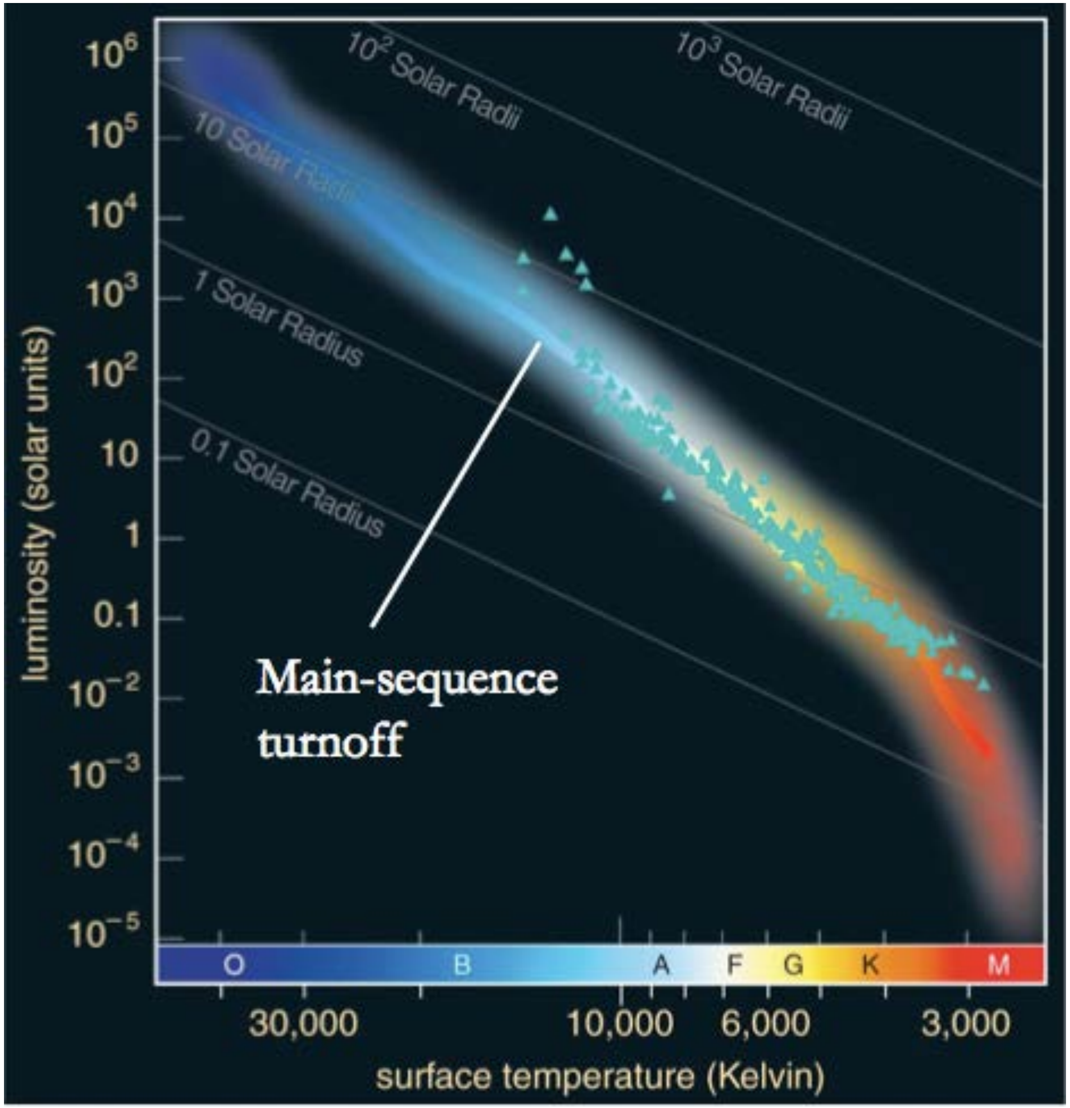
- ***Open cluster:*** is a group of up to a few thousand stars that were formed from the same giant molecular cloud and are still loosely gravitationally bound to each other.

