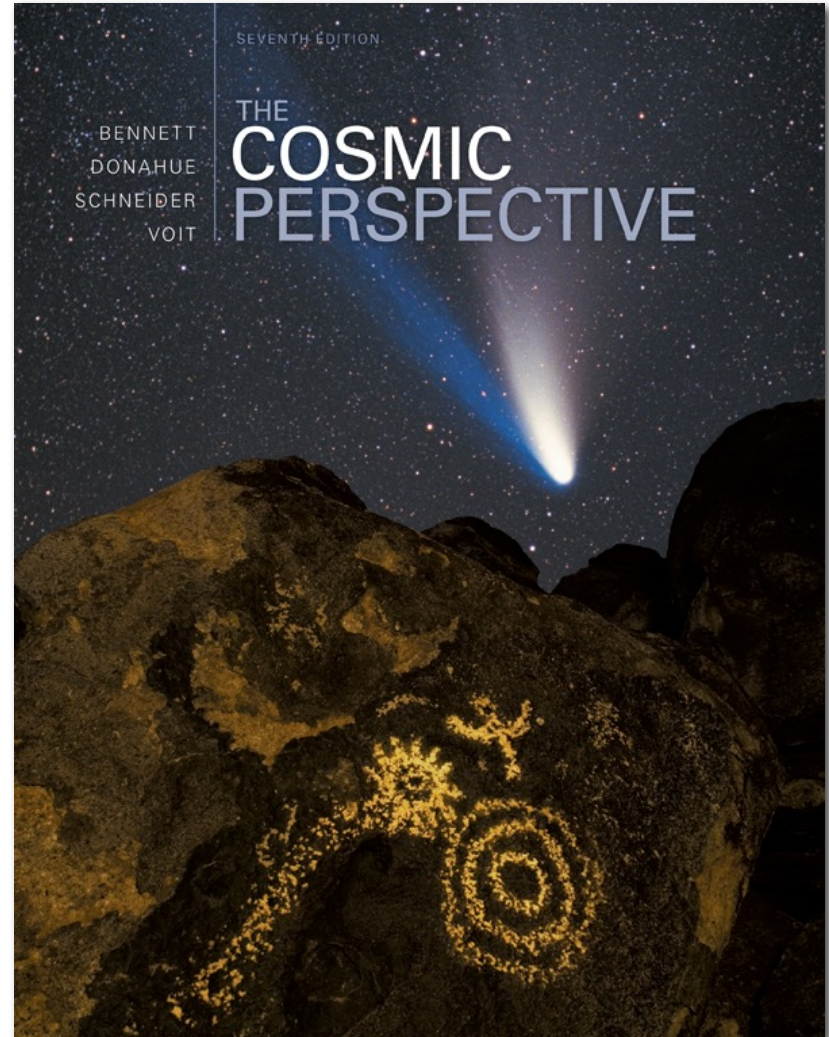


# The Cosmic Perspective

Seventh Edition

## Surveying the Stars



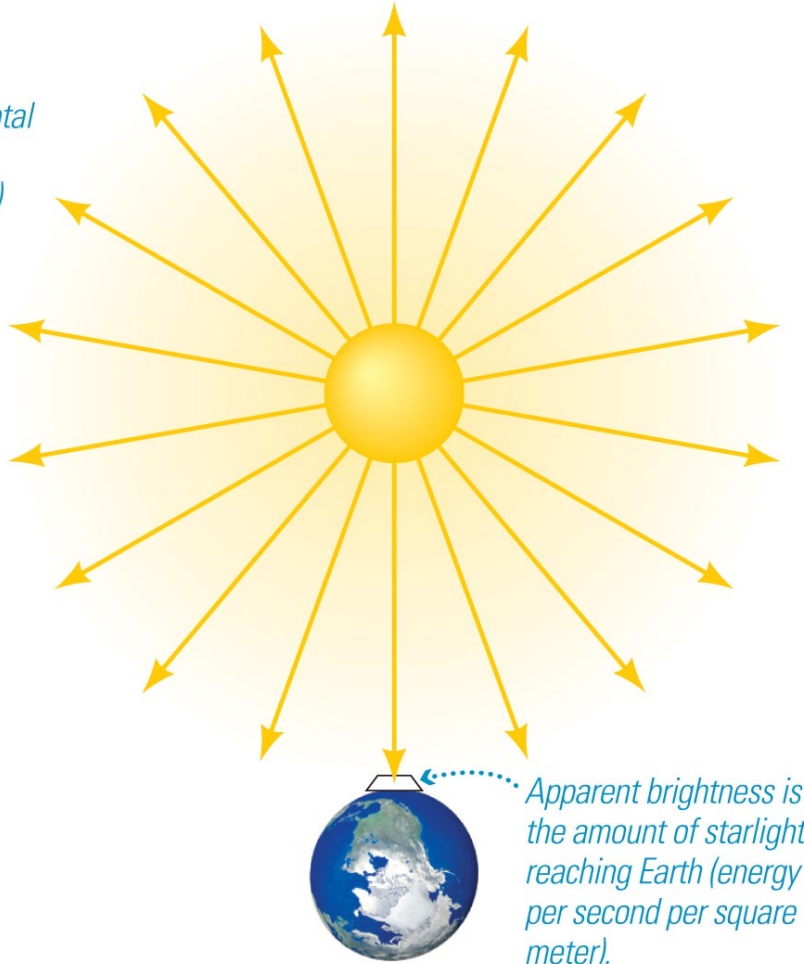
# 15.1 Properties of Stars

- 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 is the total amount of power (energy per second) the star radiates into space.*



*Not to scale!*

## ***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:

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

- 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:**  $\text{J s}^{-1} \text{m}^{-2}$

**Luminosity:**  $\text{J s}^{-1}$

# 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

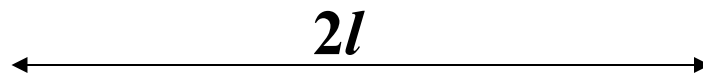
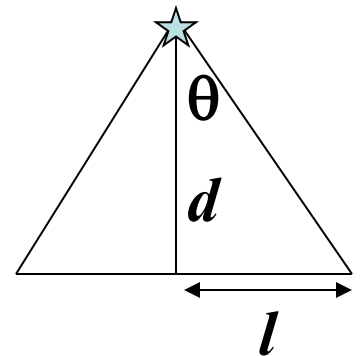
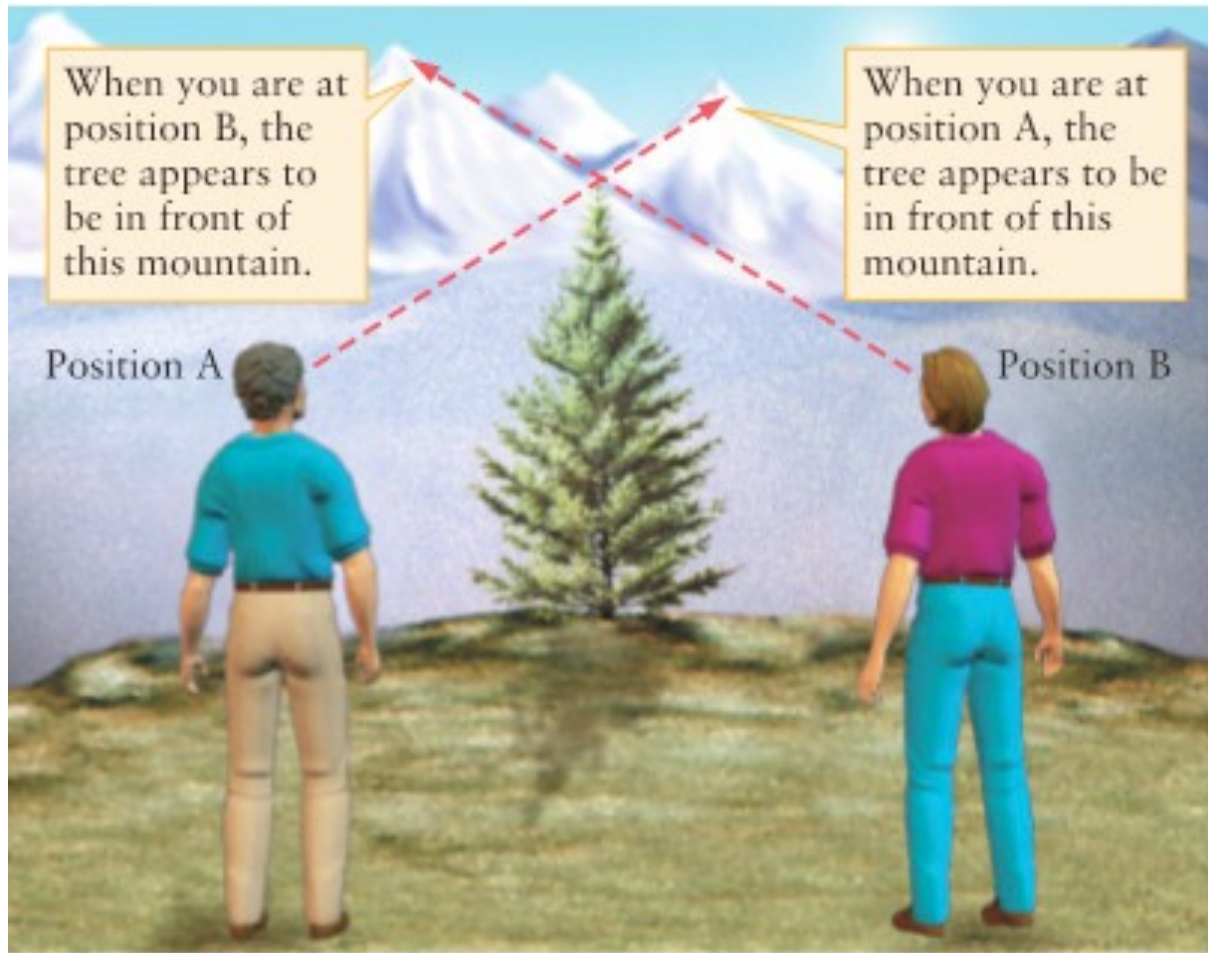
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- D. It would be three times brighter.



- So how far away are these stars?

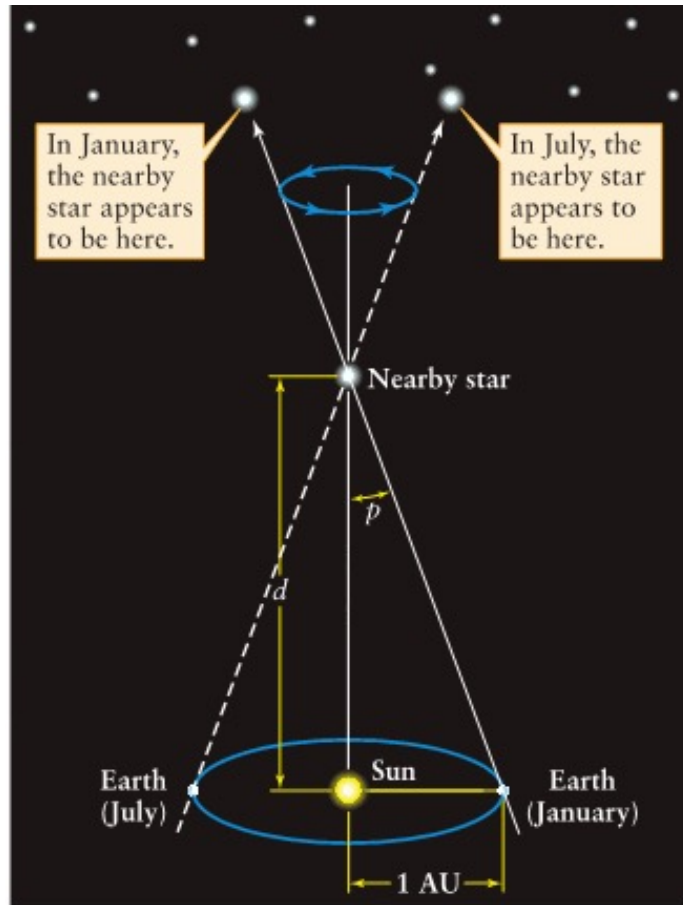
# Measuring Distances



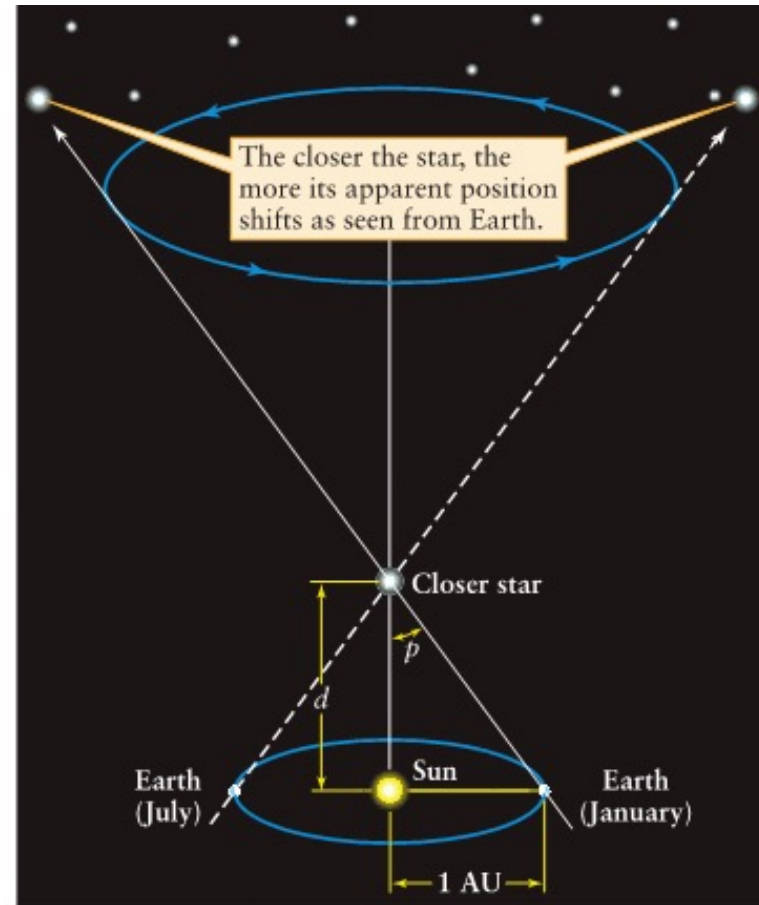
$$\tan(\theta) = l/d \rightarrow d \sim l/\theta \text{ (\theta in radians)}$$



# 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

$p$  = parallax angle

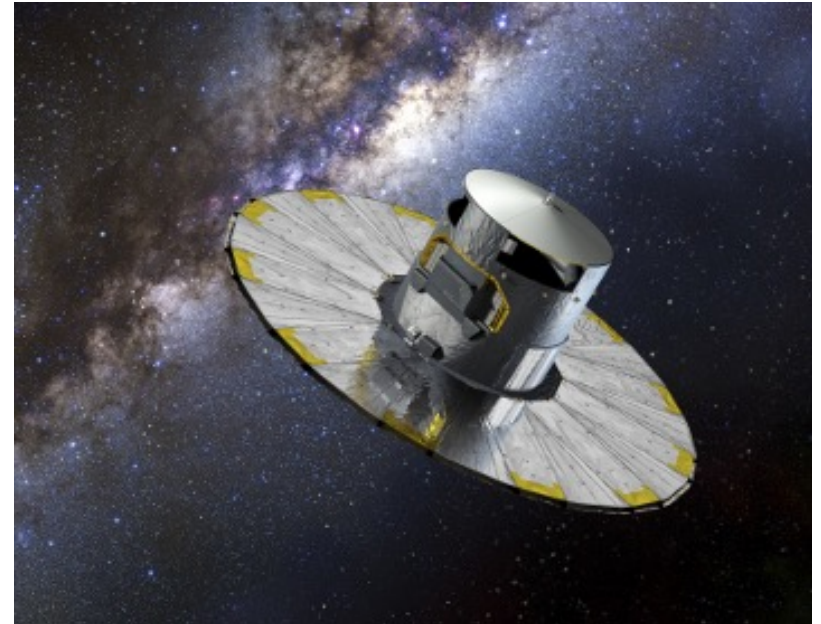
$$d \text{ (in parsecs)} = \frac{1}{p \text{ (in arcseconds)}}$$

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

# 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.

Observations made by GAIA permit measurements of parallax angles down to 200 micro arcsec (1 micro arcsec =  $10^{-6}$  arcsec) corresponding to distances of 5,000 pc.



GAIA



- Most luminous stars (not common):

$$10^6 L_{\text{Sun}}$$

- Least luminous stars (common):

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

- ( $L_{\text{Sun}}$  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  $m = 6$  magnitude star is a factor of 100 times fainter in brightness than a  $m = 1$  magnitude star

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

$m_1, m_2$  = 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

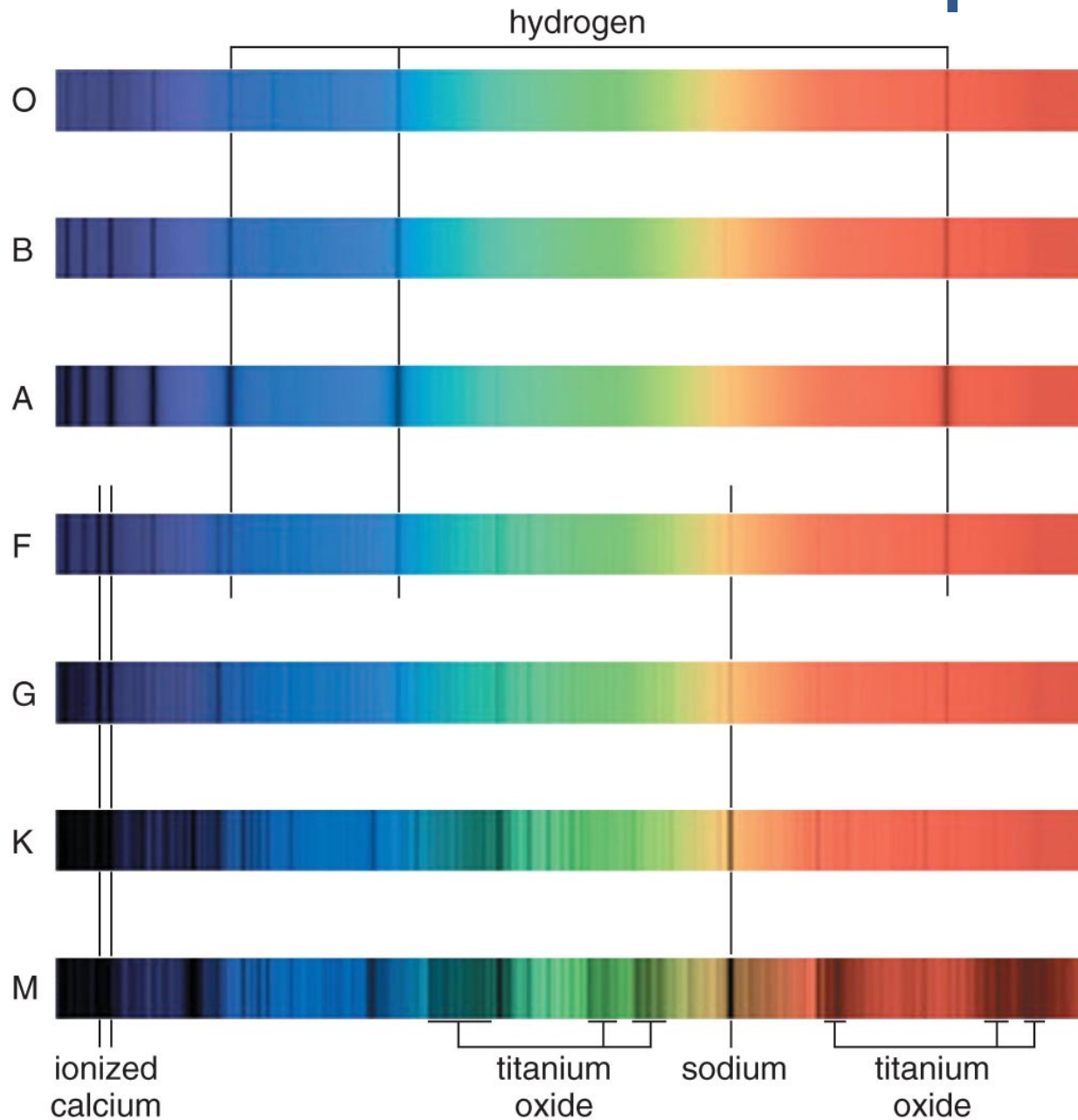
If a star has an apparent magnitude of  $m = 15$  and an absolute magnitude of  $M = 5$  what is its distance?