- ***Globular cluster:*** Up to a million or more stars in a dense ball tightly bound together by gravity

How do we measure the age of a star cluster?



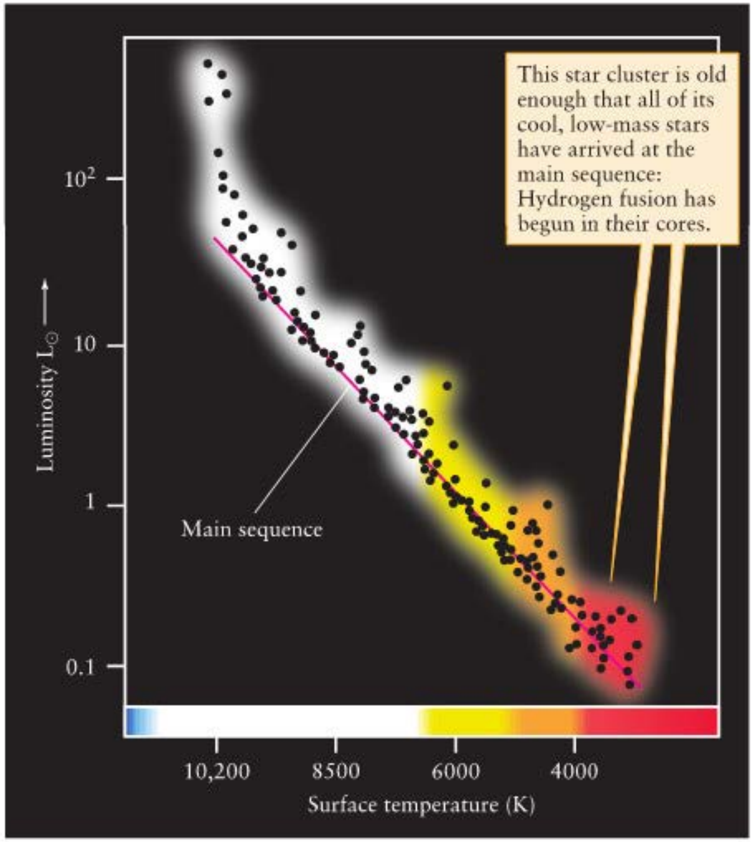
Example of Open Cluster: Pleiades



- The Pleiades cluster now has no stars with life expectancy less than around 100 million years.
- Only the most massive stars have left the main sequence