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

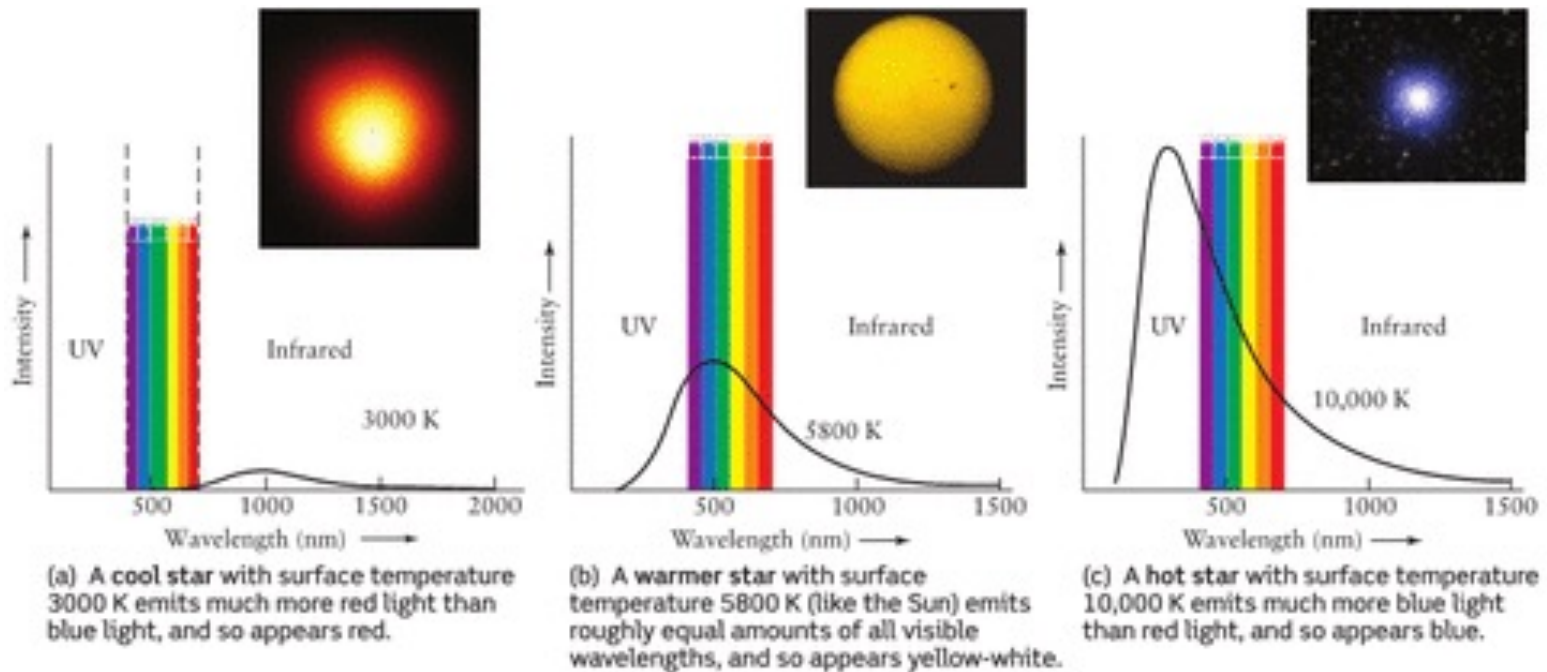
$$d = 10^{\frac{m - M + 5}{5}} \text{ pc}$$

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

# How do we measure stellar temperatures?

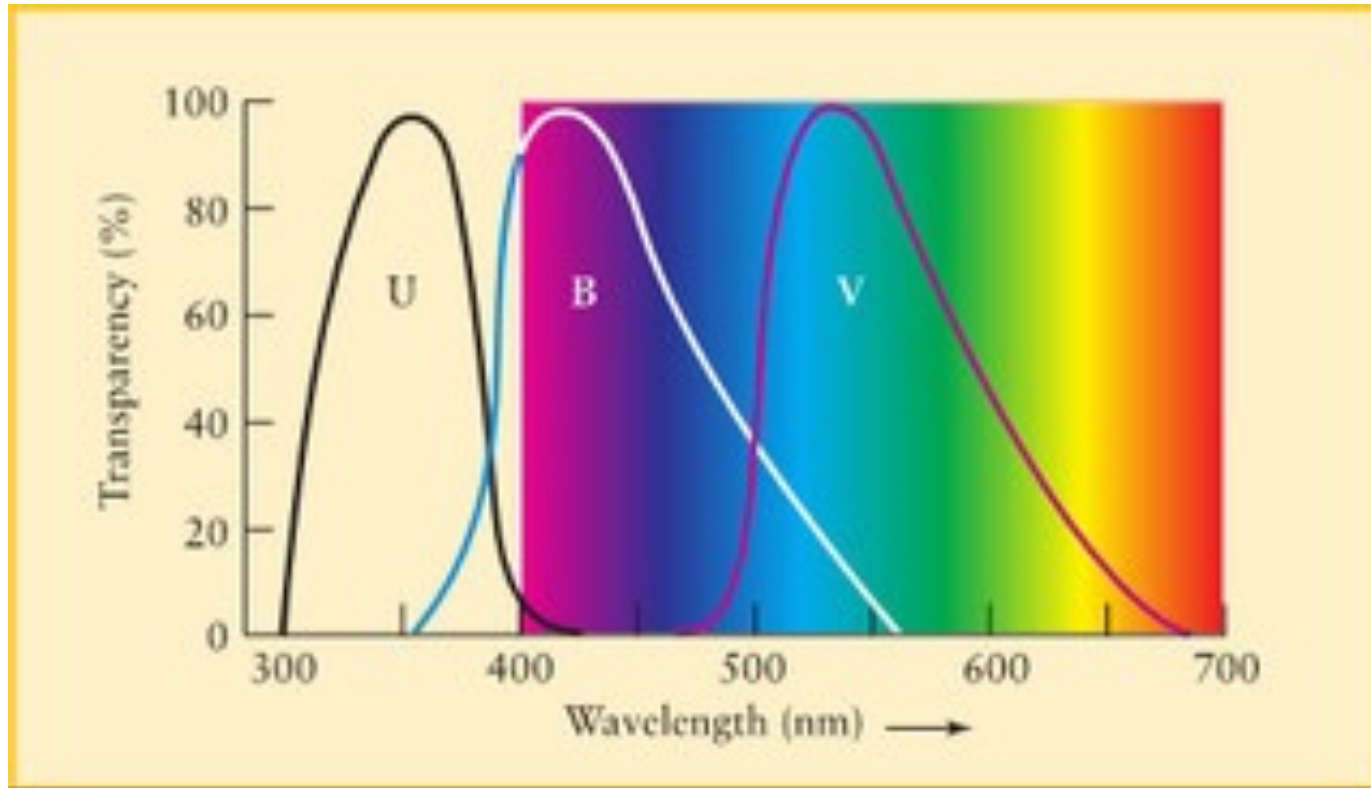


# Colors and Temperature



A star's temperature is related to its color. Red stars are 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  $b_V$ .

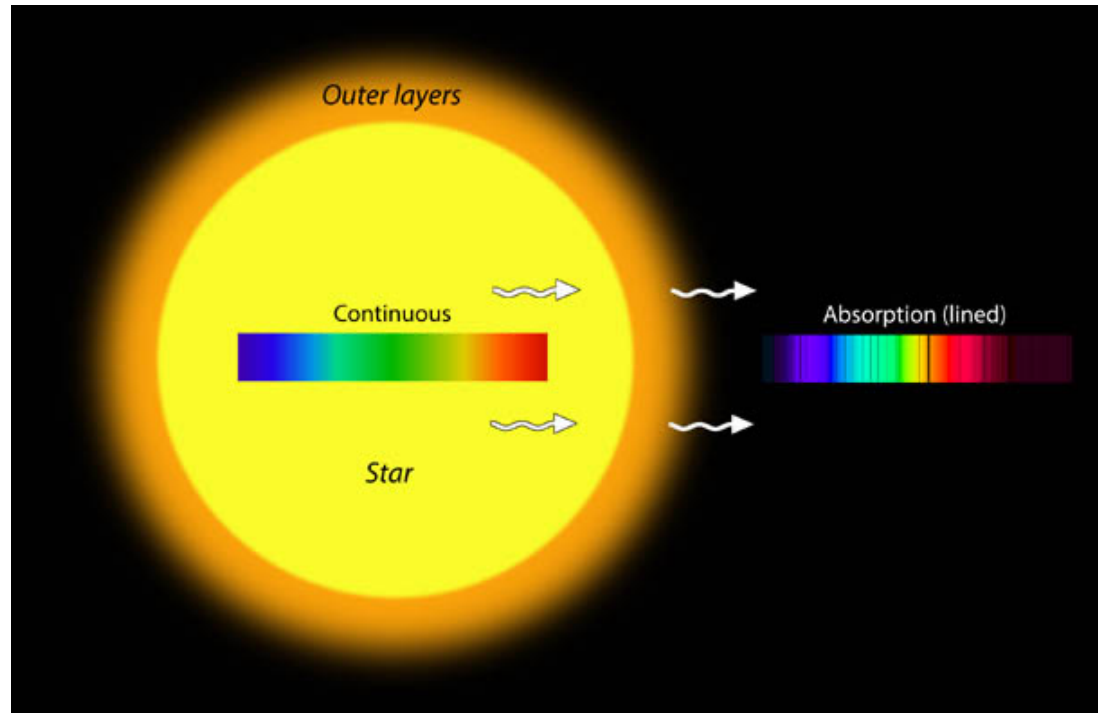
Then compare the relative fluxes by taking the ratios  $b_V/b_B$  and  $b_B/b_U$ . These ratios indicate the temperature of the stars surface.

# Spectra of Stars

**Absorption spectra** in stars are produced in the following way:

A star produces a **continuum spectrum** from hot dense gas in its atmosphere.

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



# 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**.

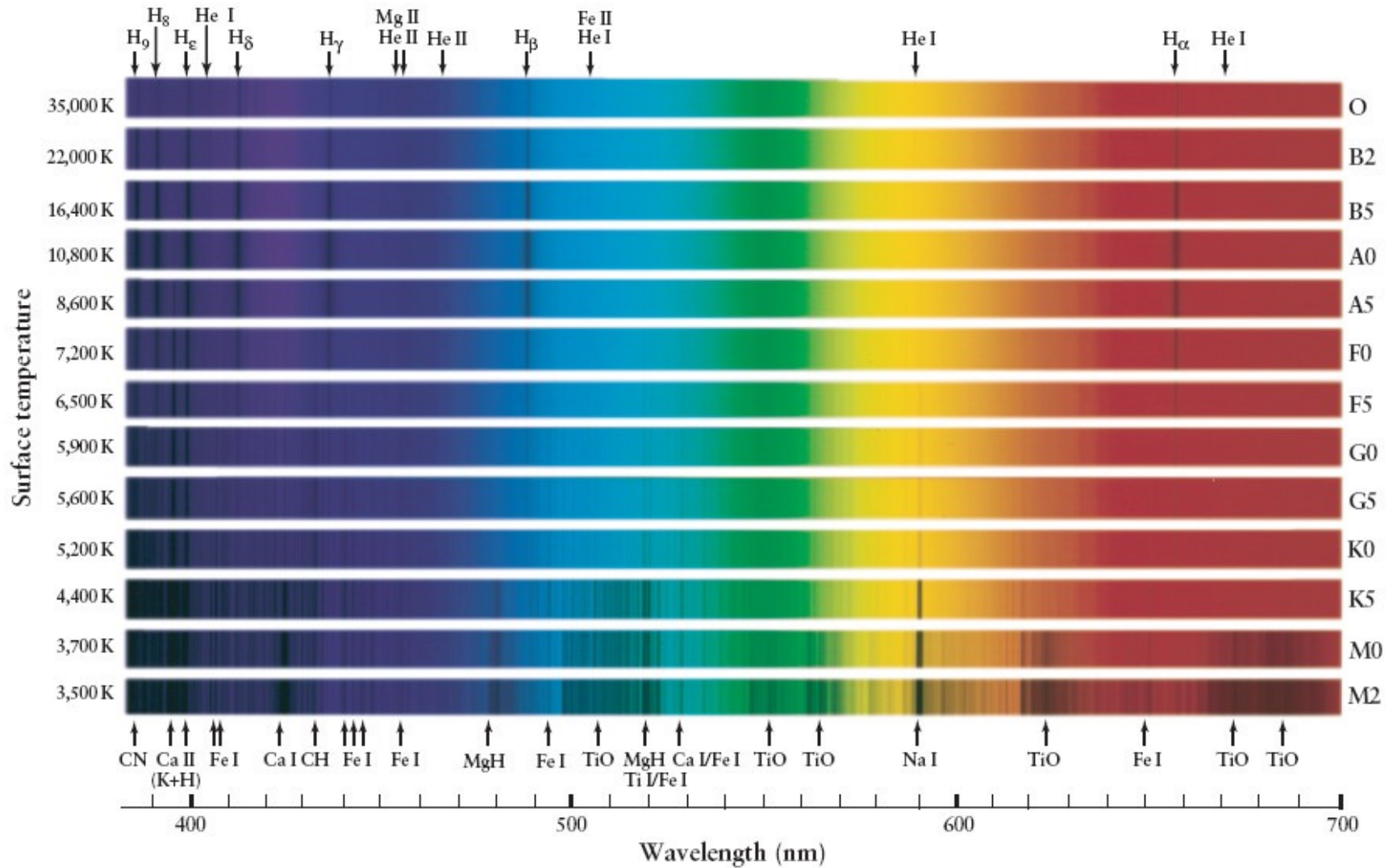
The **spectral classes** are labeled:  
**O B A F G K M L T**

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

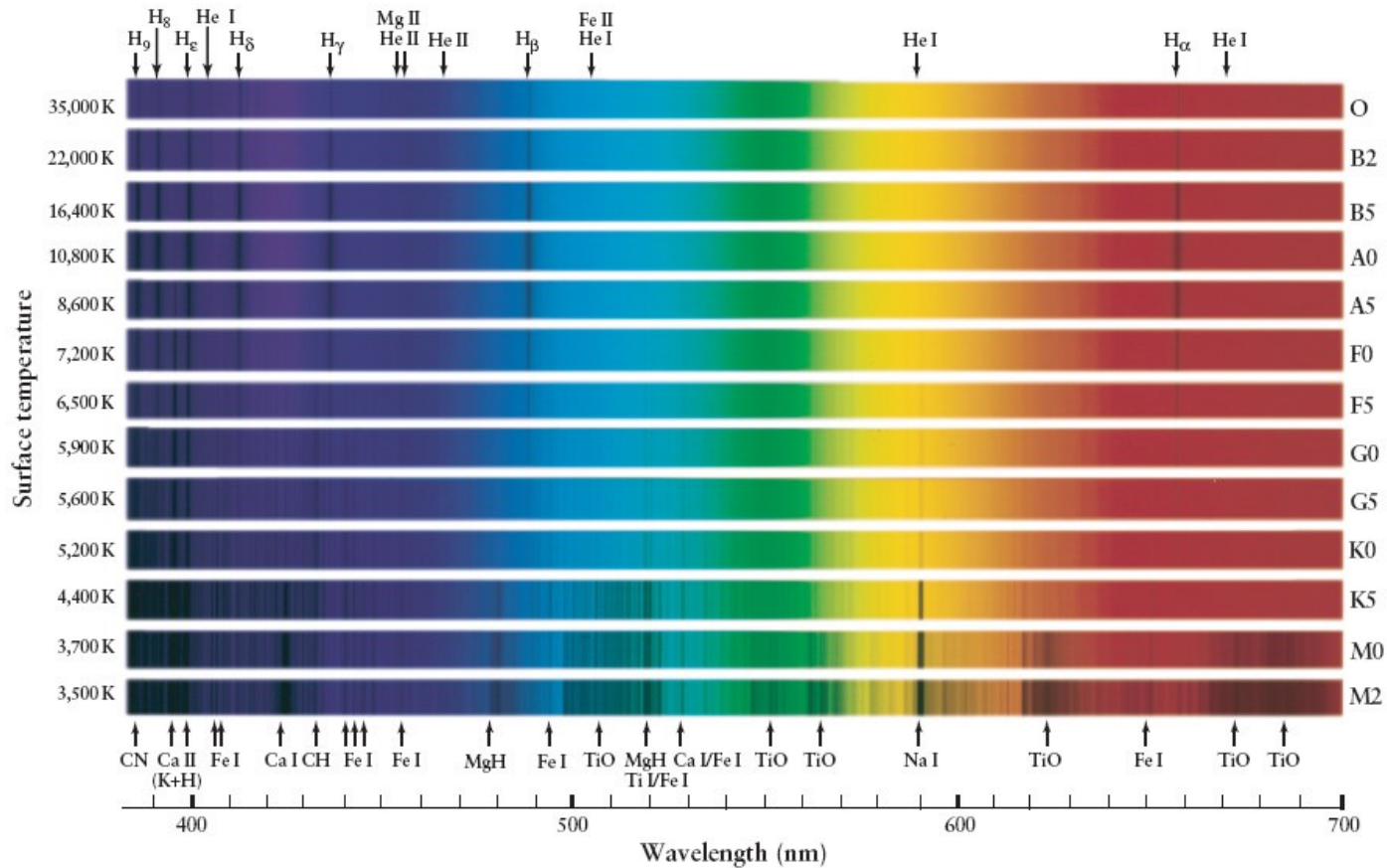


In the late 1800's a team of women at the Harvard College Observatory undertook the task of classifying the spectra of hundreds of thousands of stellar spectra.

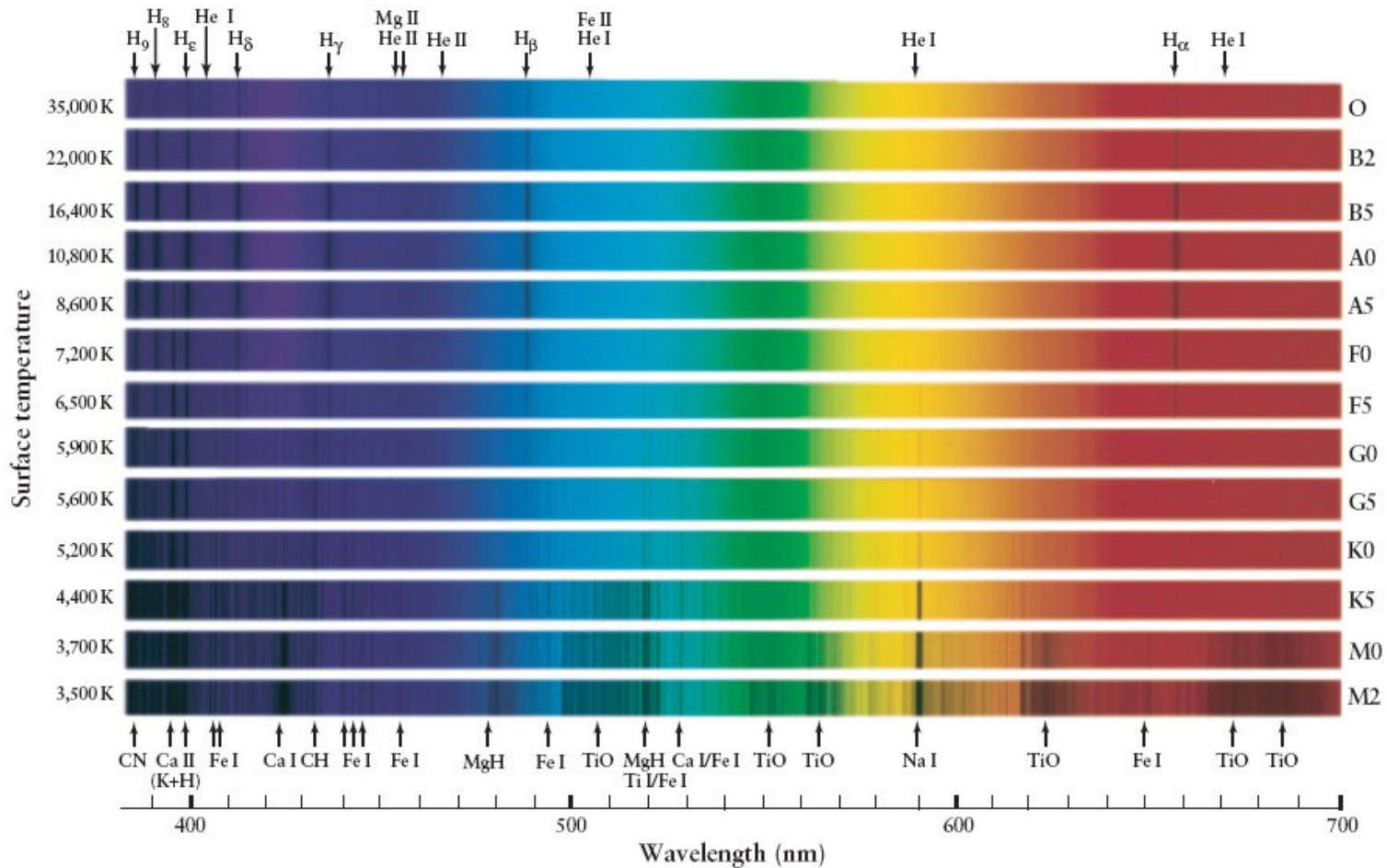
# Stellar Spectra and Temperature







- Absorption lines in a star's spectrum tell us its 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

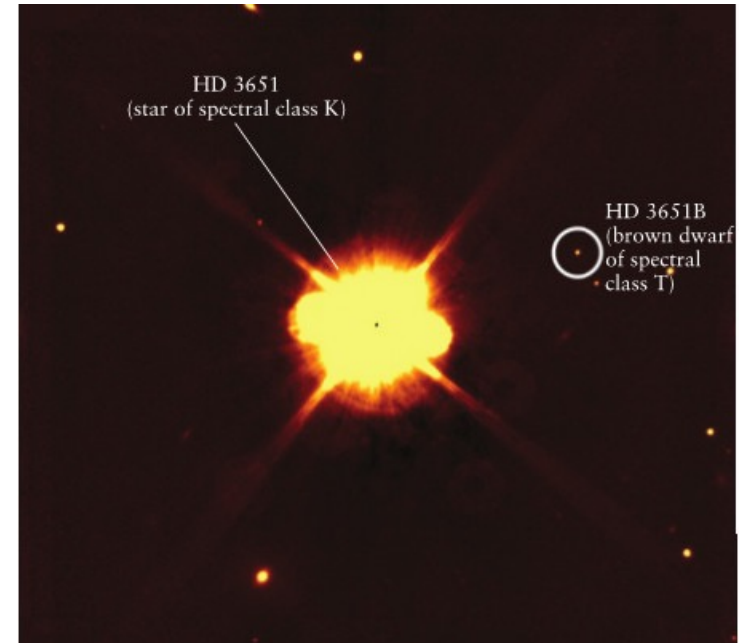
# Brown Dwarfs

**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.

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.

# Stellar Radii

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

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

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

L = stars luminosity in W

R = radius of stars emitting surface in meters

T = temperature of stars surface in kelvins

$\sigma$  = Stefan - Boltzmann constant =  $5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$

# Stellar Radii

$$L = 4\pi R^2 \sigma T^4 \quad \text{Equation (1)}$$

$$L_{\odot} = 4\pi R_{\odot}^2 \sigma T_{\odot}^4 \quad \text{Equation (2)}$$

Dividing equation 1 by equation 2 we have:

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

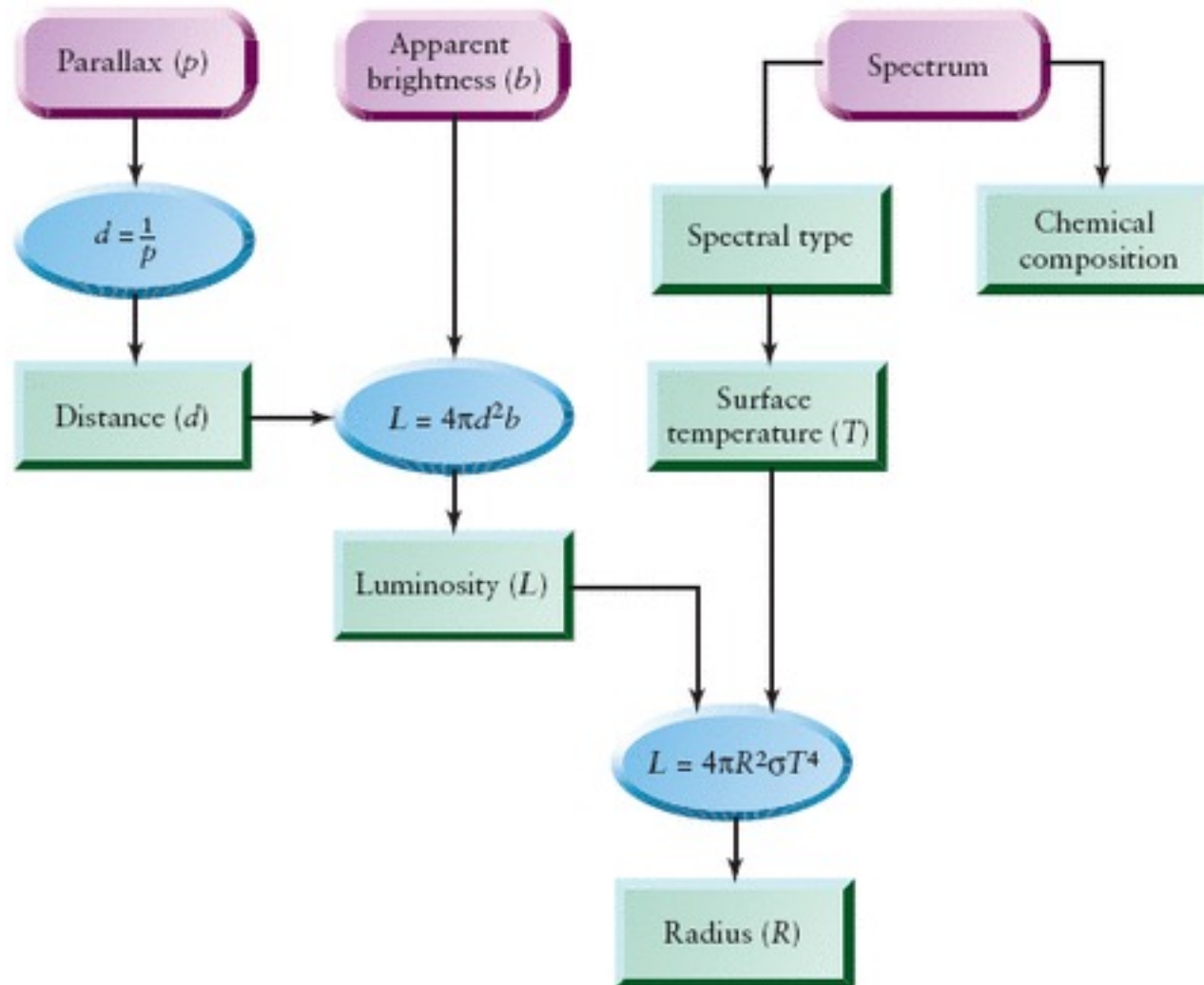
Solving for  $R/R_{\odot}$  we have:

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

**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 ?

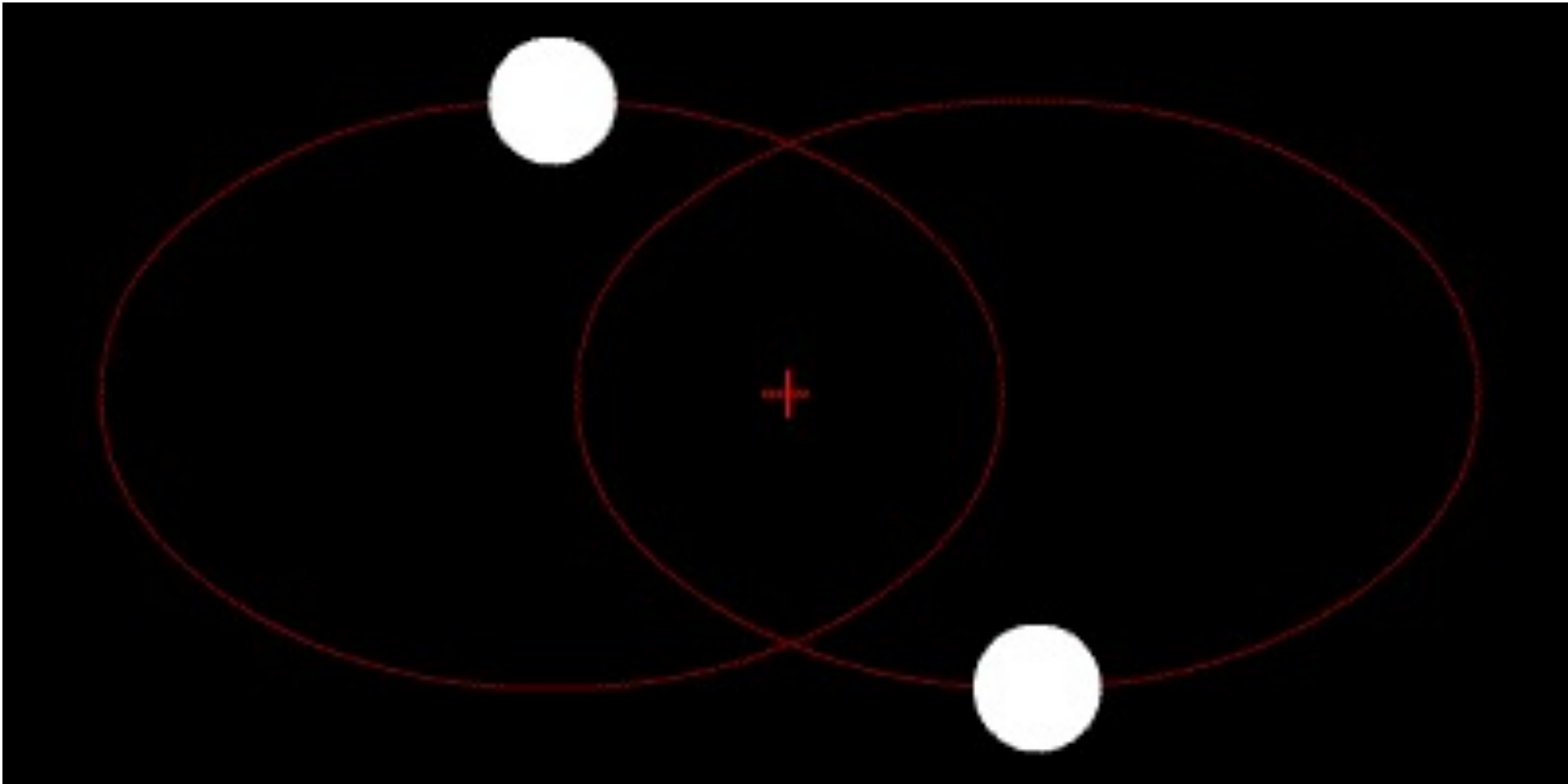
$$(T_{\odot} = 5,800 \text{ K})$$

# Measuring the Properties of Stars





# Binary Star Systems

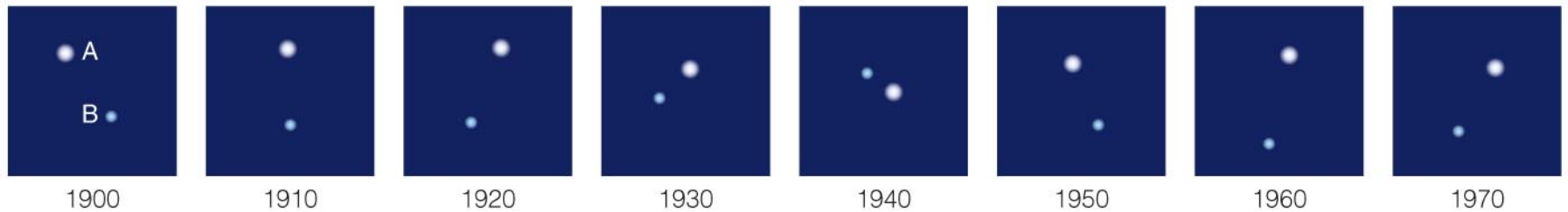


# Types of Binary Star Systems

- Visual binary
- Spectroscopic binary
- Eclipsing binary

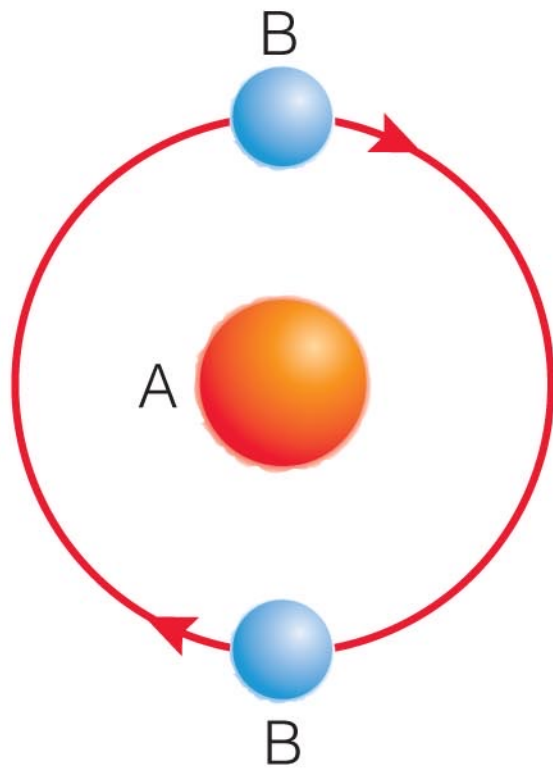
*About half of all stars are in binary systems.*

# Visual Binary



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

# Spectroscopic Binary



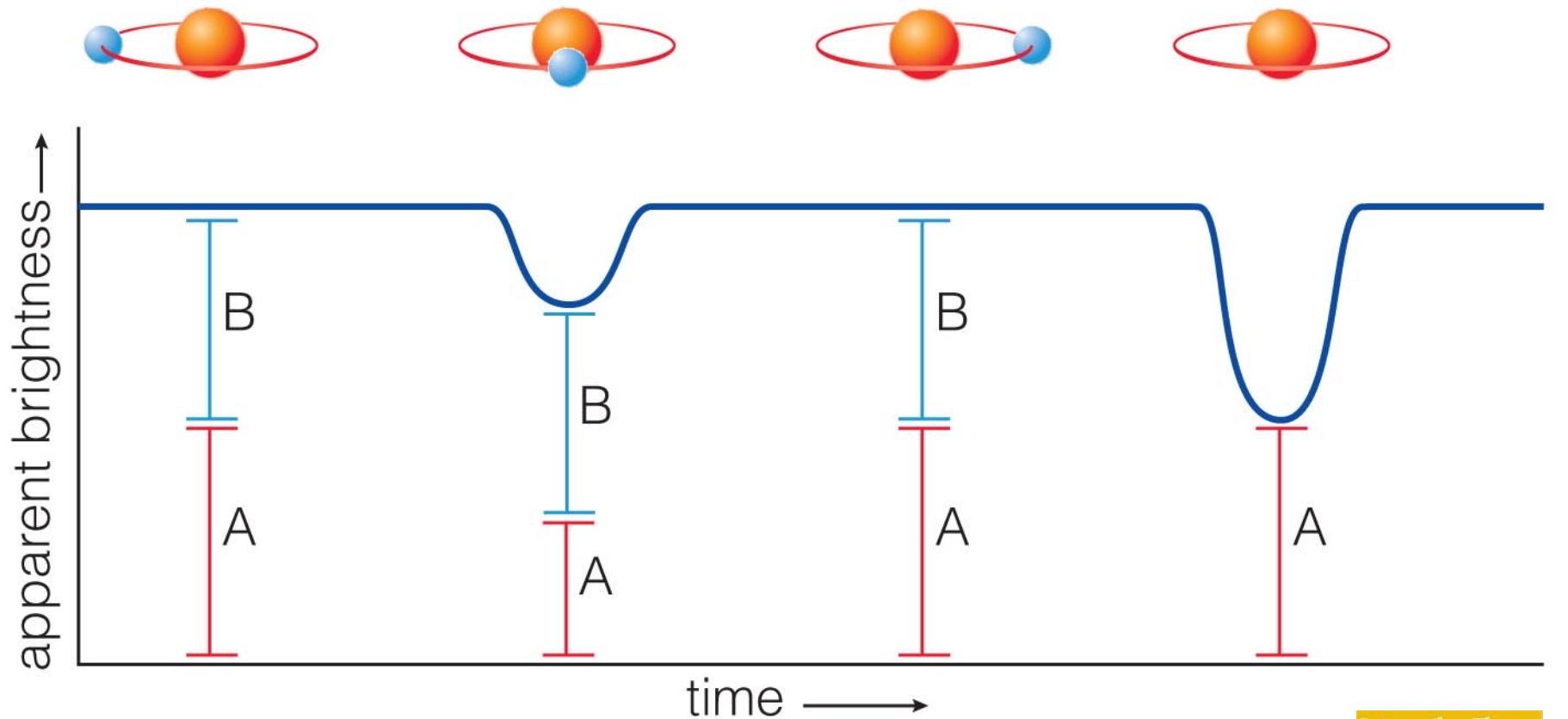
to Earth



Interactive Figure 

- We determine the orbit by measuring Doppler shifts.

# Eclipsing Binary



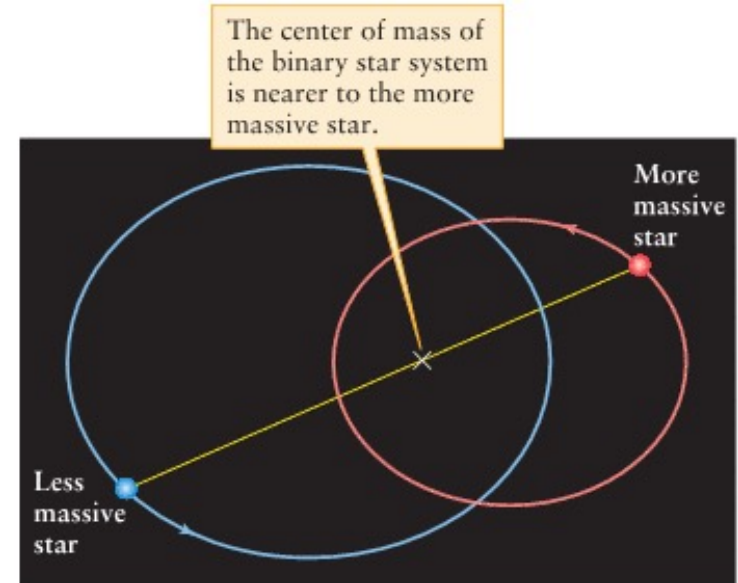
Interactive Figure 

- We can measure periodic eclipses.

# Masses of Stars in Binary Systems

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

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



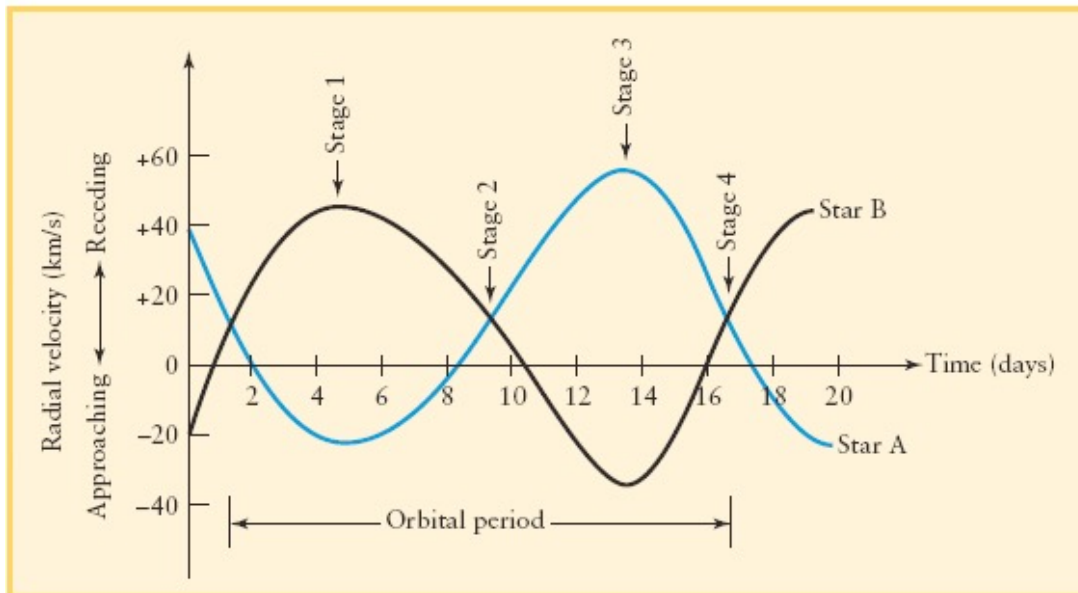
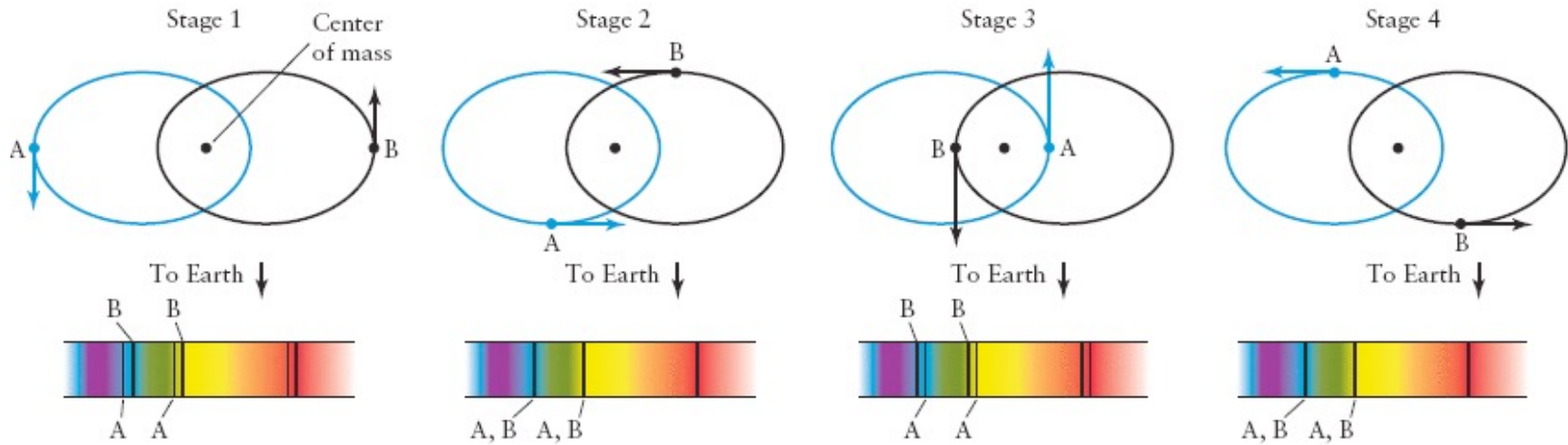
(b) A binary star system

$P$  = 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



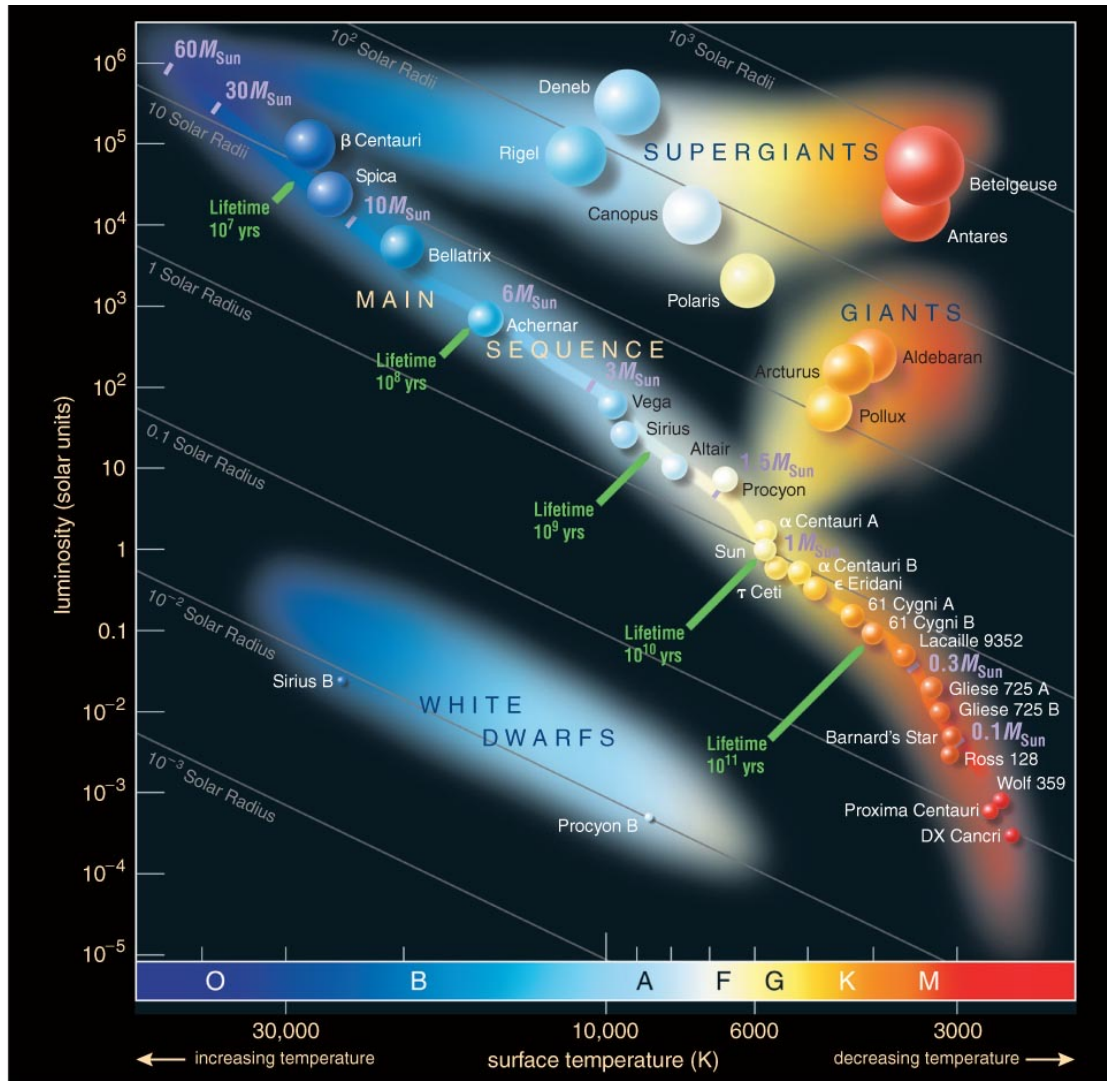
Radial Velocity Curves of Spectroscopic binary system HD 171978

# 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?**

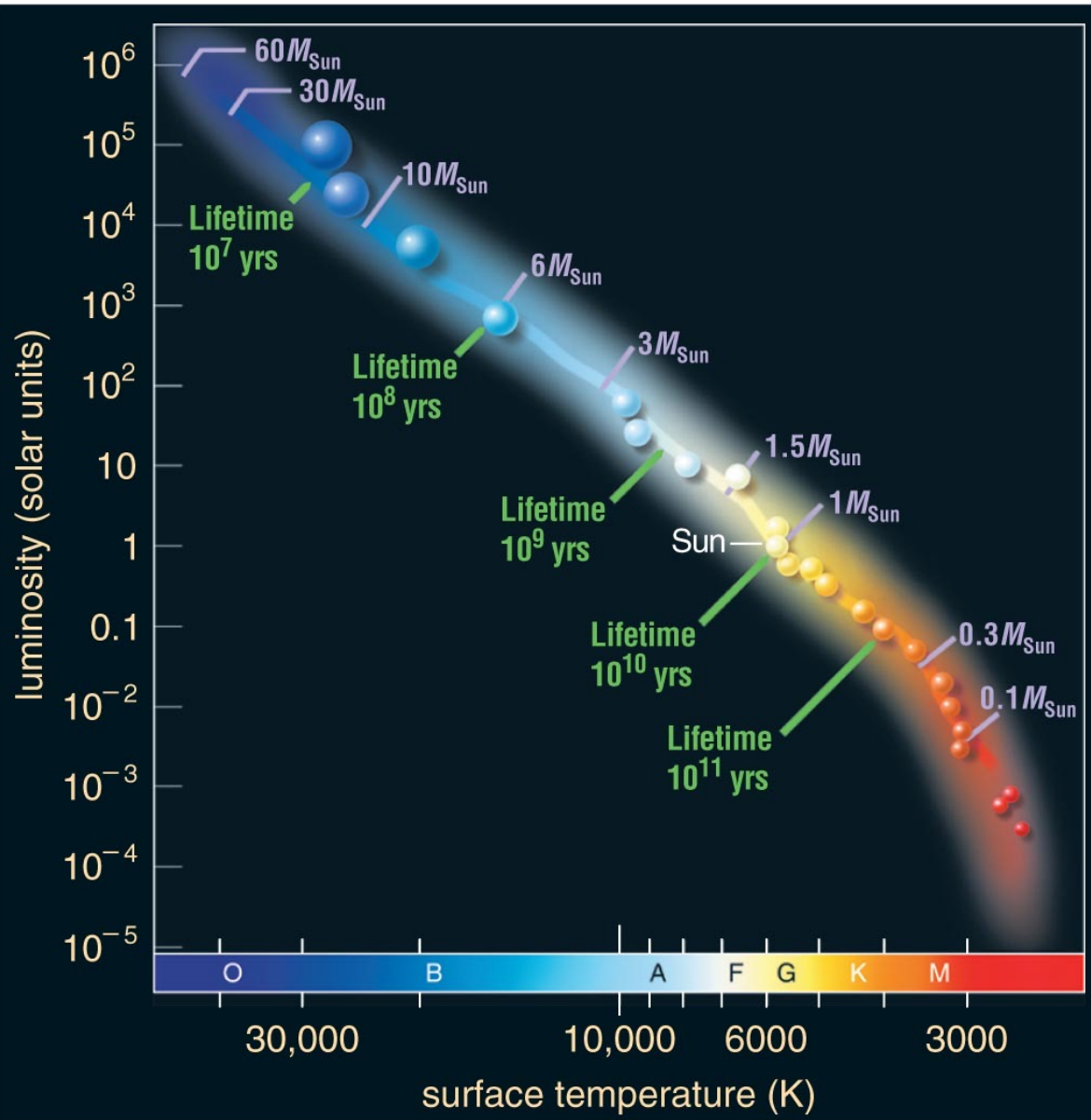


Luminosity ↑

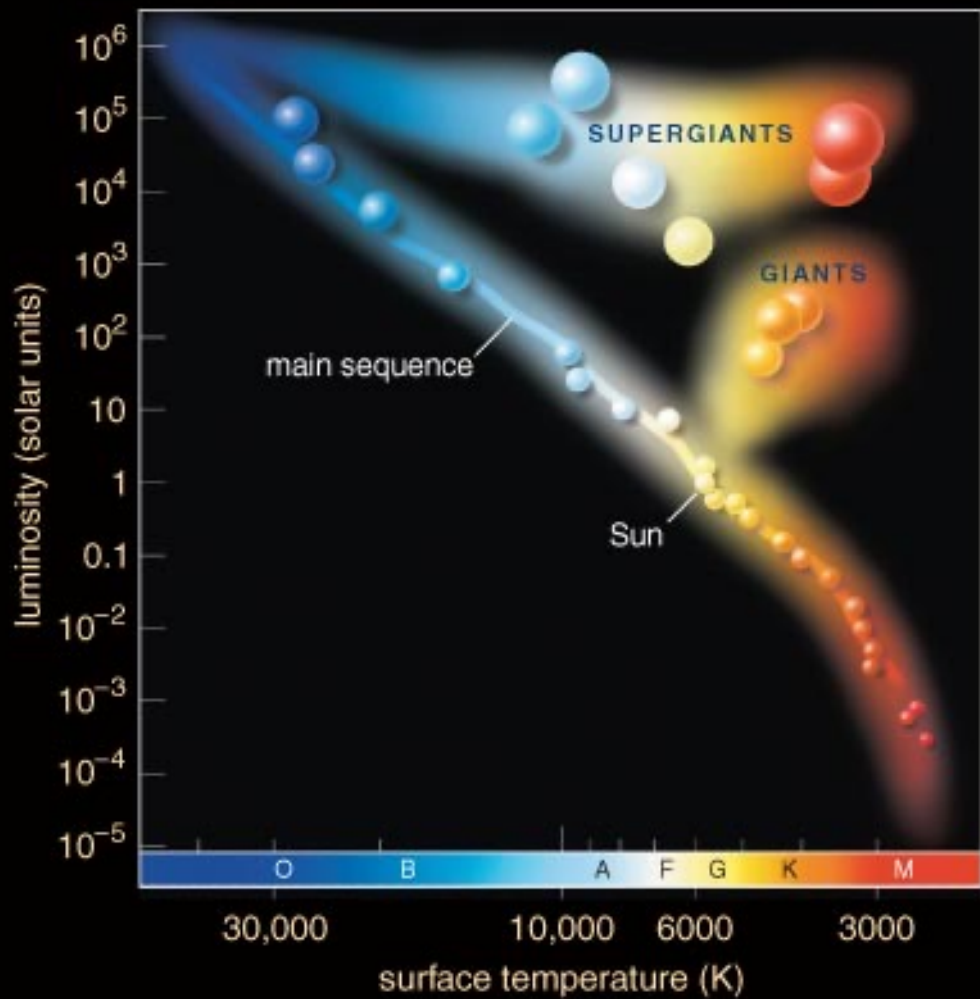


- An H-R diagram plots the luminosity and temperature of stars.