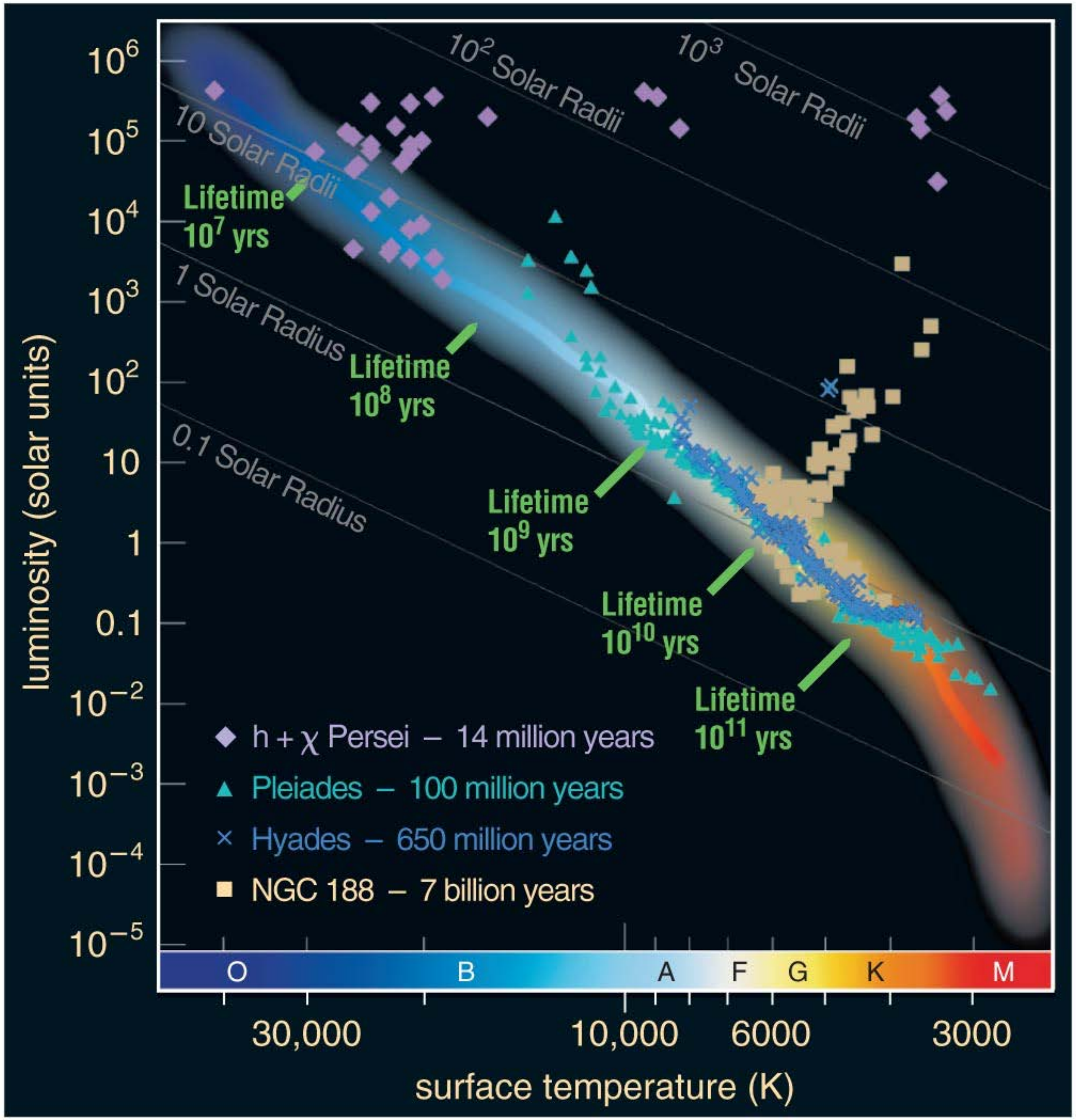
Example of Open Cluster: Pleiades

(a) The Pleiades star cluster R I V U X G

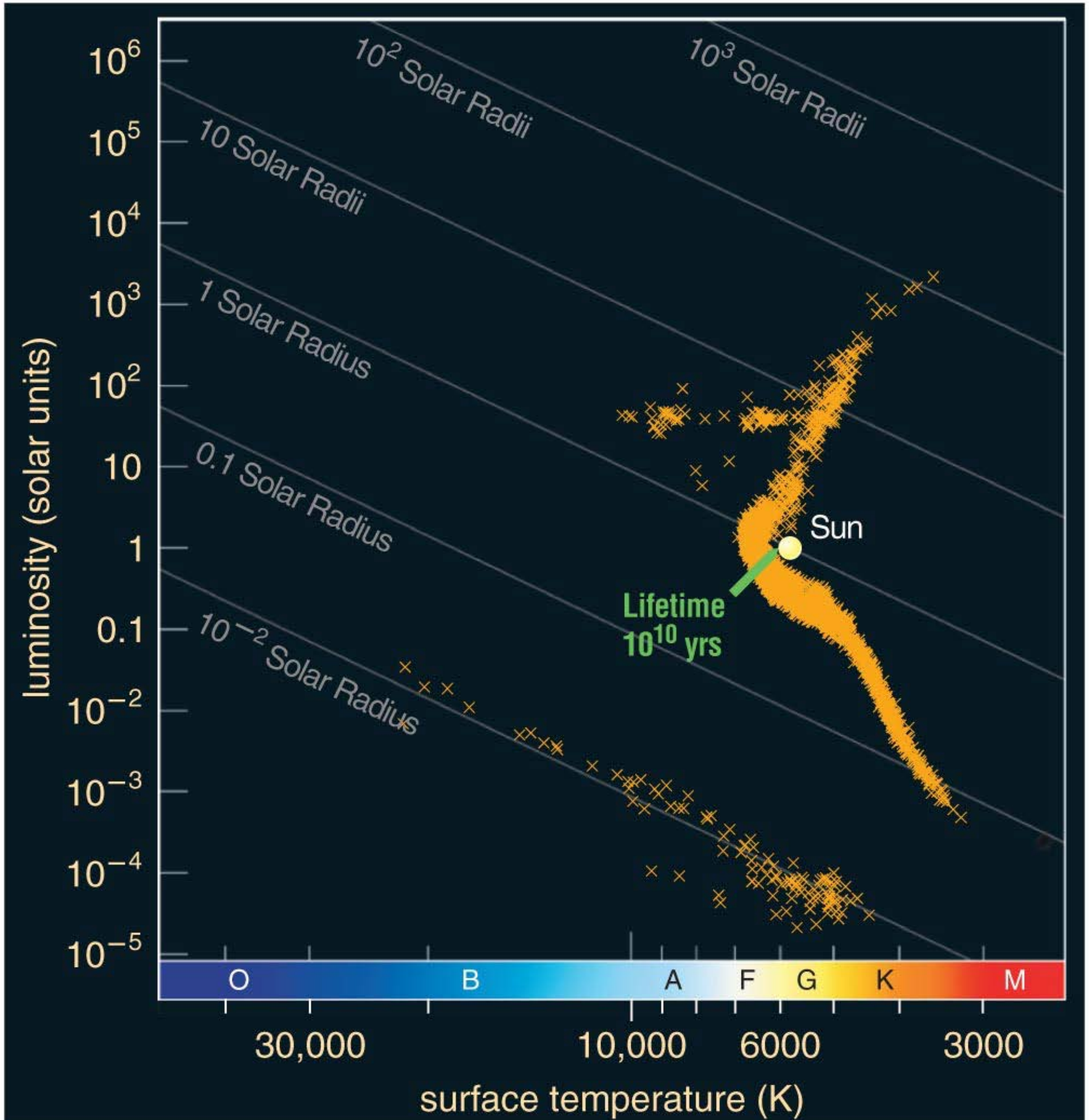


(b) An H-R diagram of the stars in the Pleiades

The Pleiades and its H-R Diagram (a) The Pleiades star cluster is 380 ly from Earth in the constellation Taurus. (b) Each dot plotted on this H-R diagram represents a star in the Pleiades. The Pleiades is ~50×10^6 years old. Notice that the most massive stars have stopped fusing H to He in the core and have moved off the main sequence.