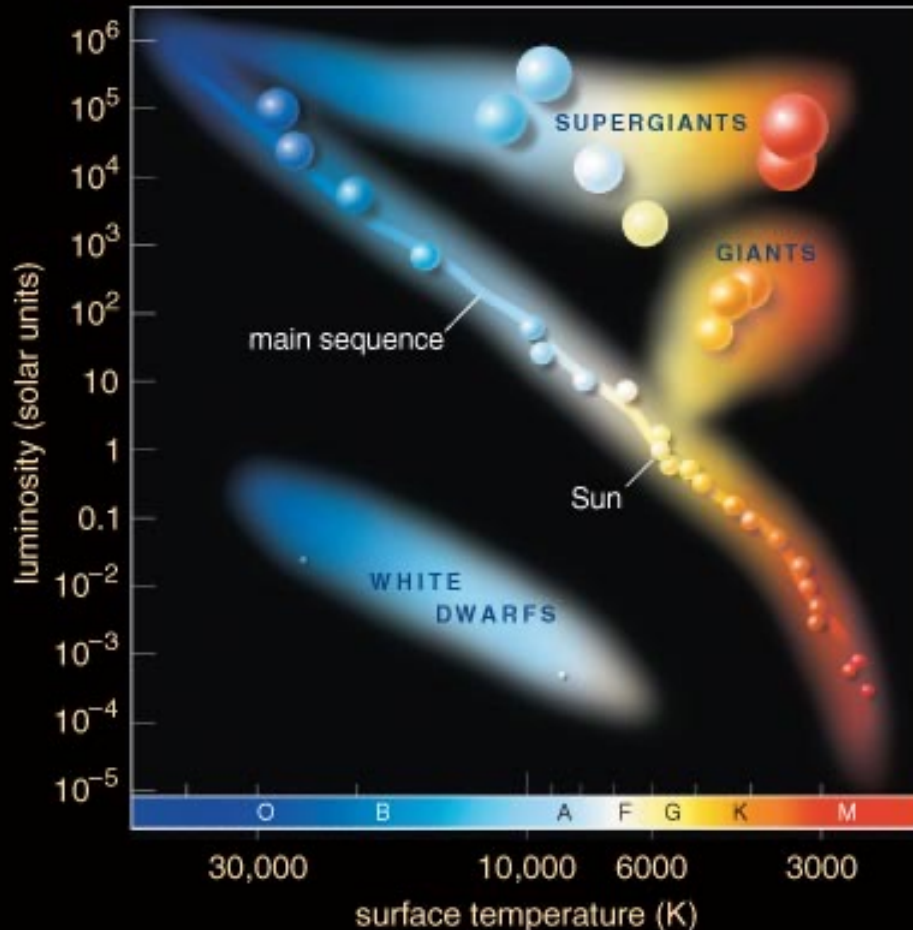
← Temperature



- 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.

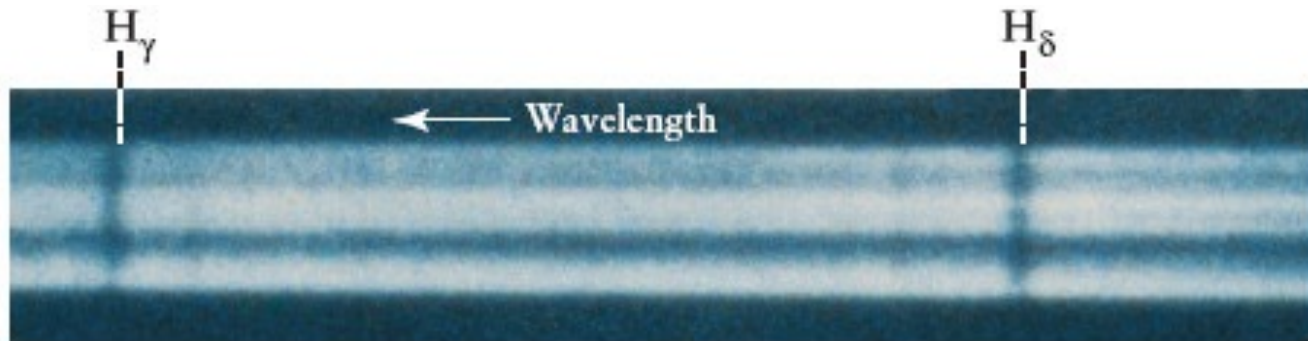
**Giant stars:** luminosities of 100–1000  $L_{\odot}$  and temperatures of 3000–6000 K. Red giants have  $T : 3000\text{--}5000$  K.

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

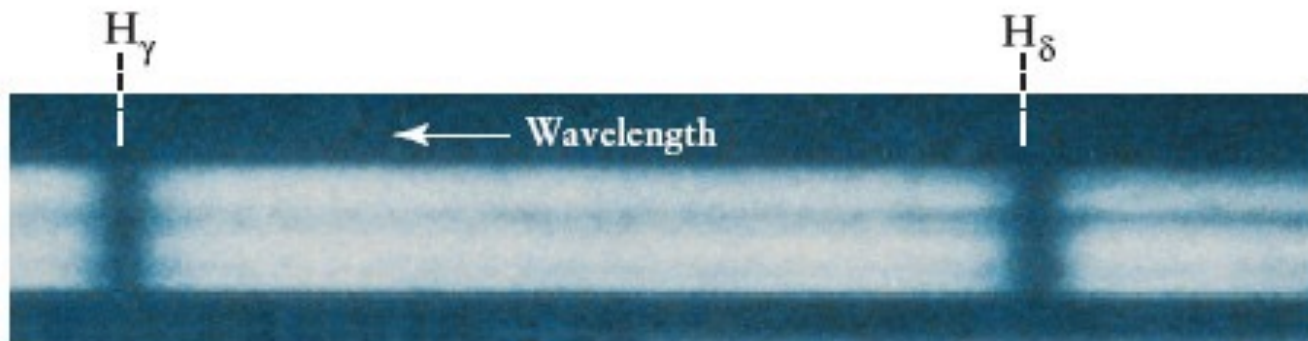
**White Dwarfs:** A low-mass star that has exhausted all its thermonuclear fuel and contracted to a size roughly equal to the size of the Earth (*has-been star*).

**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.

Stars are classified 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** and **luminosity class**:

- 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

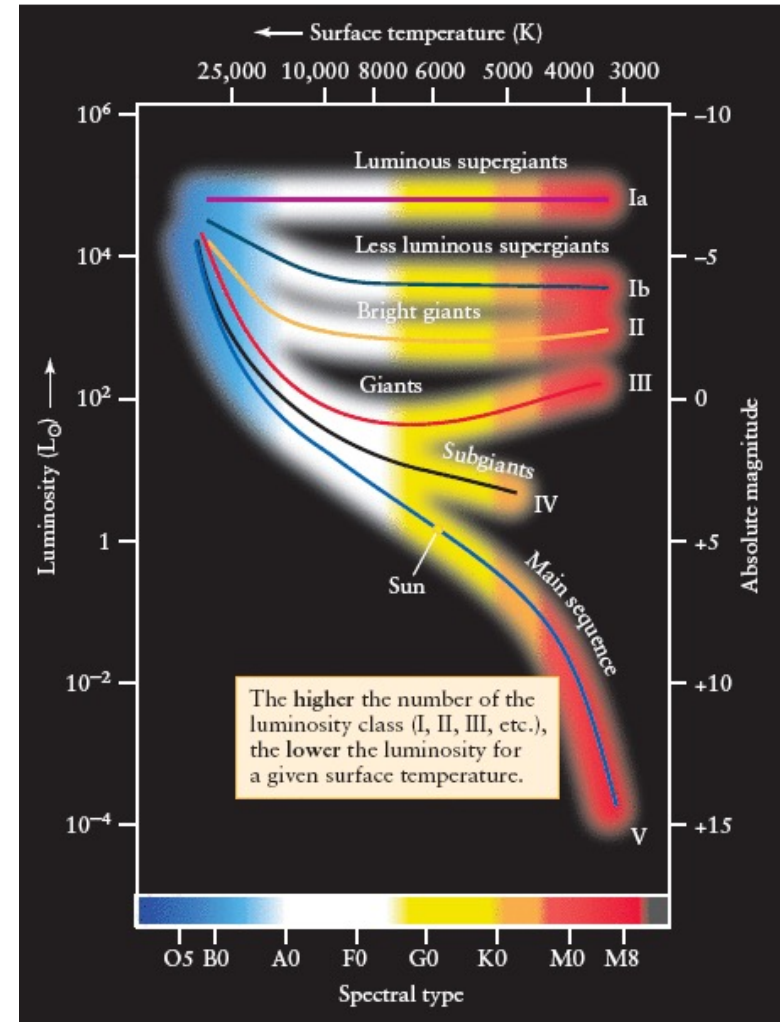


# Stellar Spectral Type and Luminosity Class

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

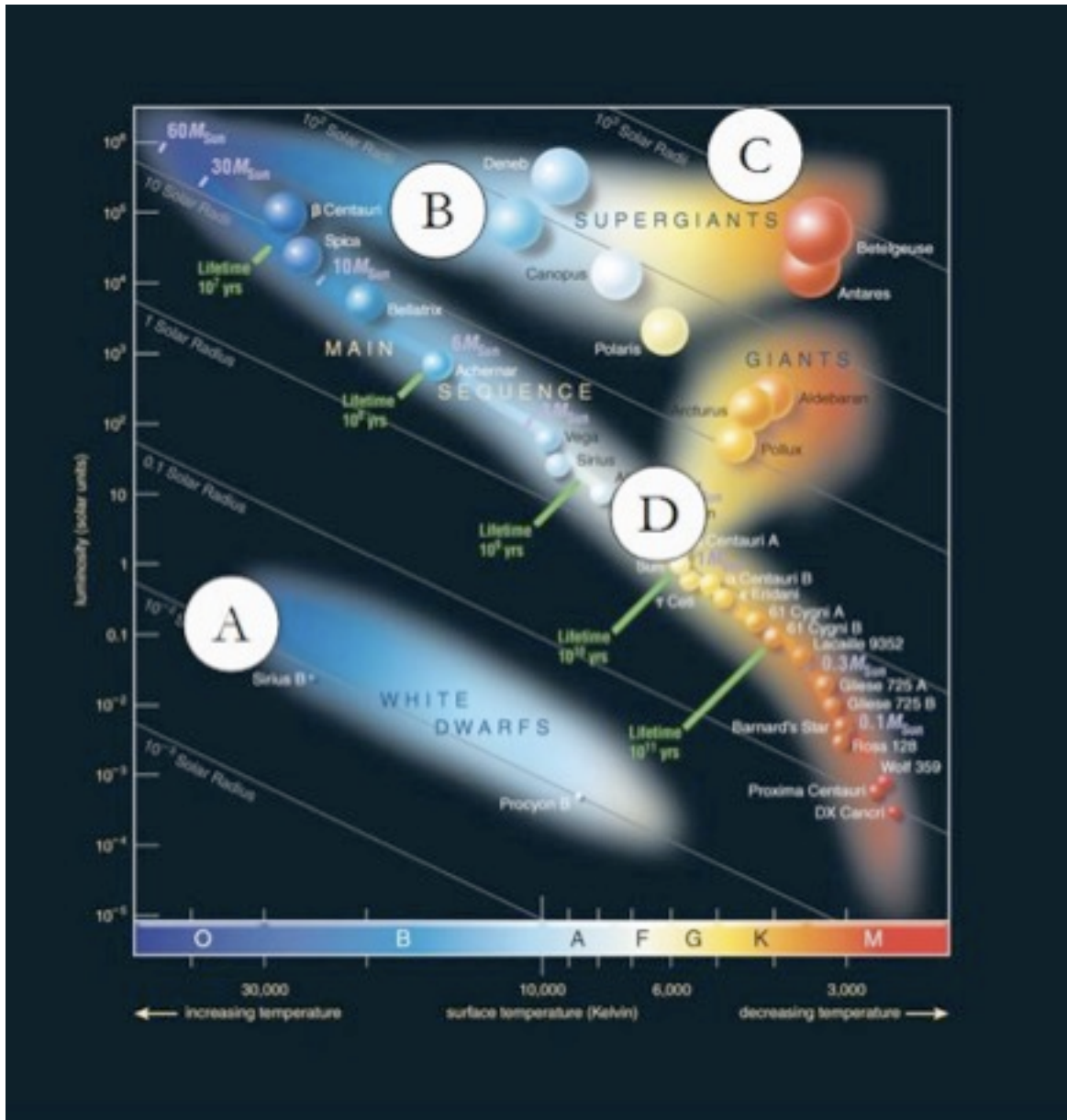
- a G2 V star ?
- a M0 II star ?
- a B0 Ia star ?



H-R diagram with Luminosity Classes..

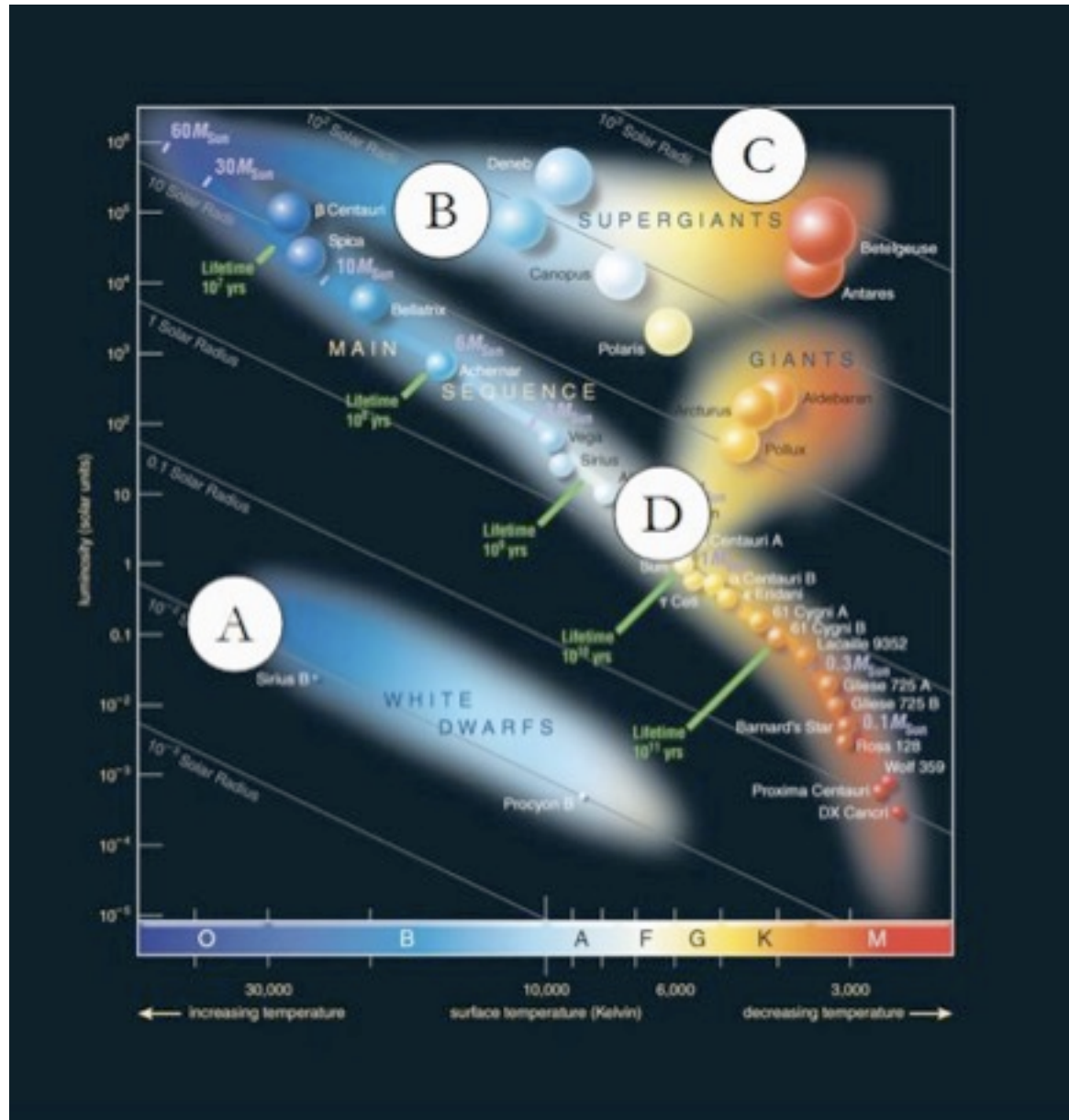
- Which star is the hottest?

Luminosity ↑



← Temperature

Luminosity ↑

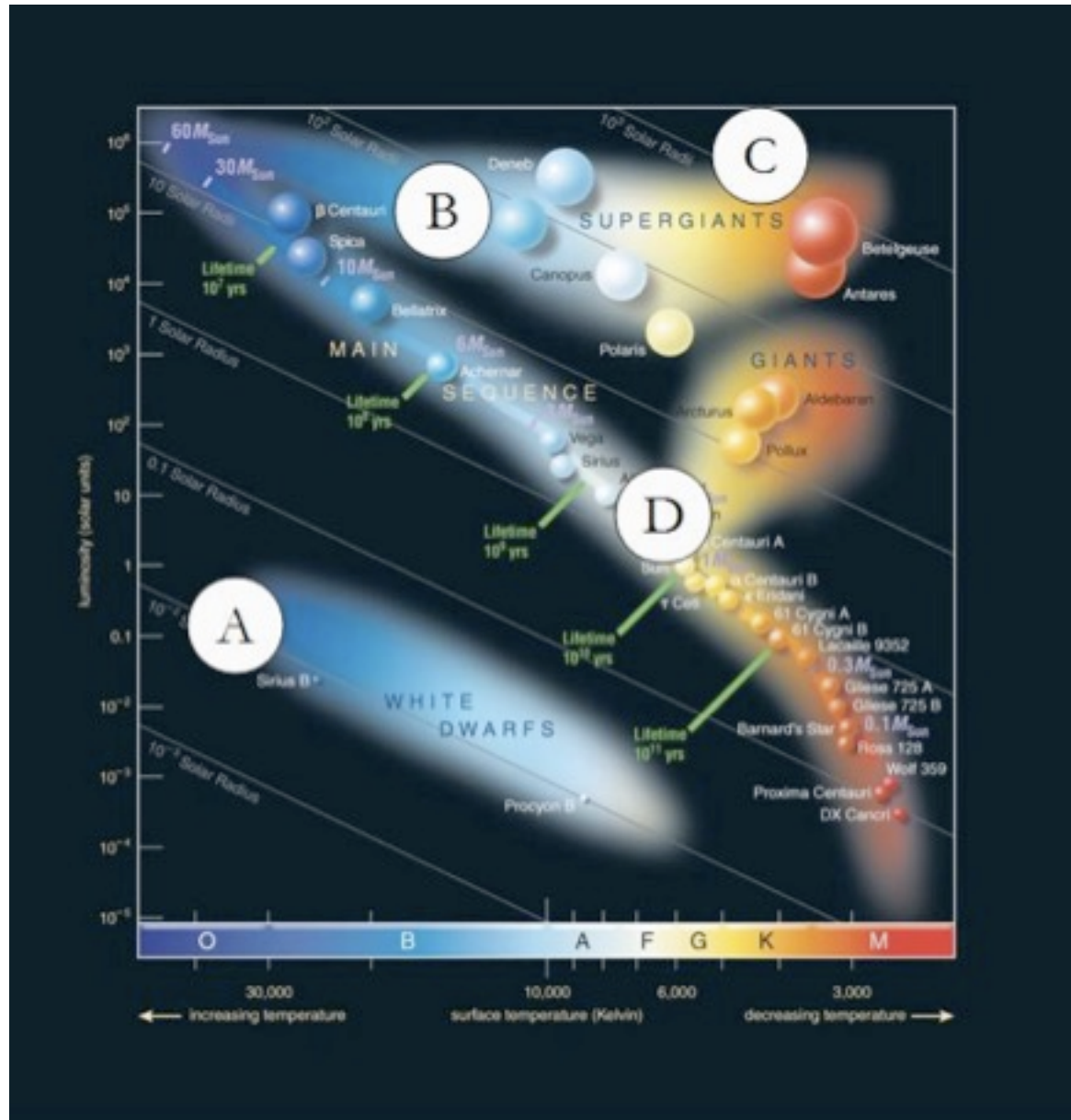


- Which star is the hottest?

A

← Temperature

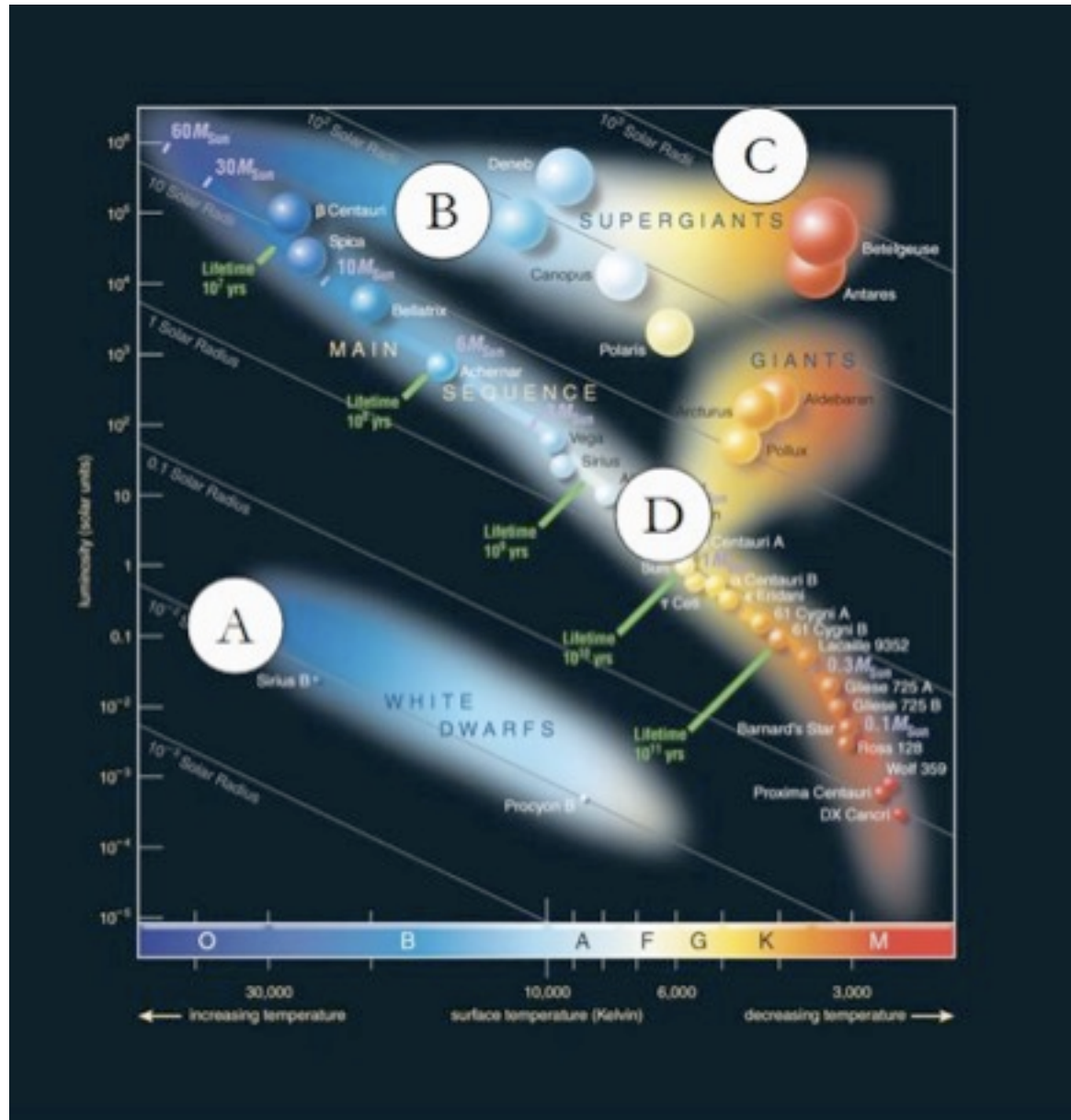
Luminosity ↑



- Which star is the most luminous?

← Temperature

Luminosity ↑

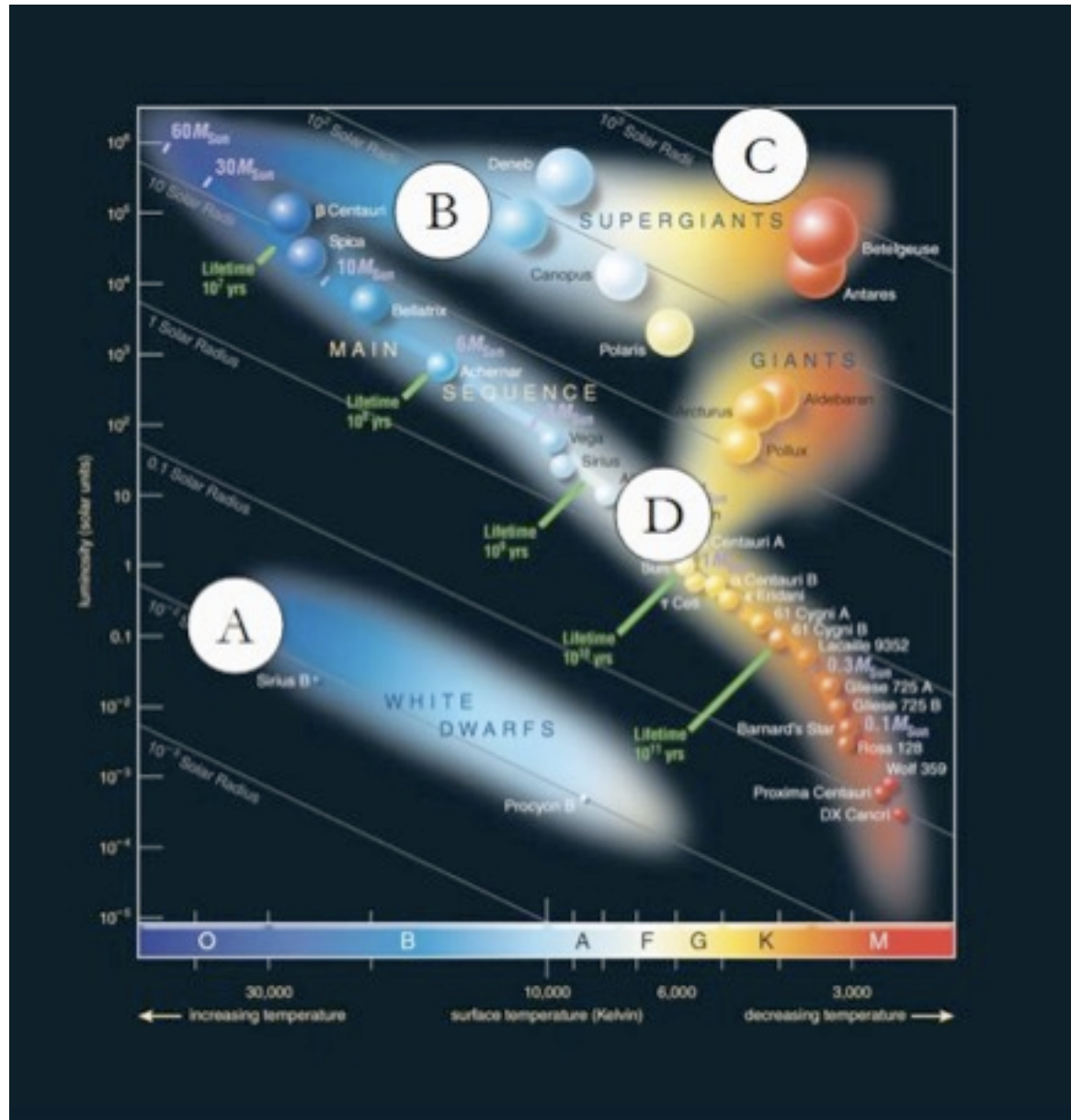


- Which star is the most luminous?

C

← Temperature

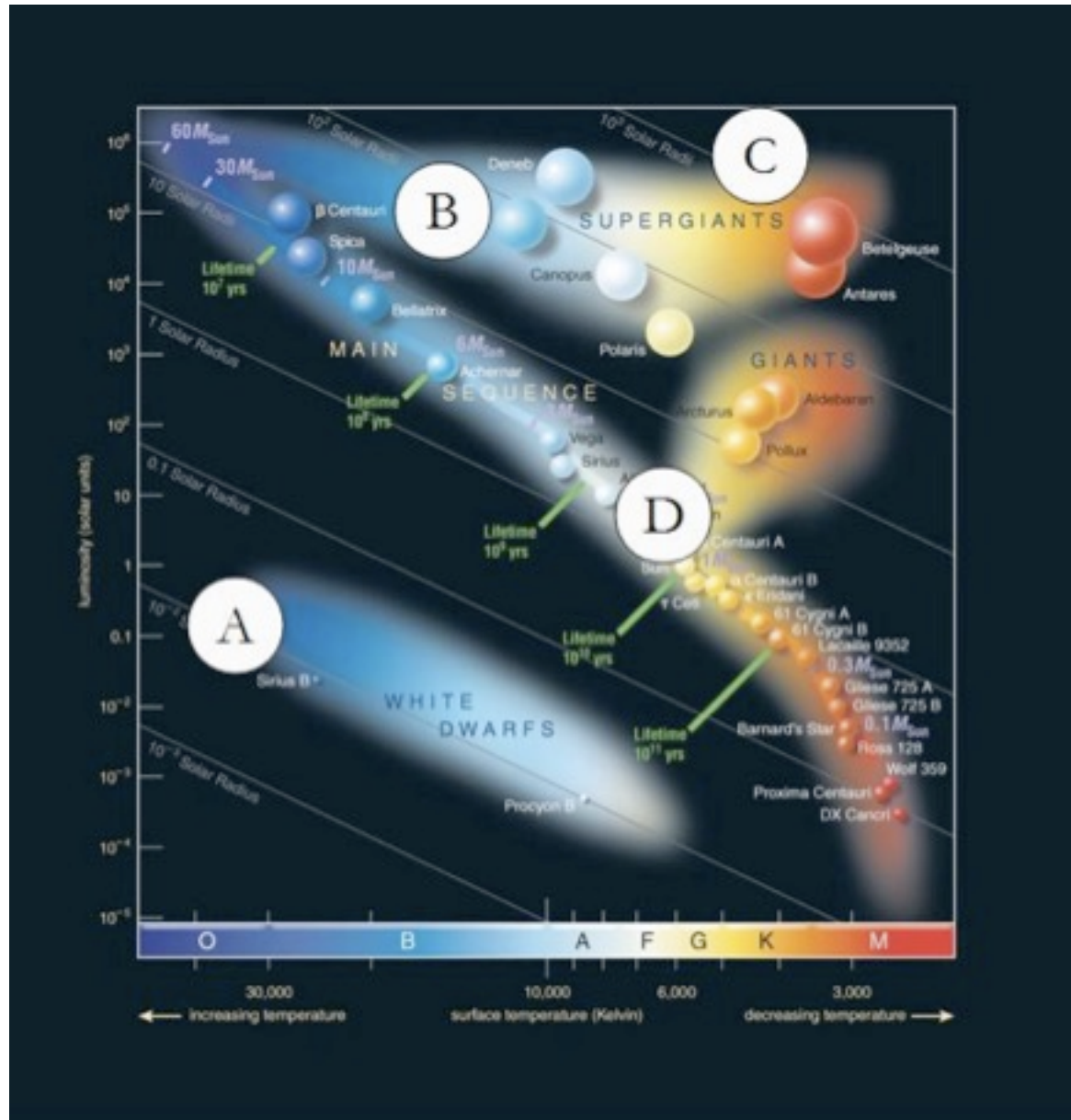
Luminosity  $\uparrow$



$\leftarrow$  Temperature

- Which star is a main-sequence star?

Luminosity  $\uparrow$



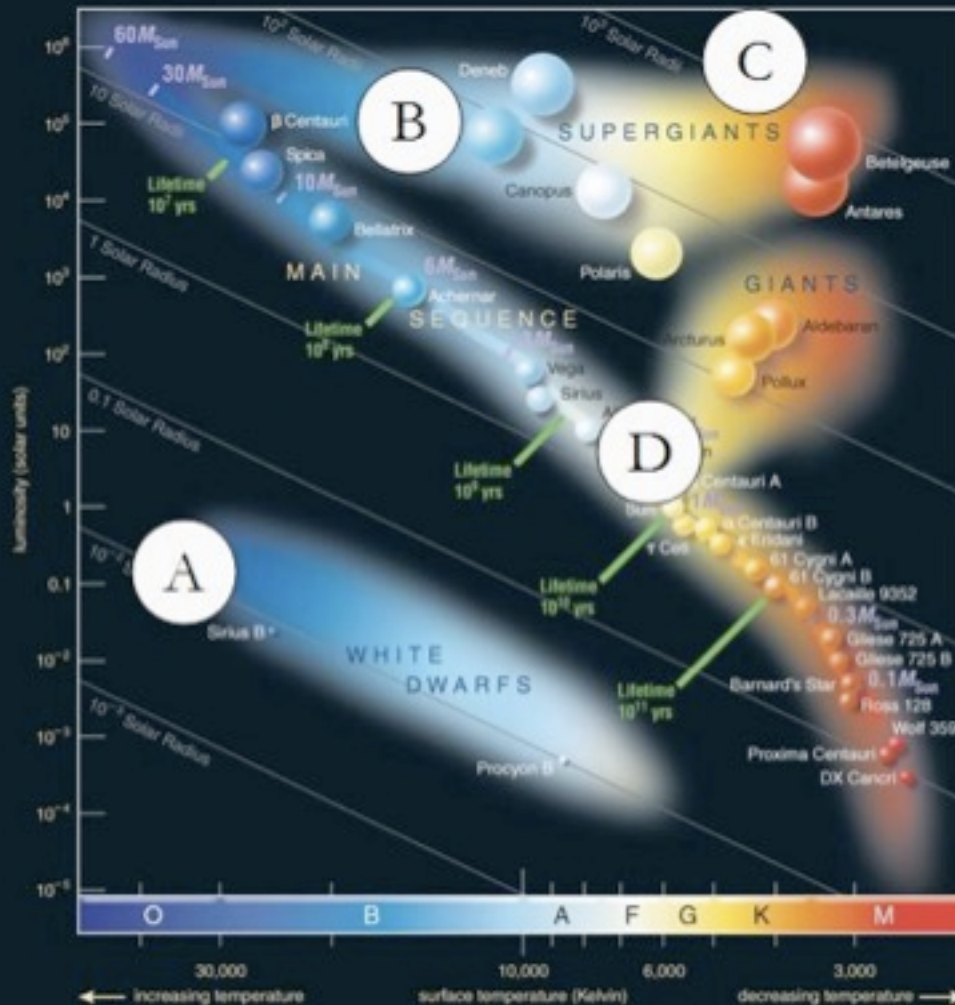
$\leftarrow$  Temperature

- Which star is a main-sequence star?

D

- Which star has the largest radius?

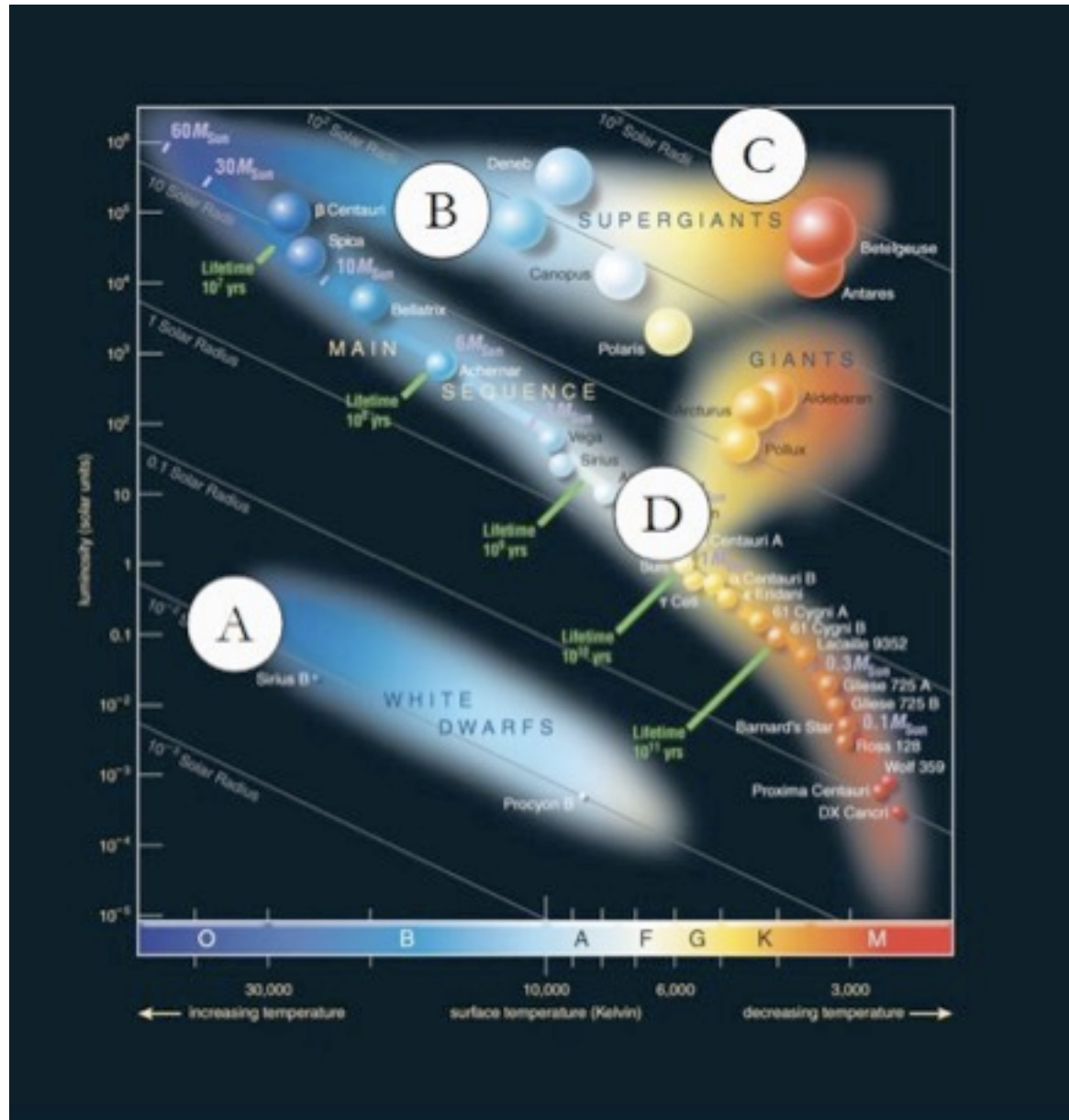
Luminosity ↑



← Temperature



Luminosity  $\uparrow$

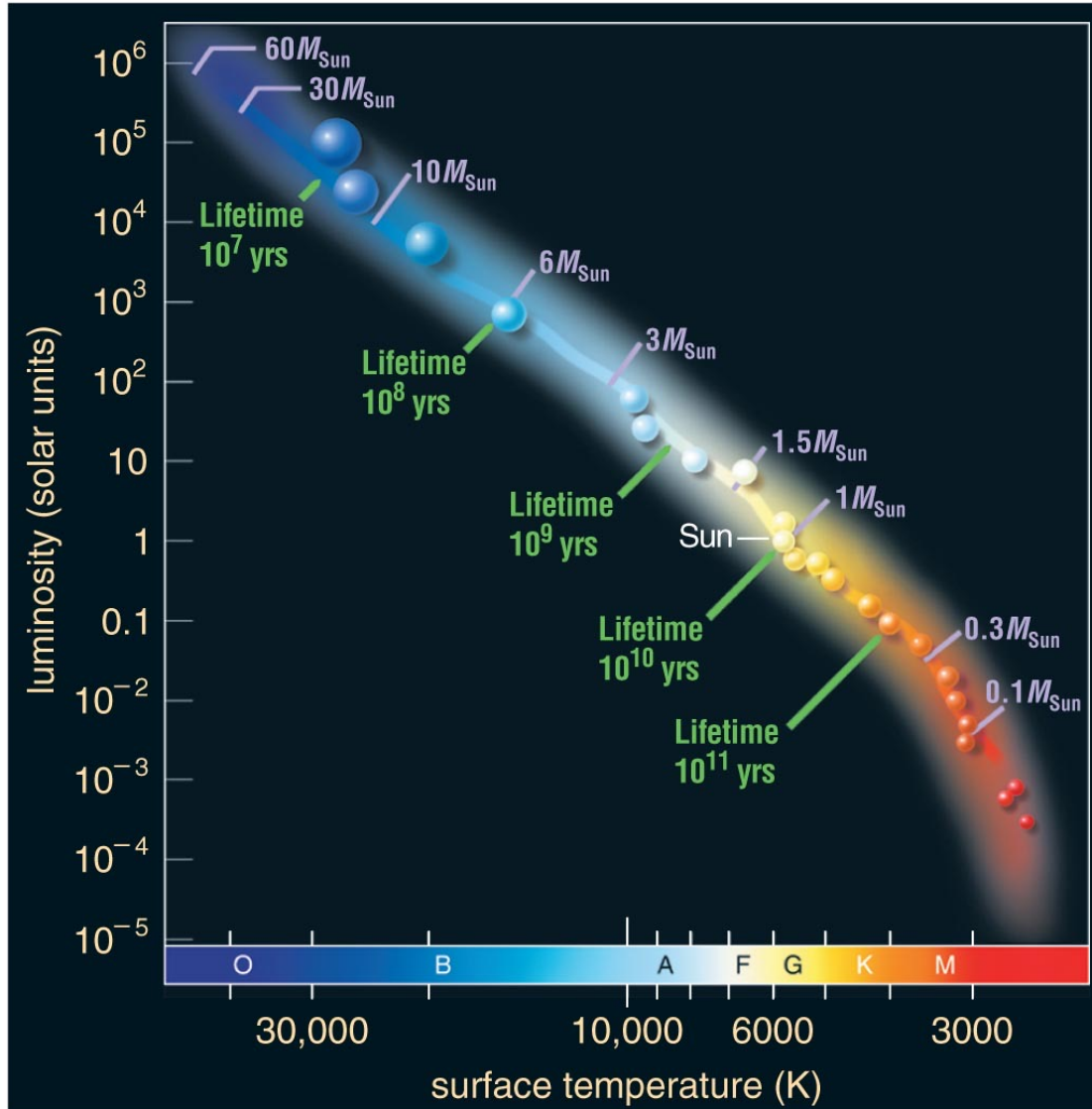


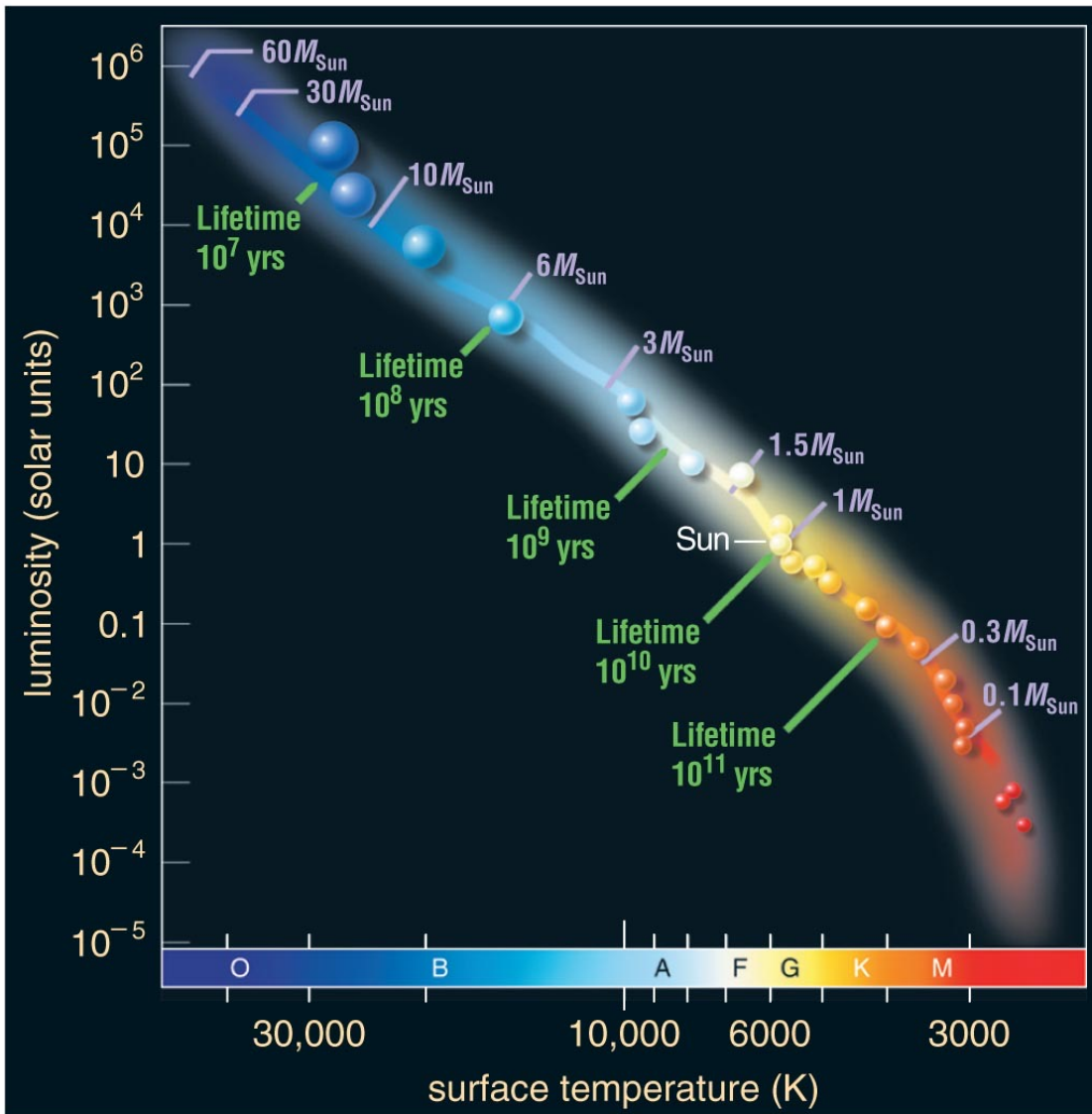
- Which star has the largest radius?