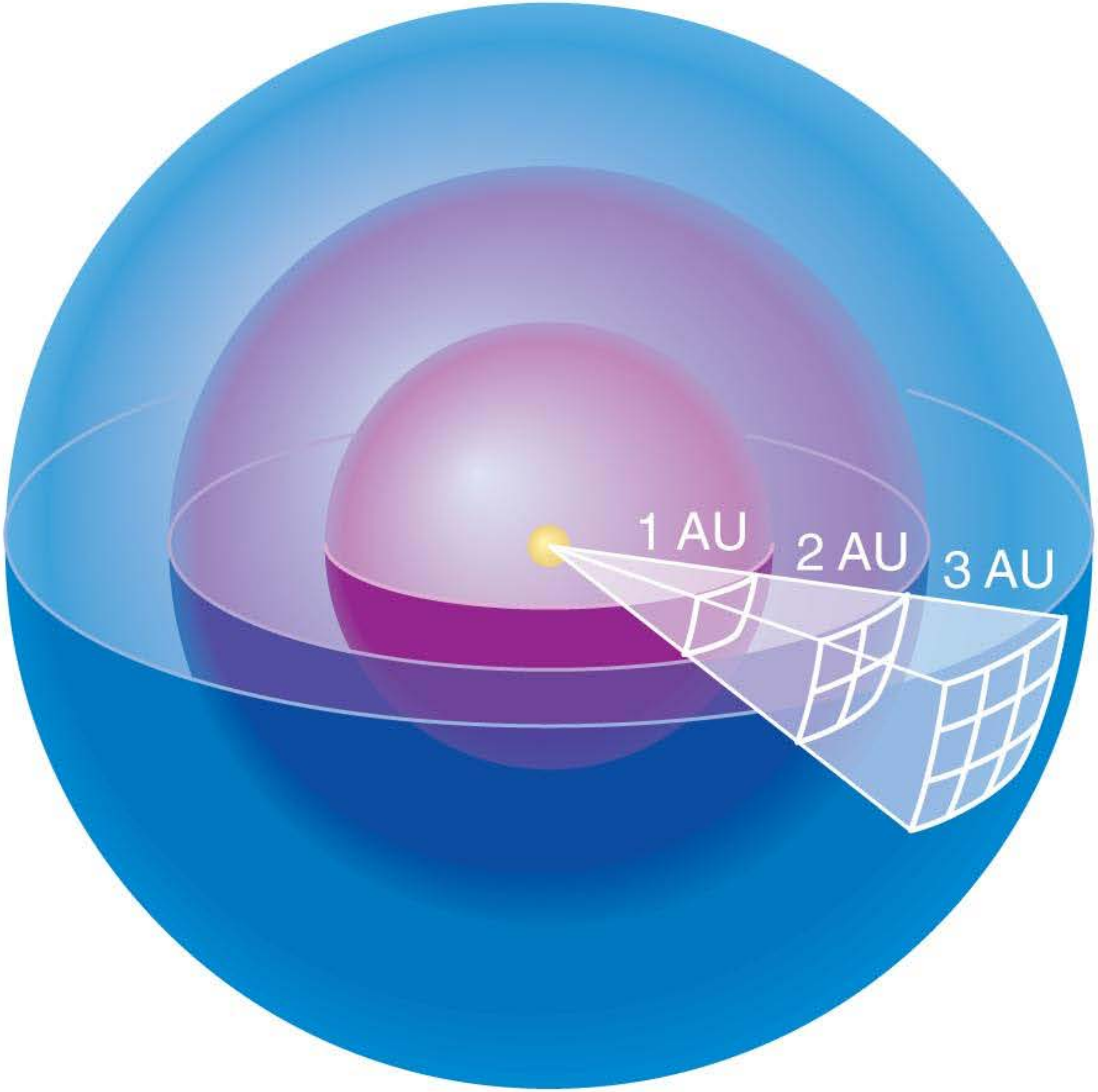
- The main-sequence turnoff point of a cluster tells us its age.



- Detailed modeling of the oldest globular clusters reveals that they are about 13 billion years old.

What have we learned?