C

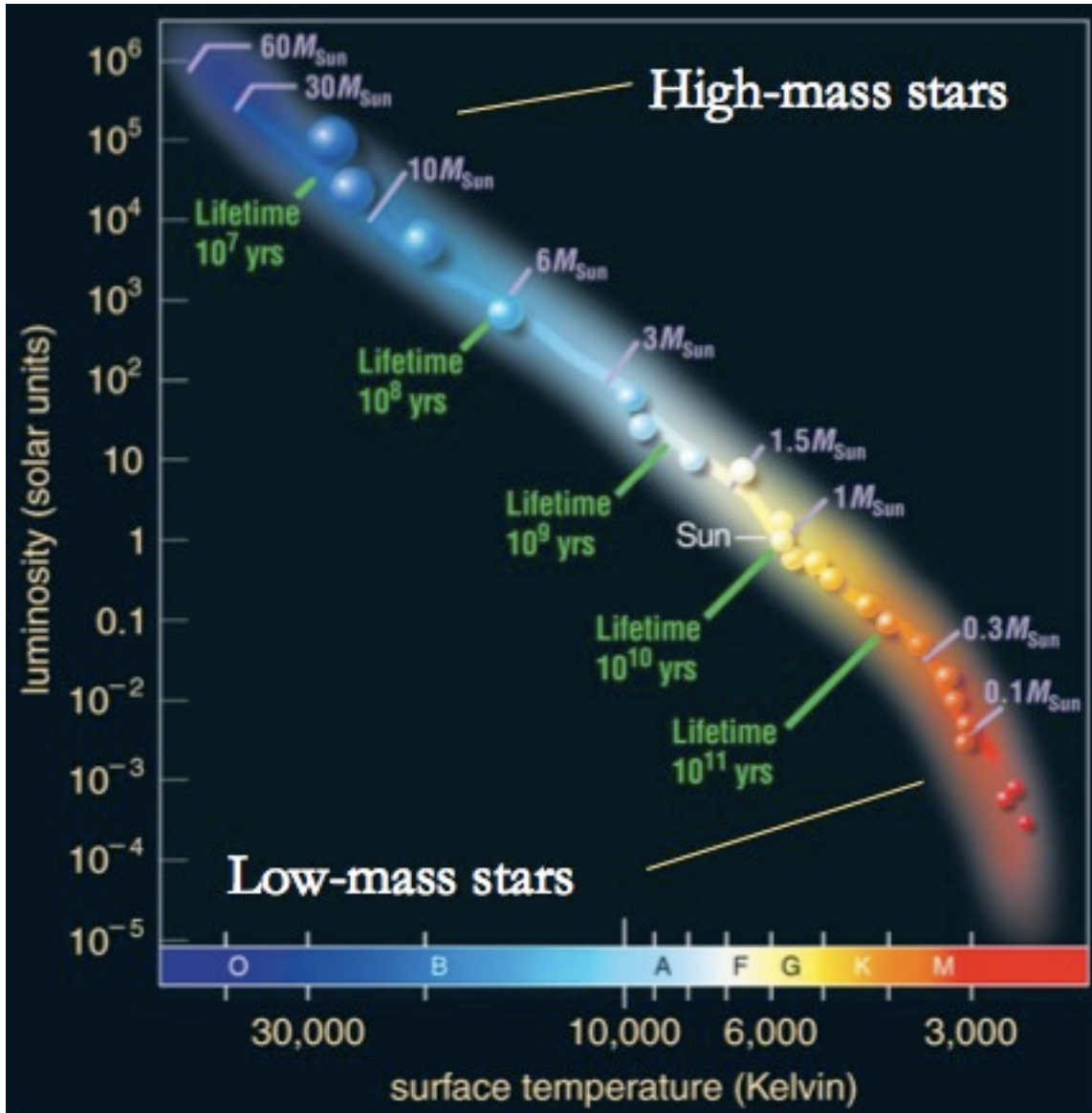
$\leftarrow$  Temperature

# 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.

# Stellar Properties Review

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

$$10^{-4}L_{\text{Sun}}-10^6L_{\text{Sun}}$$

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

$$3000 \text{ K}-50,000 \text{ K}$$

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

$$0.08M_{\text{Sun}}-100M_{\text{Sun}}$$

# 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?

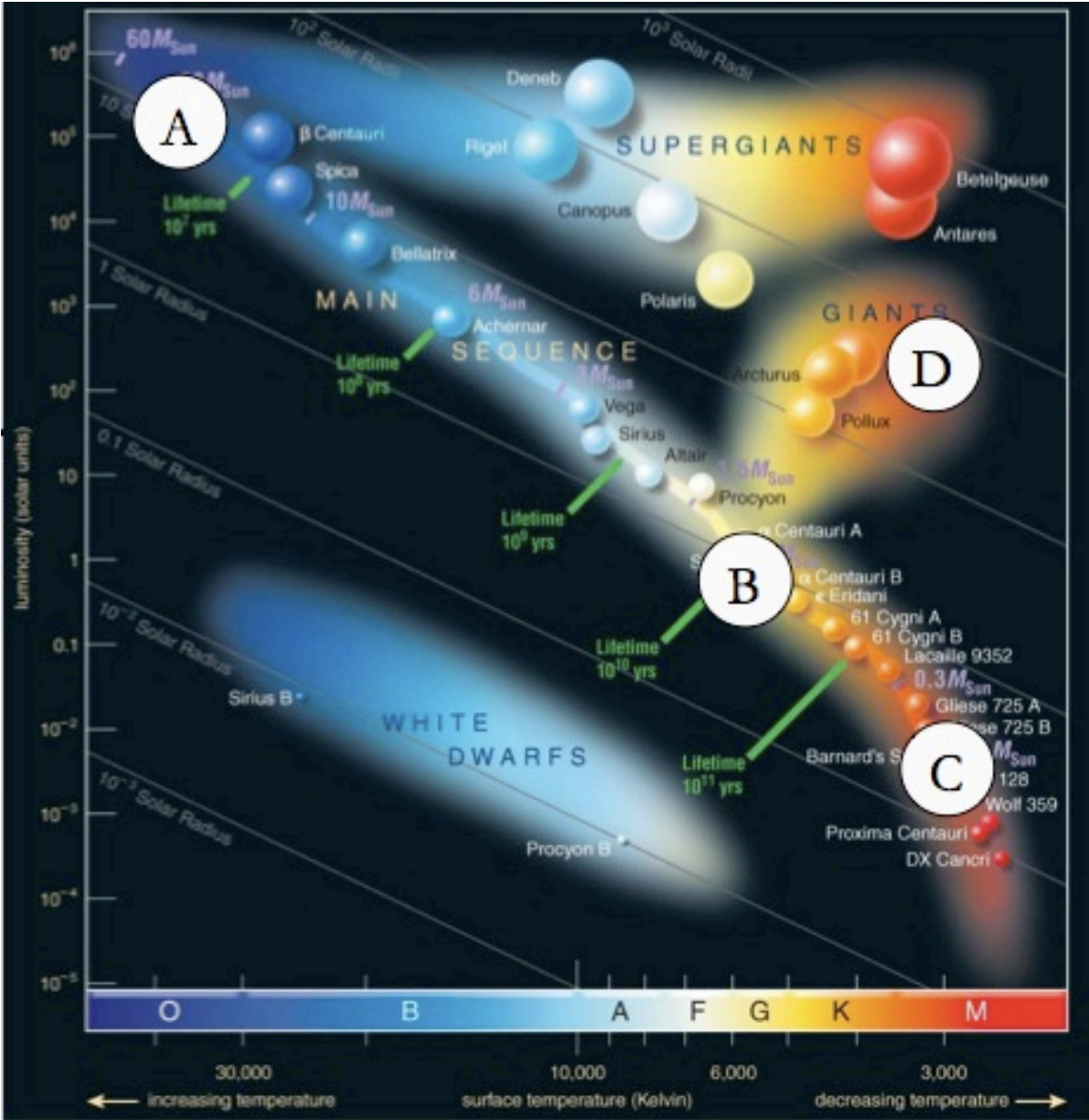


# Off the Main Sequence

- Those stars 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**.



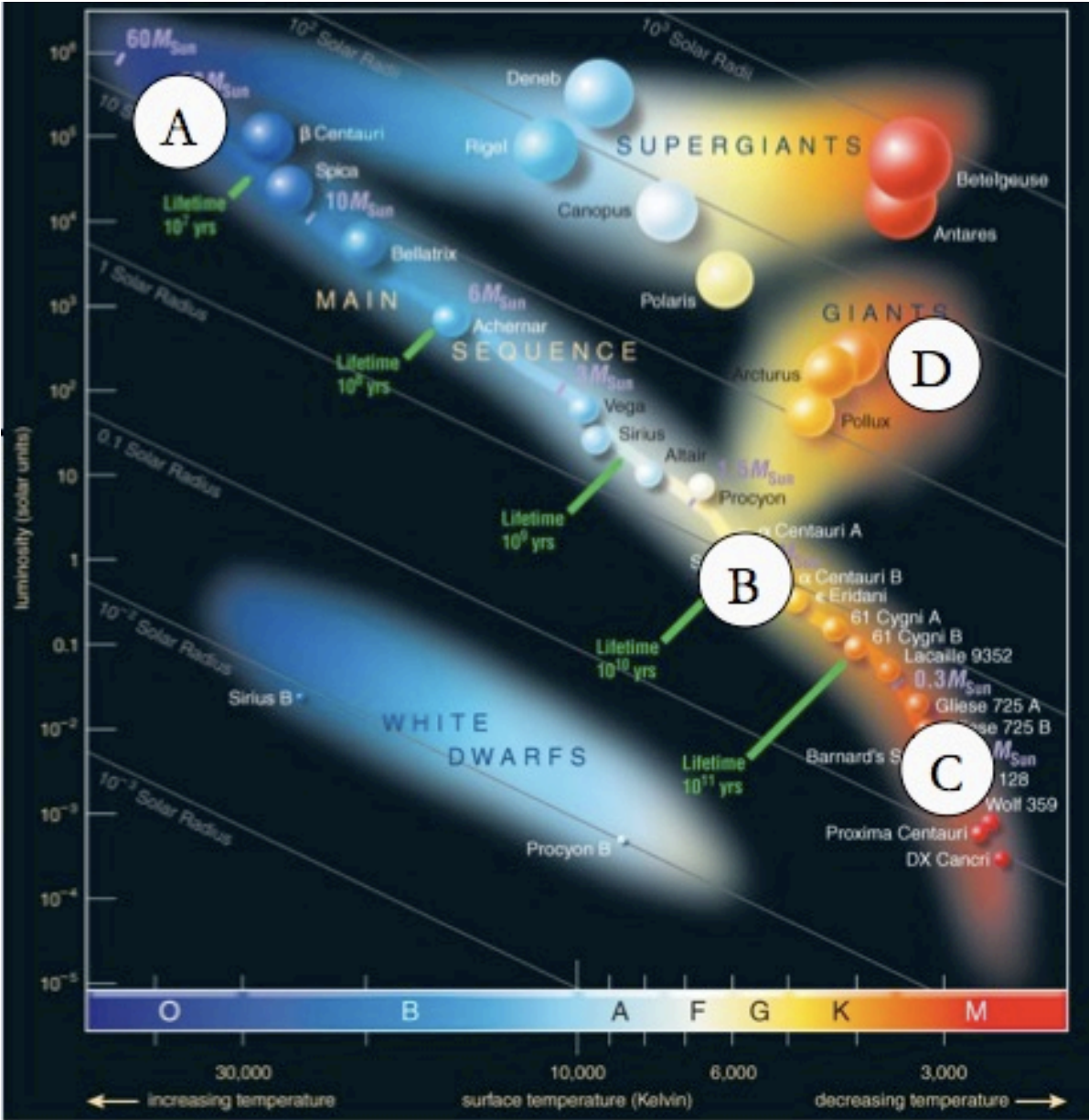
Luminosity ↑



- Which star is most like our Sun?

← Temperature

Luminosity ↑

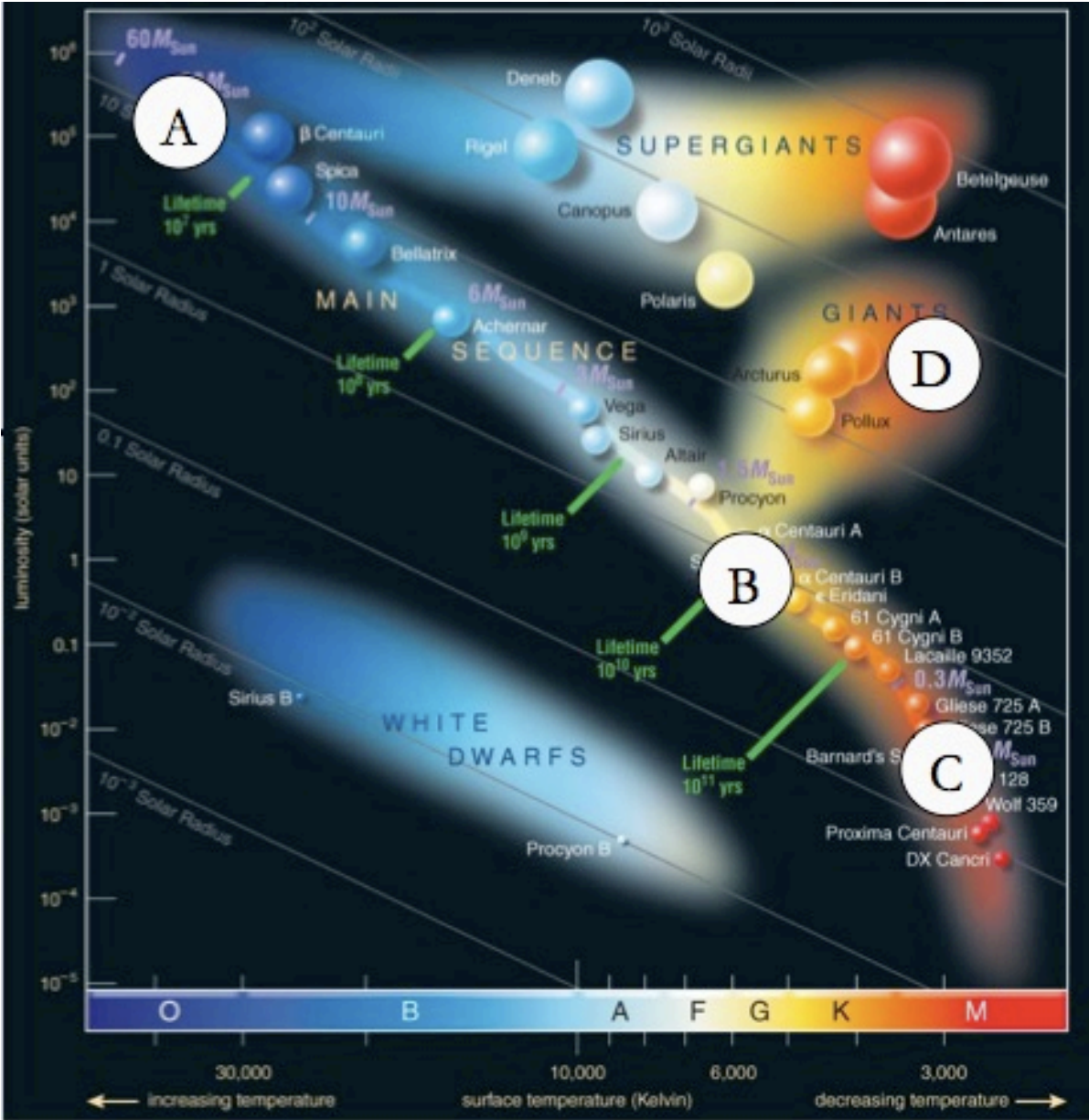


- Which star is most like our Sun?

(B)

← Temperature

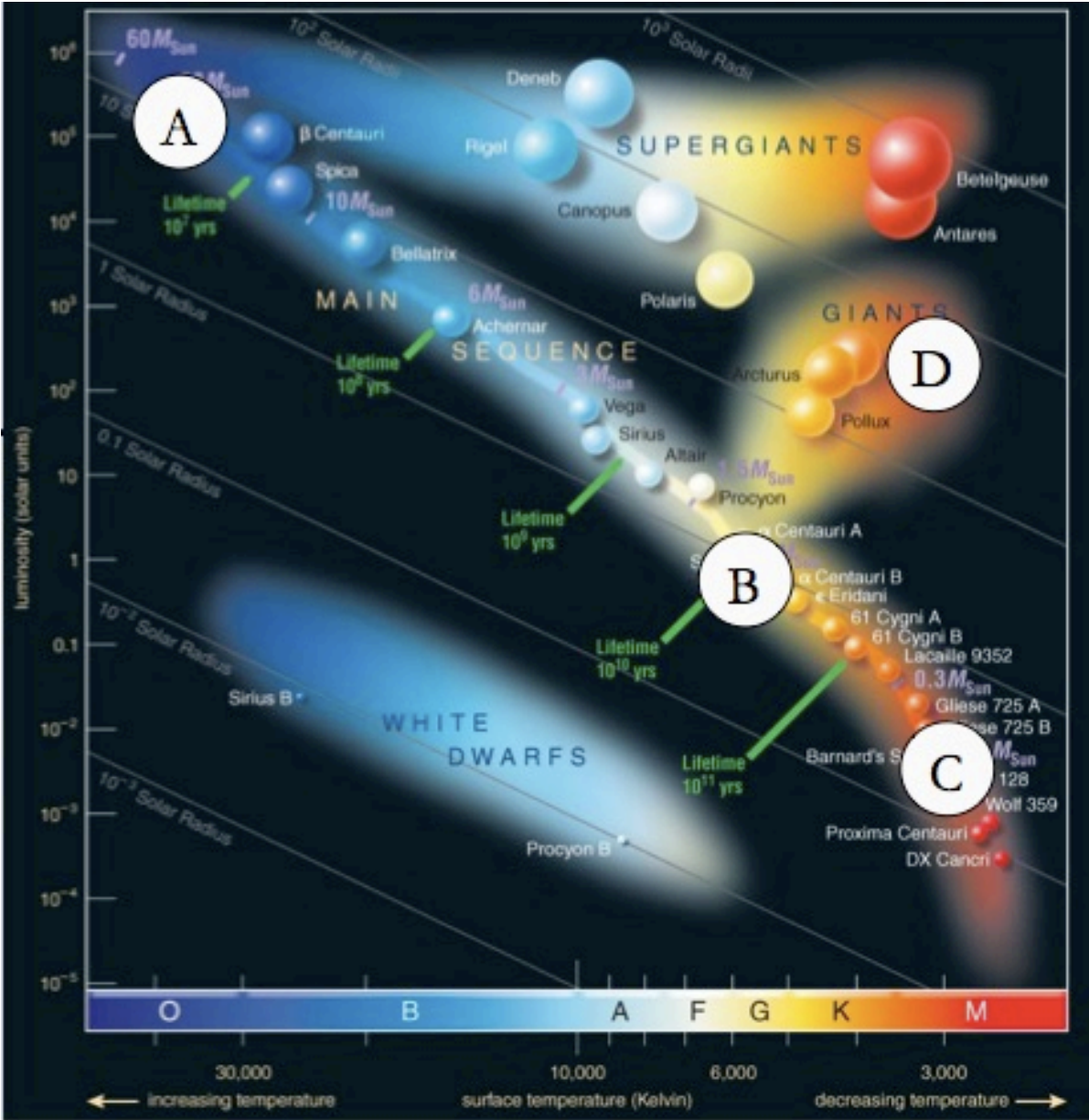
Luminosity ↑



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

← Temperature

Luminosity ↑

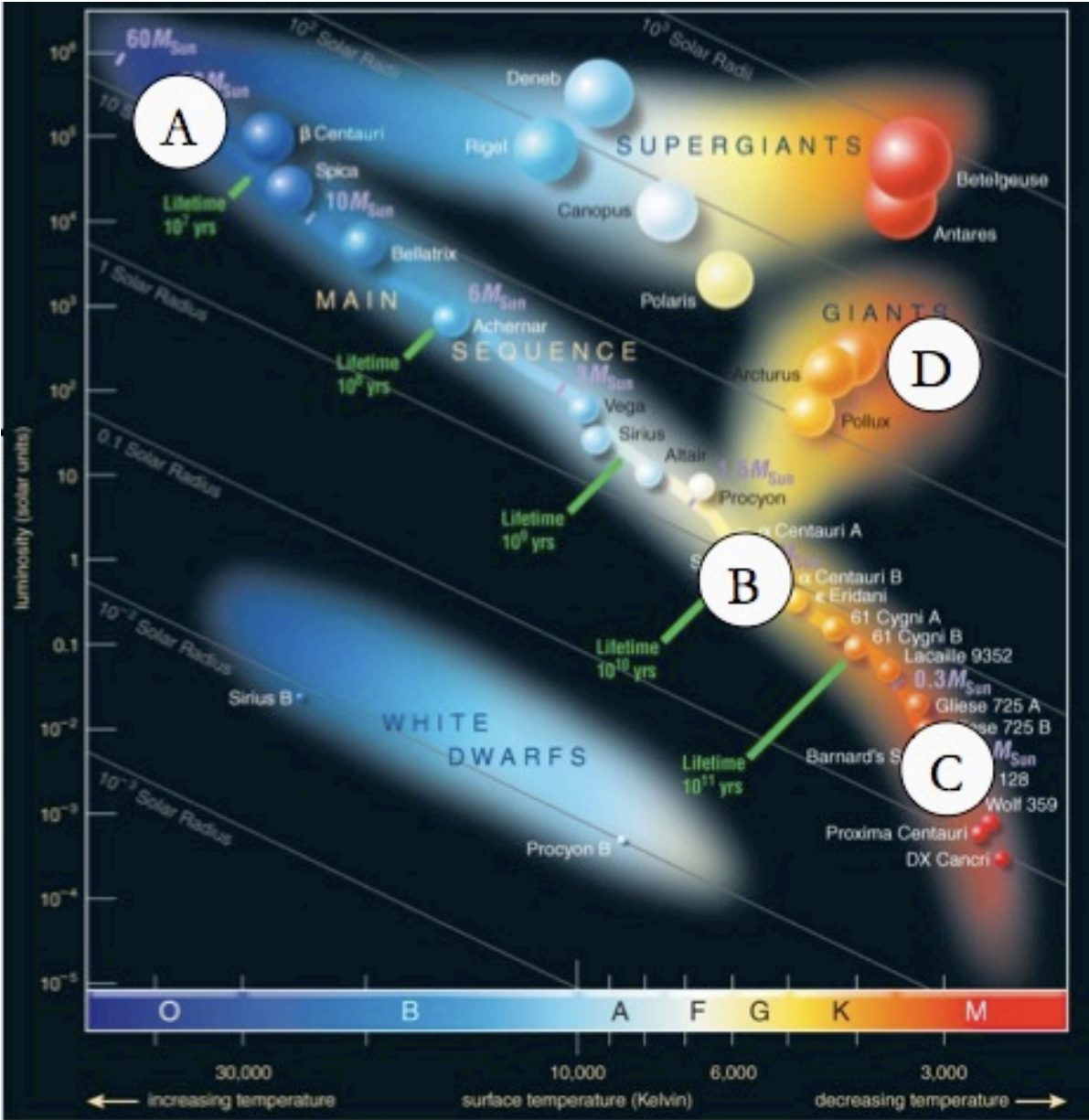


← Temperature

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

C

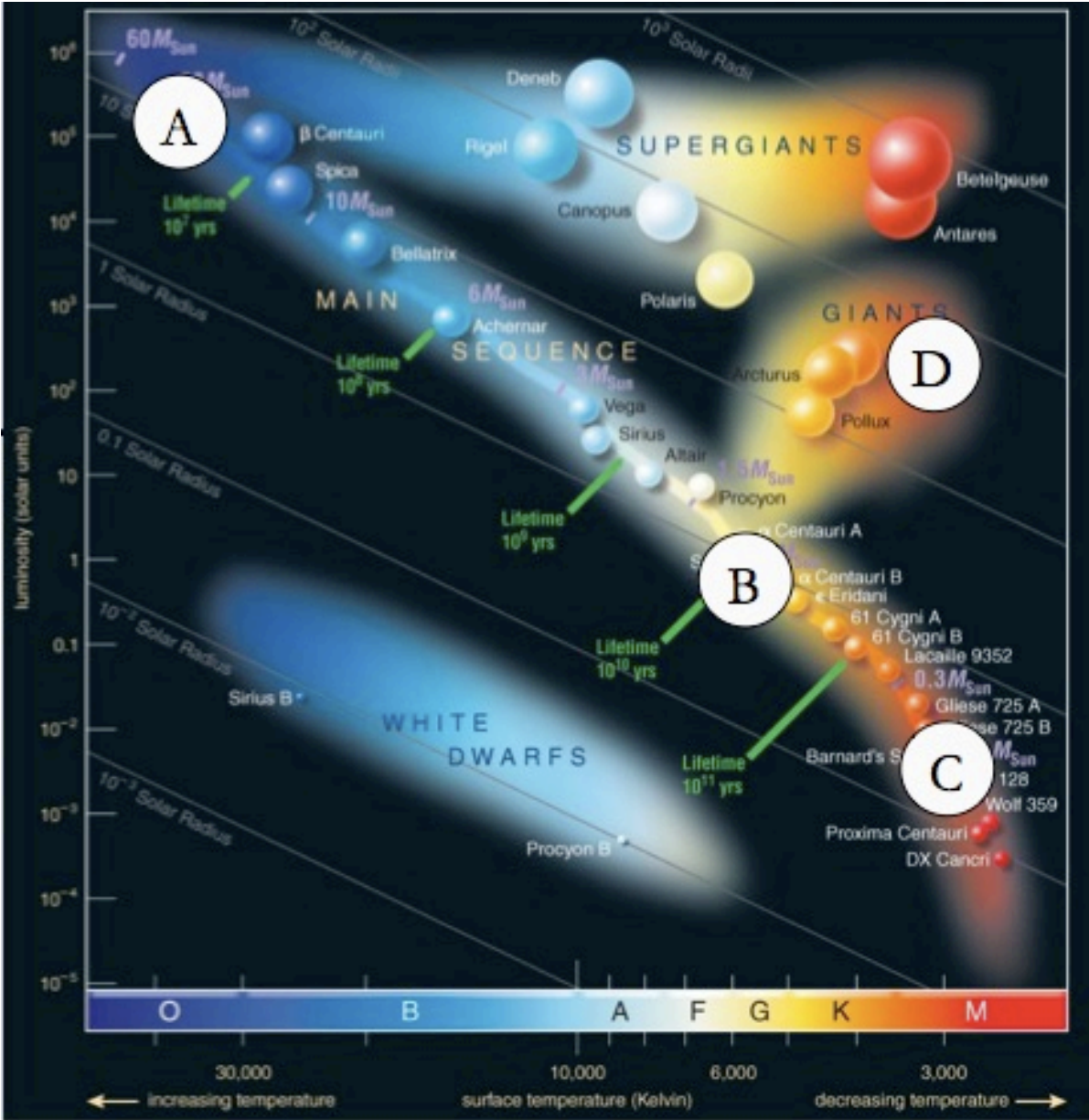
Luminosity ↑



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

← Temperature

Luminosity ↑

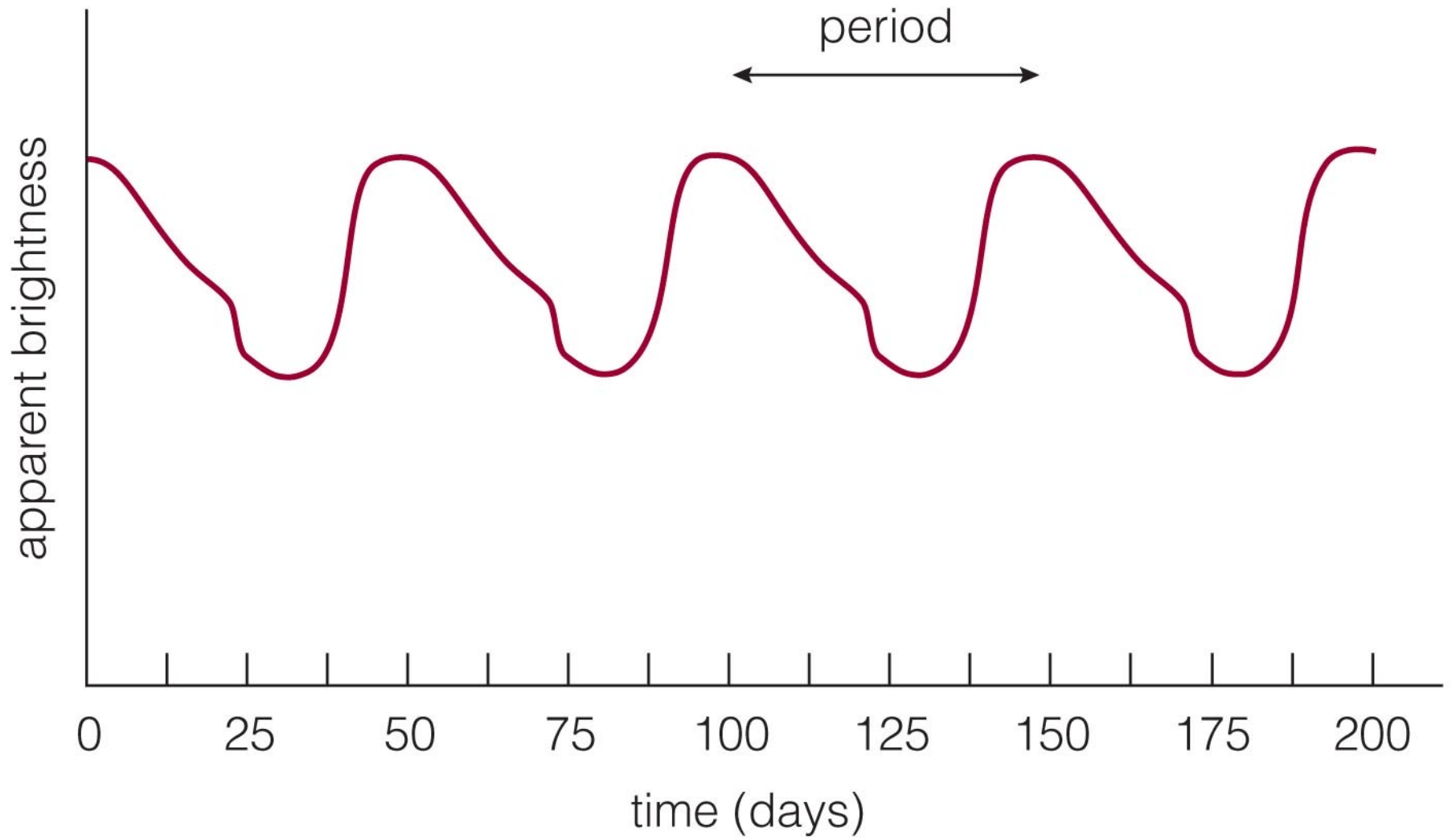


← Temperature

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

A

# Variable Stars



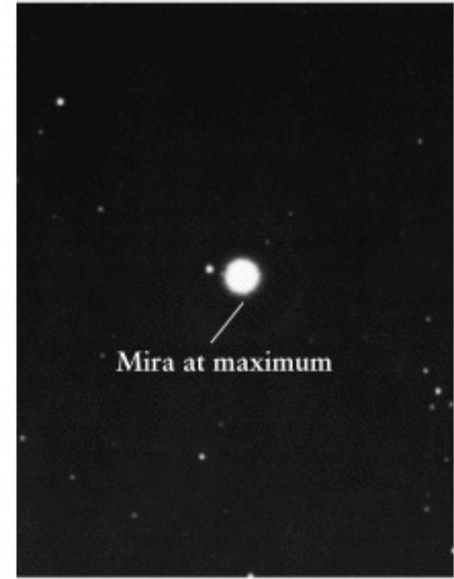
# Variable Stars: Long-Period Variables

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  $\sim 3,500\text{K}$  and luminosities of  $10\text{-}10,000 L_{\text{solar}}$ .



(a)



(b)

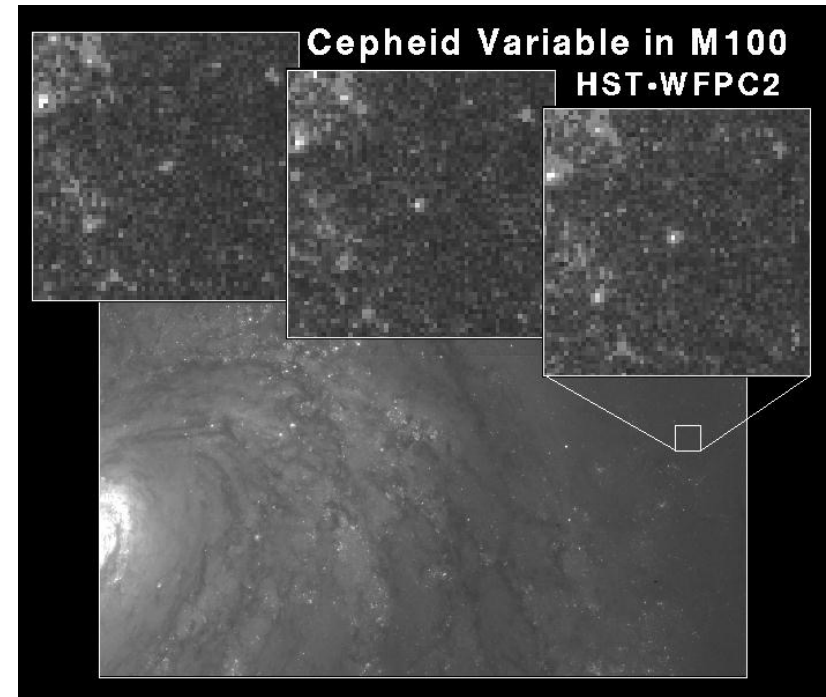
The first **long-period variable** star discovered was Mira (Period  $\sim 332$  days).



# 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  $\delta$  Cephei.



# Variable Stars: RR Lyrae Stars

**RR Lyrae variables** are pulsating horizontal branch stars (fusing He in their core) 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.

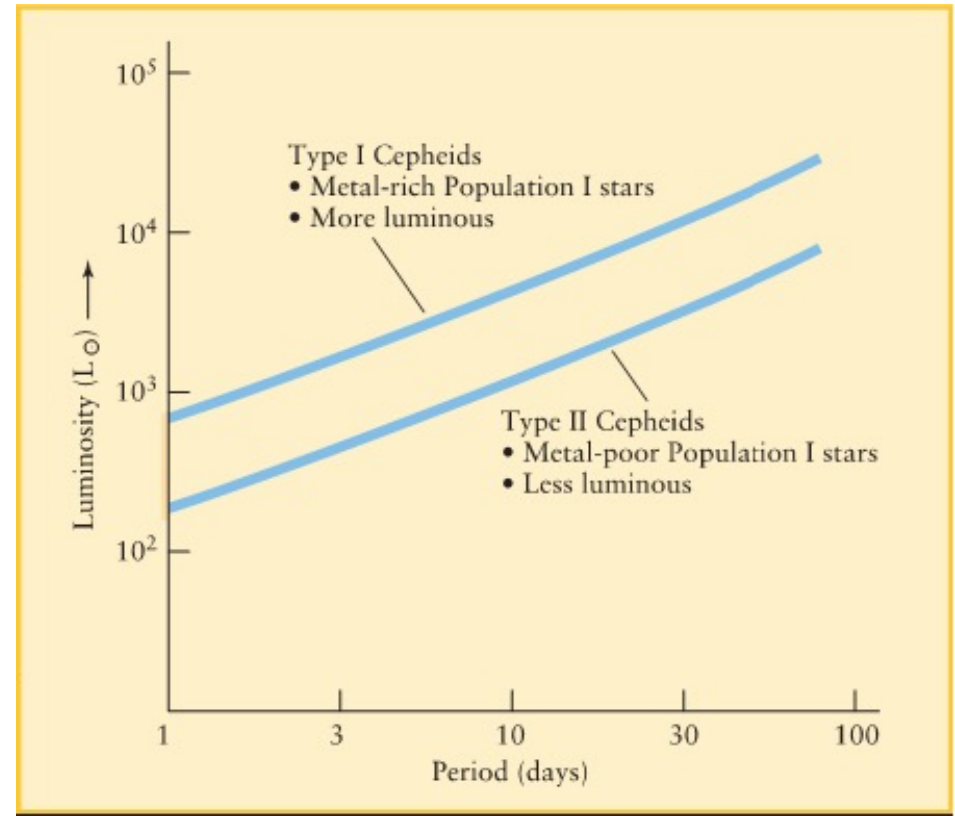
# Cepheid Variables: Period-Luminosity Relation

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.



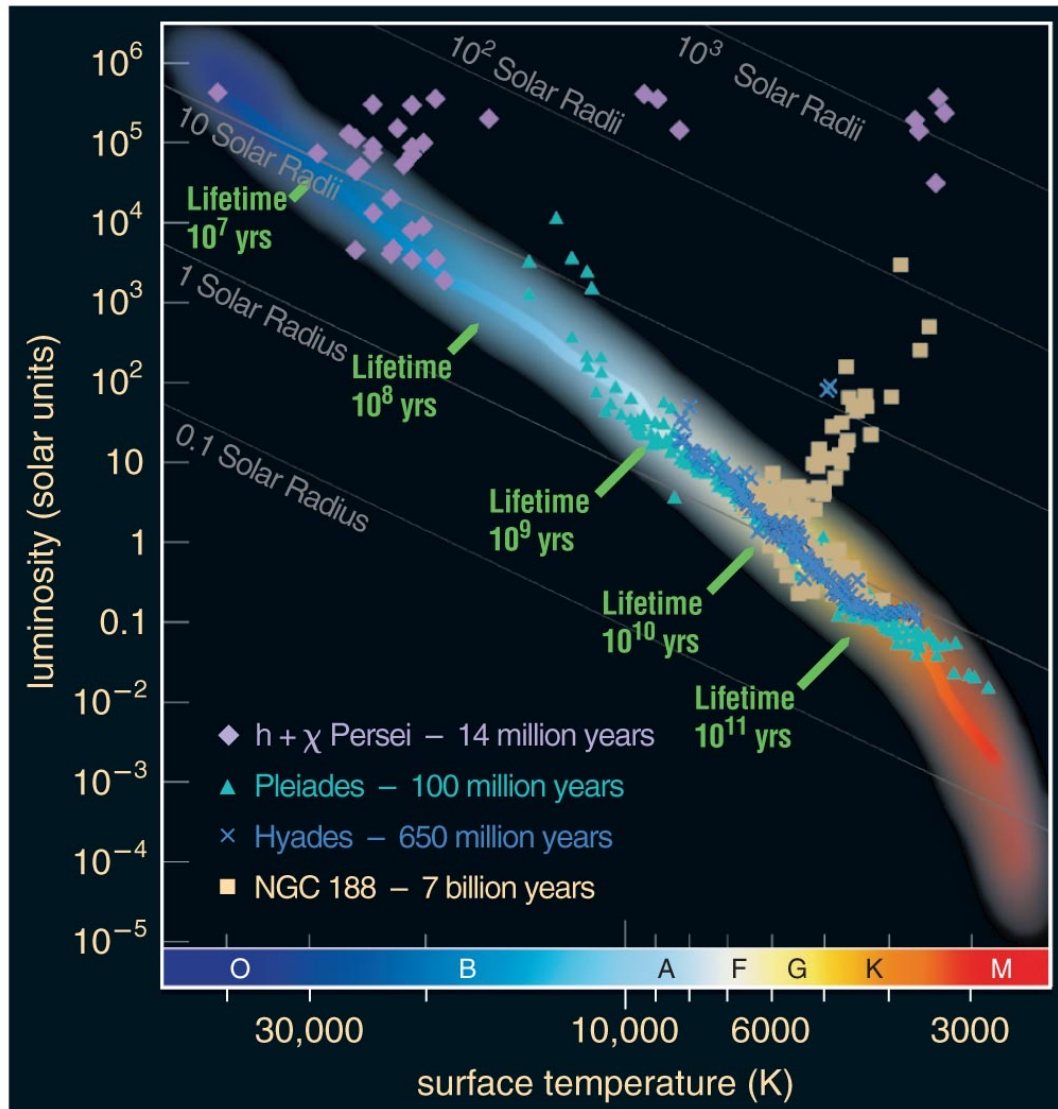


- ***Open cluster:*** is a group of up to a few thousand stars that were formed from the same giant molecular cloud and are still loosely gravitationally bound to each other.




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

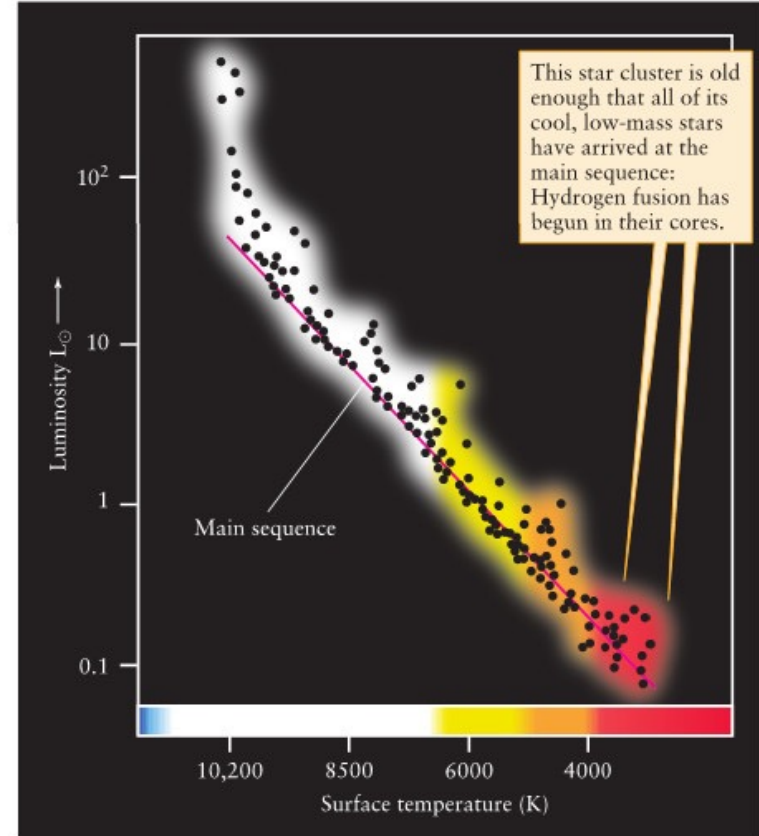
# How do we measure the age of a star cluster?