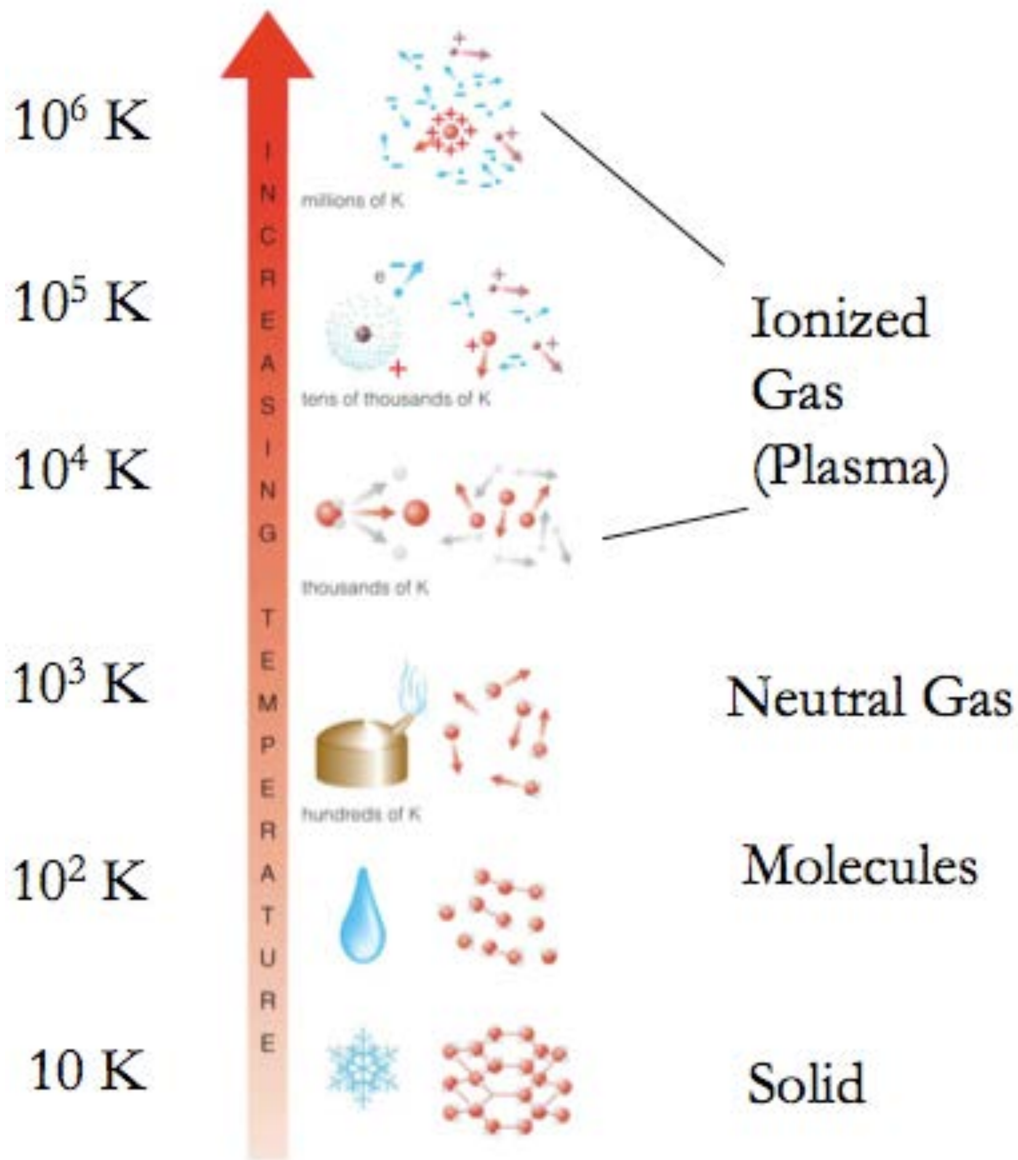
- **What are the two types of star clusters?**
  - Open clusters are loosely packed and contain up to a few thousand stars.
  - Globular clusters are densely packed and contain hundreds of thousands of stars.
- **How do we measure the age of a star cluster?**
  - A star cluster's age roughly equals the life expectancy of its most massive stars still on the main sequence.



- The amount of luminosity passing through each sphere is the same.

  Area of sphere:
  4π (radius)^2

- Divide luminosity by area to get brightness.



- Level of ionization also reveals a star's temperature.