# Example of Open Cluster: Pleiades

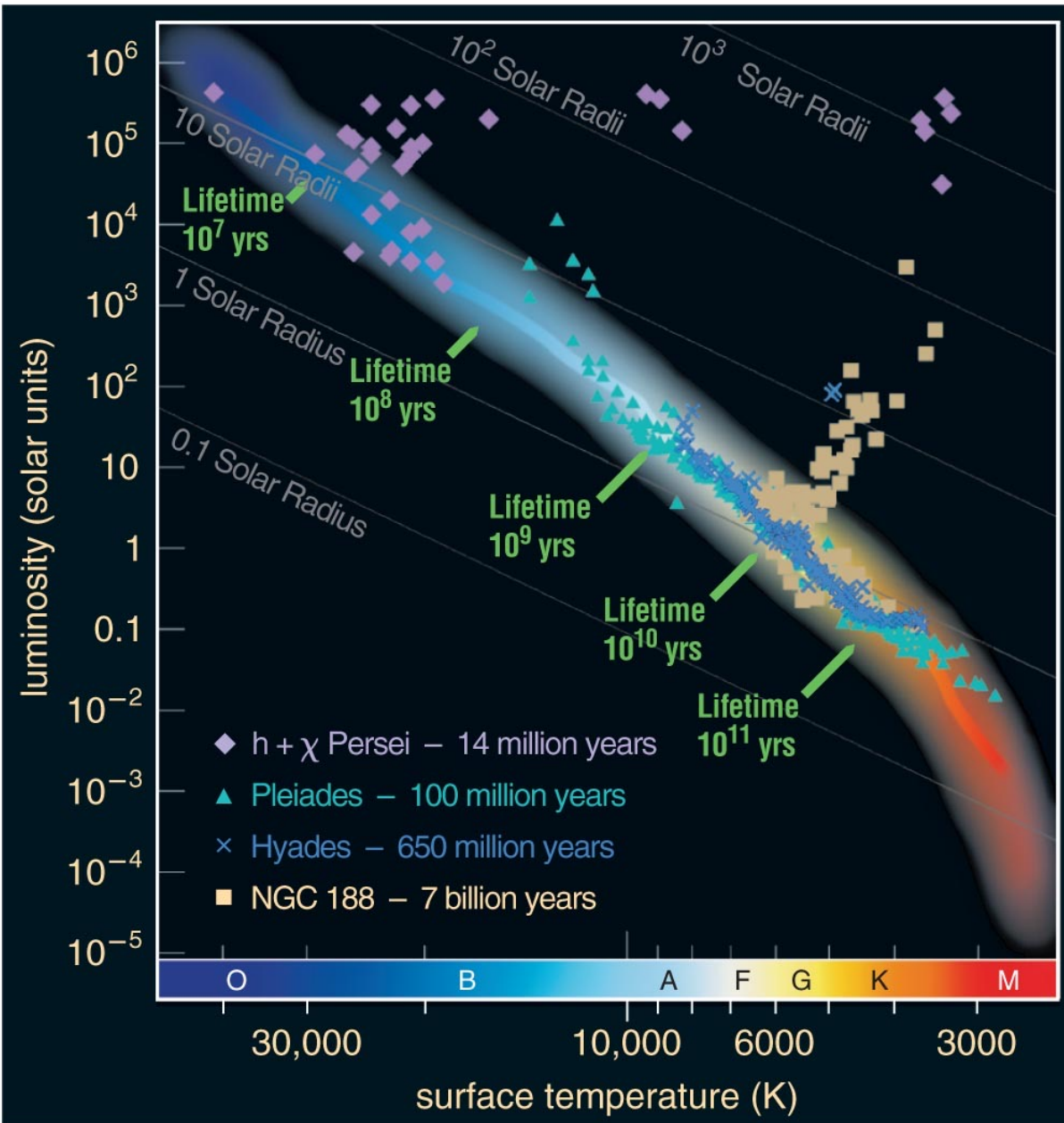


(a) The Pleiades star cluster R I  U X G

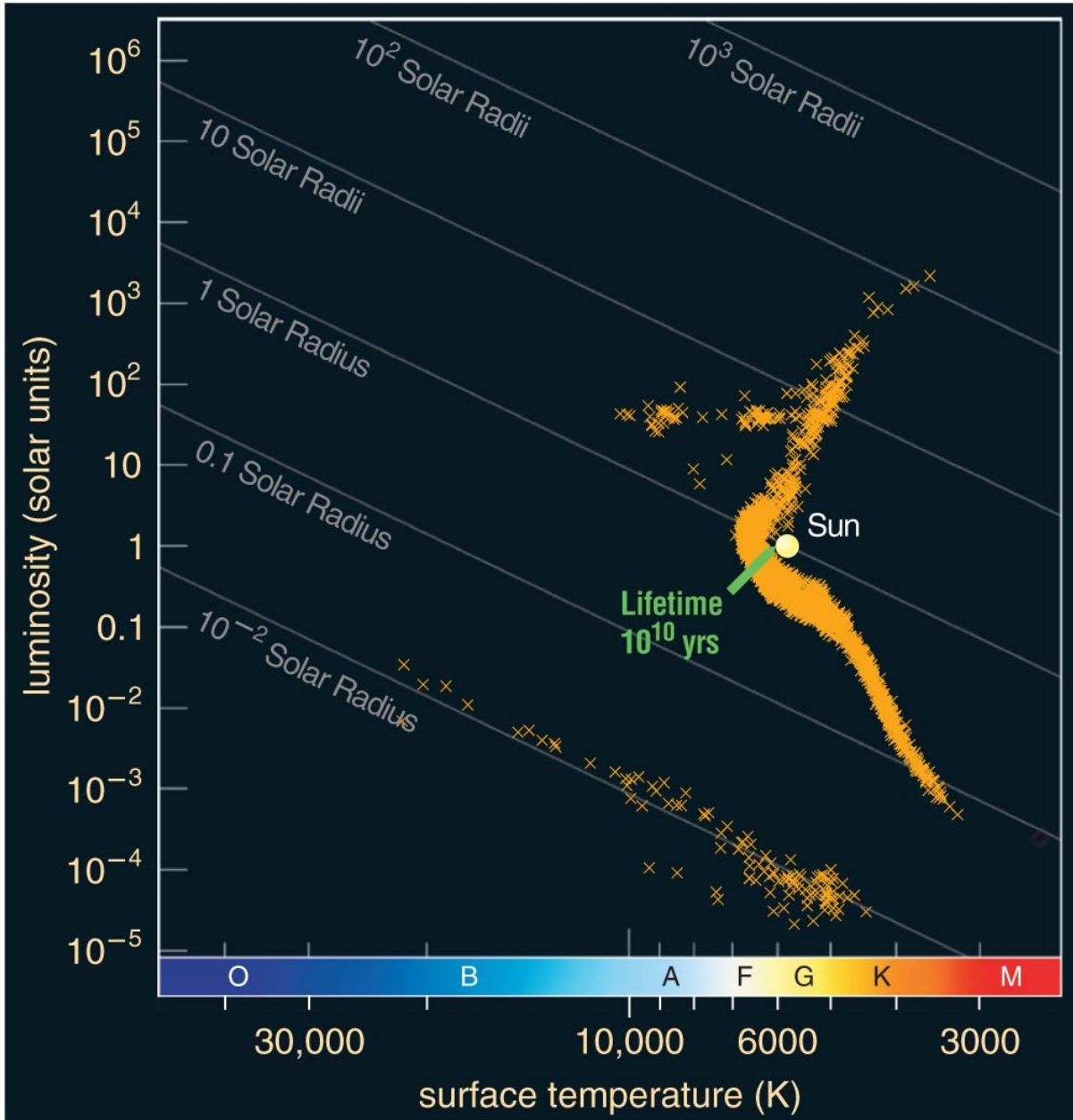


(b) An H-R diagram of the stars in the Pleiades

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  $\sim 100 \times 10^6$  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.



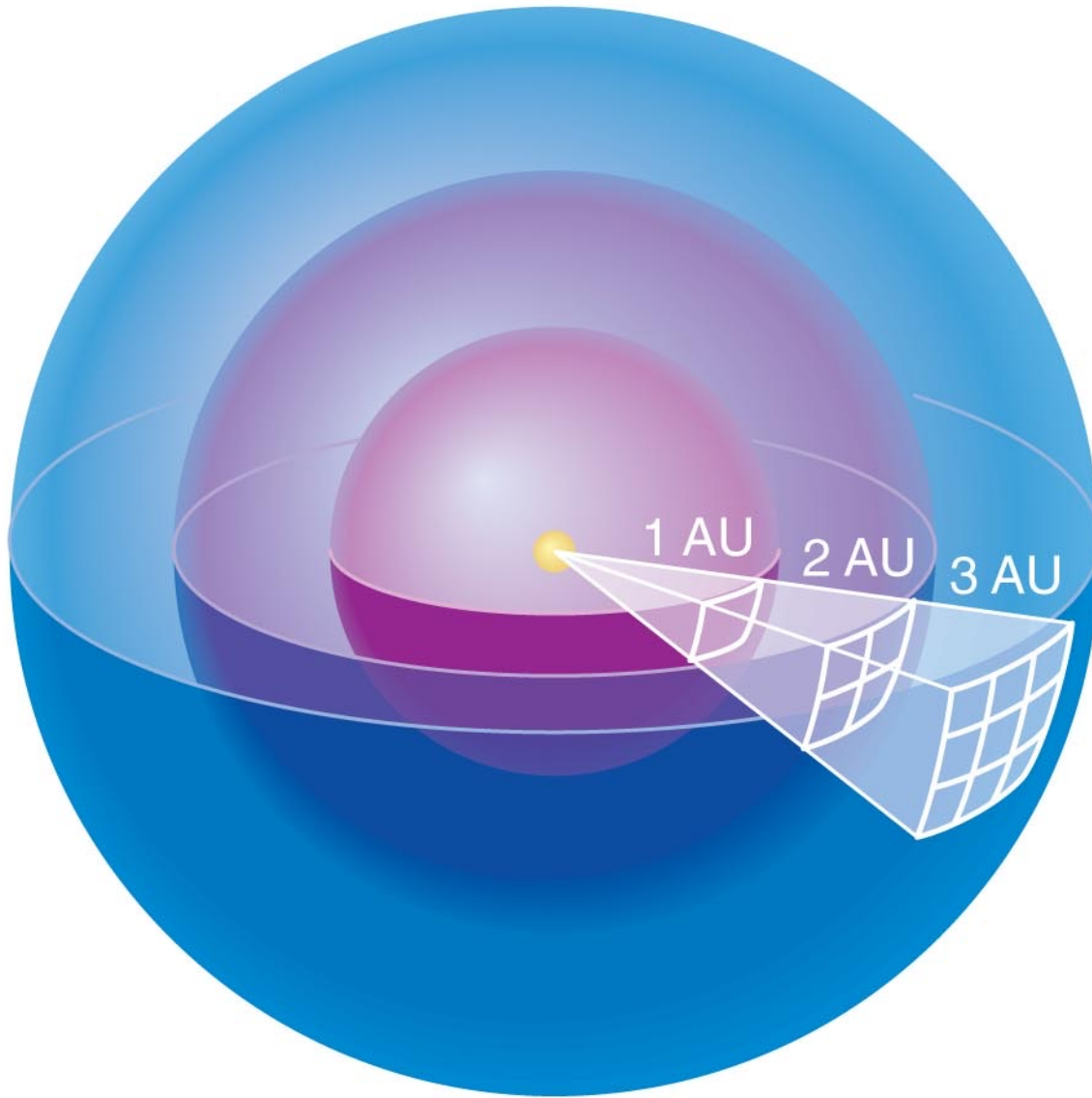
- Detailed modeling of the oldest globular clusters reveals that they are about 13 billion years old.

# 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.

# EXTRA SLIDES



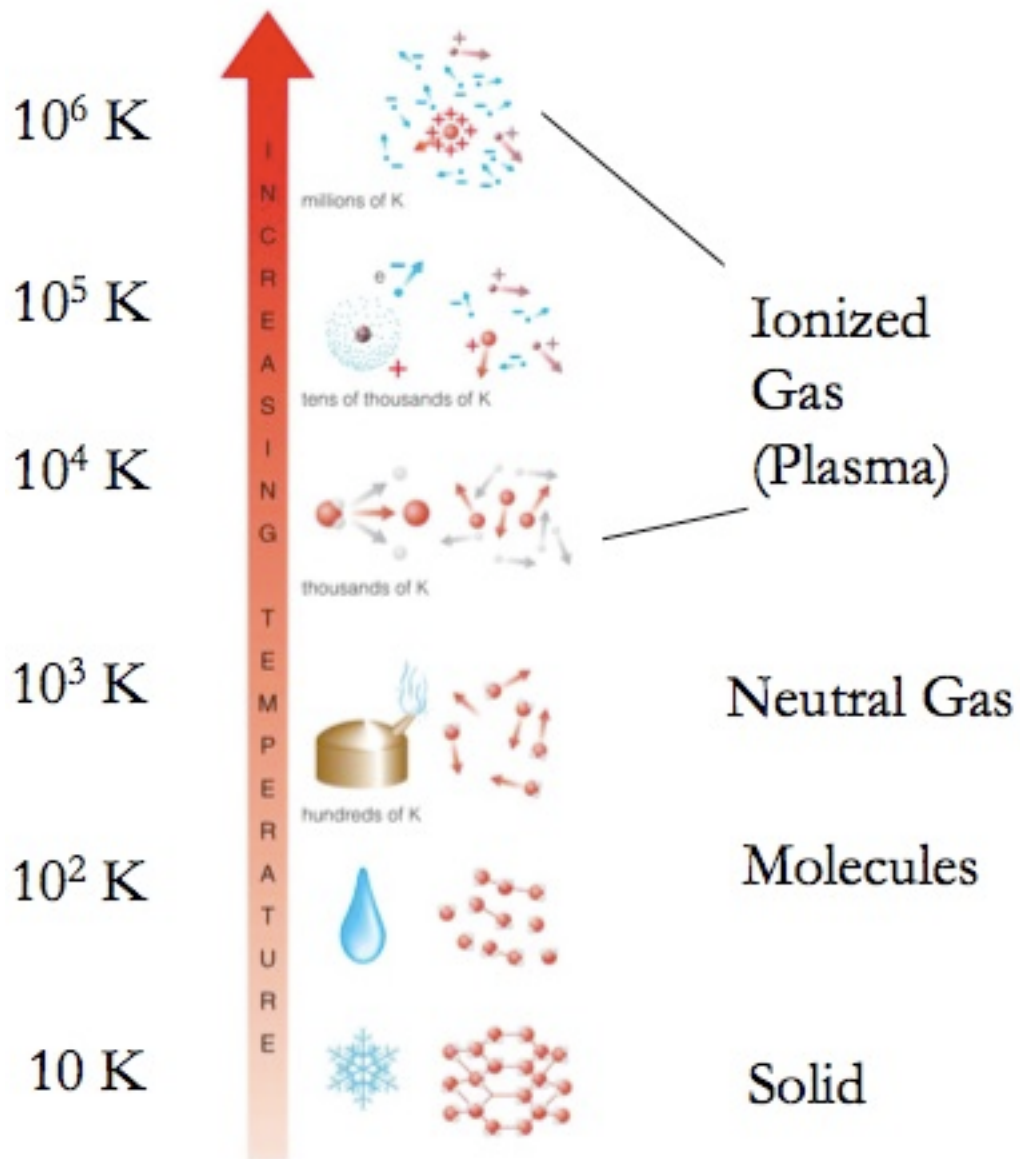


- The amount of luminosity passing through each sphere is the same.

Area of sphere:

$$4\pi (\text{radius})^2$$

- Divide luminosity by area to get brightness.



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

# 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.

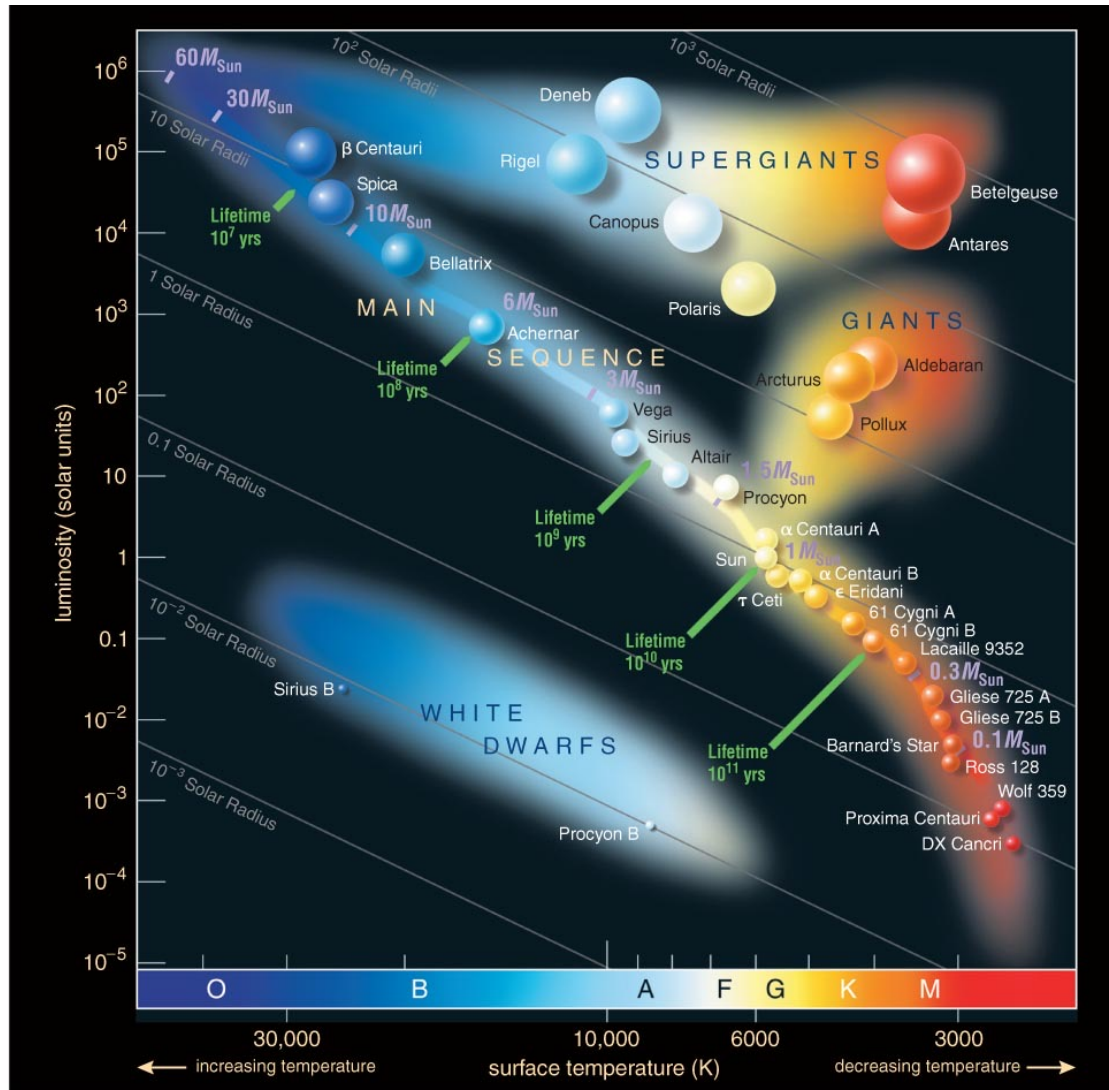


**Hipparcos** has measured about 118,000 stars using the parallax method.

- H-R diagram depicts:

Temperature  
 Luminosity  
 Luminosity Class  
 Radius

Luminosity ↑

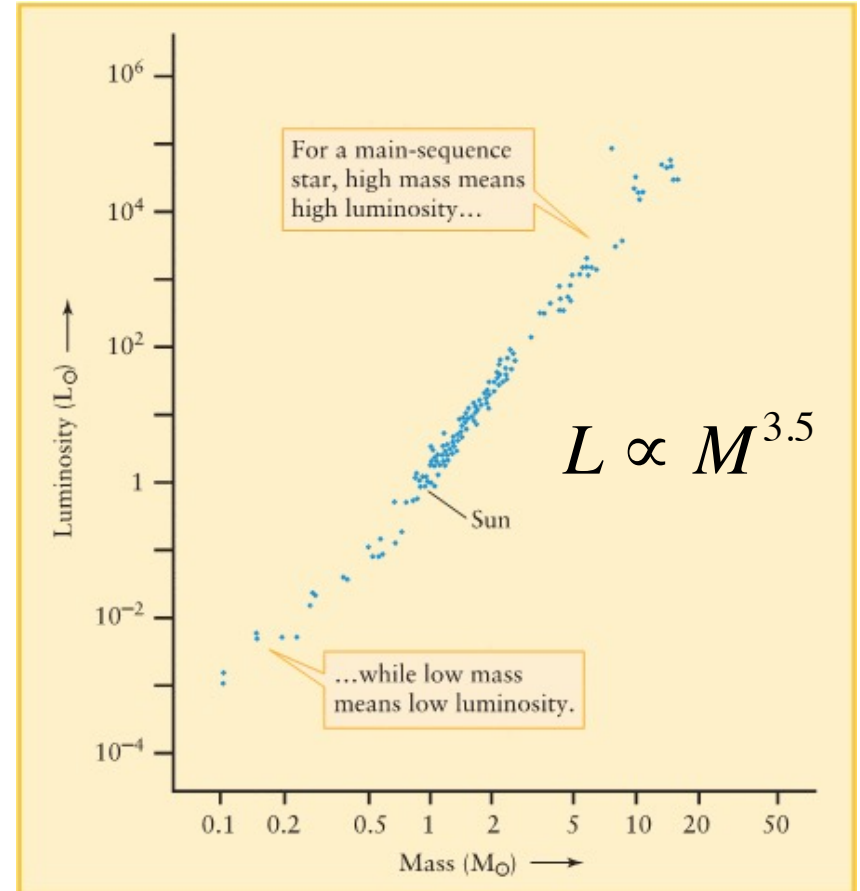


← Temperature

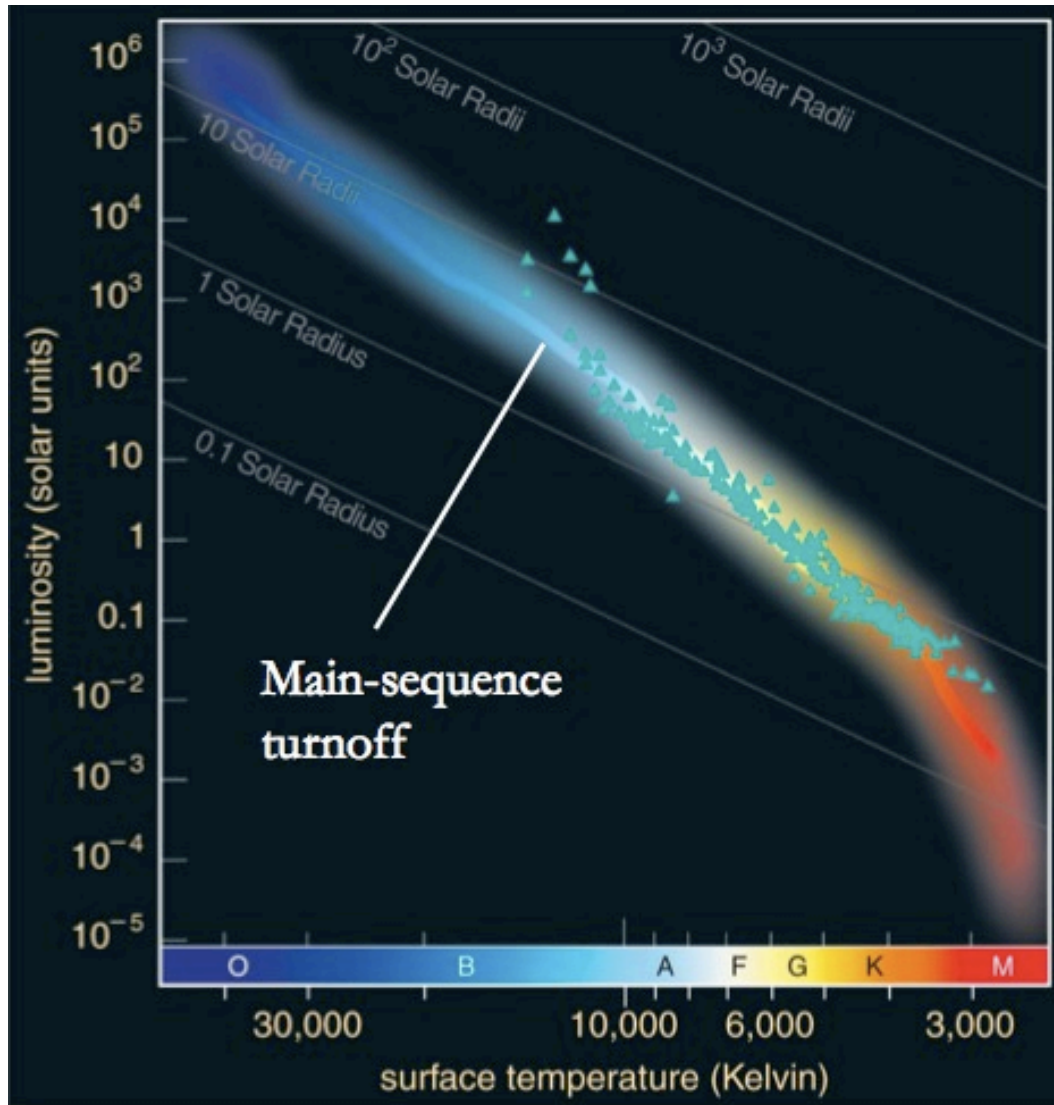
# Mass-Luminosity Relation for Main Sequence Stars

## 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.



# 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

# Variable Stars

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

