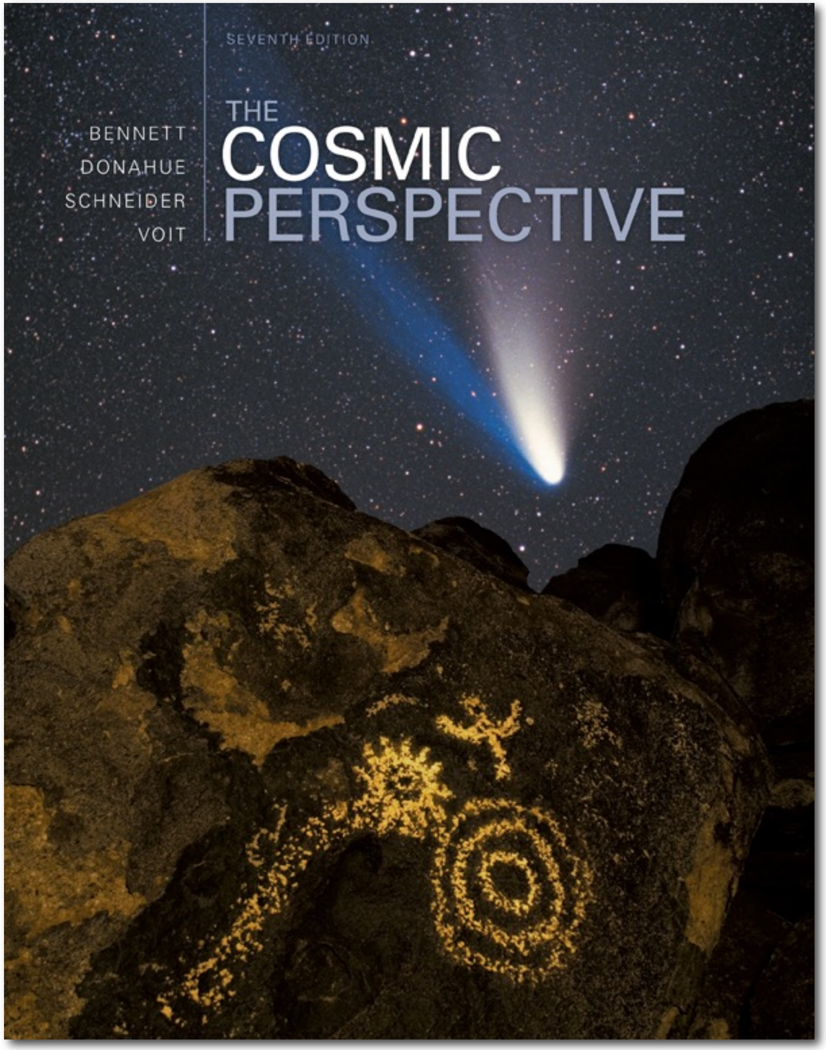
The Cosmic Perspective

Seventh Edition

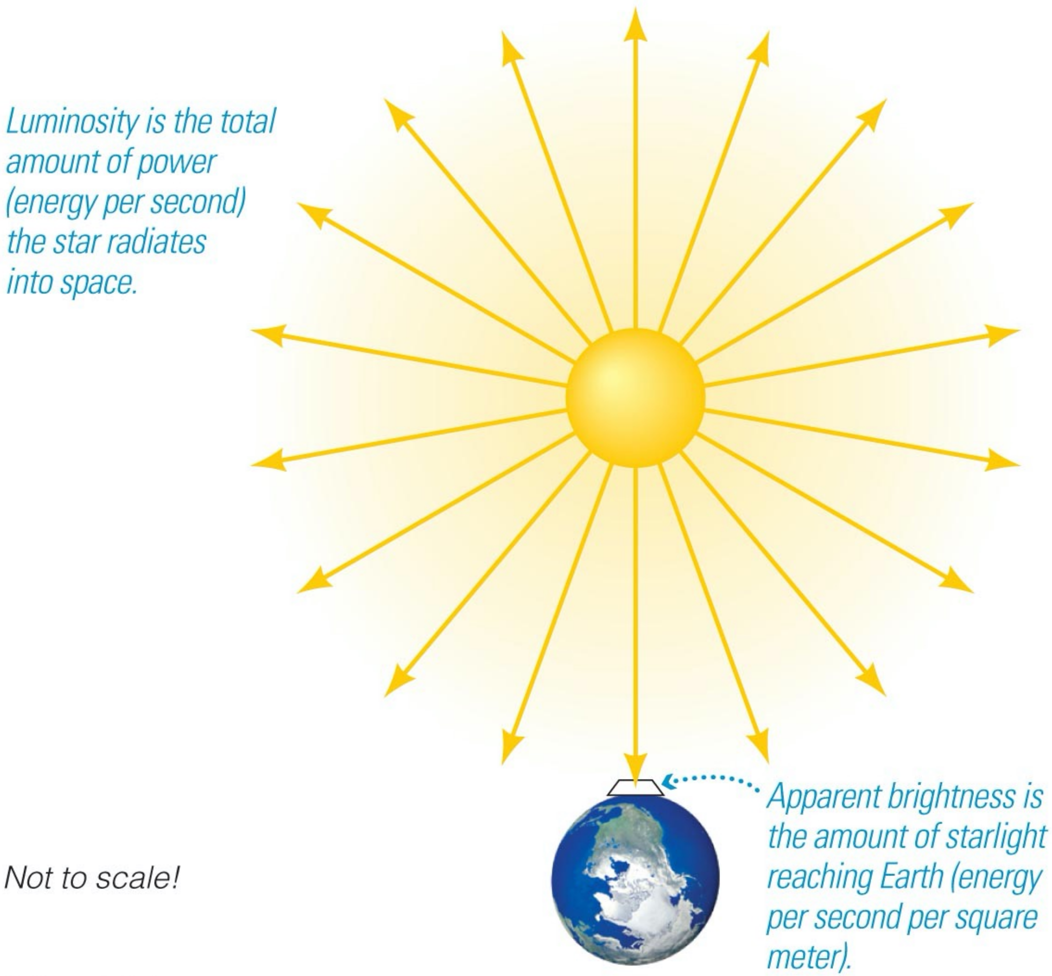


Surveying the Stars

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

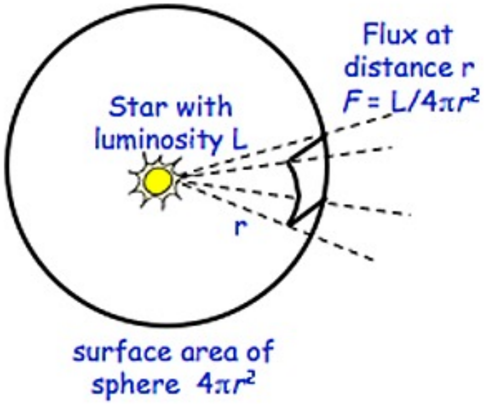
- The relationship between apparent brightness and luminosity depends on distance:

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

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

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

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 five 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 1/25 as bright.
D. It would be three times brighter.

Thought Question

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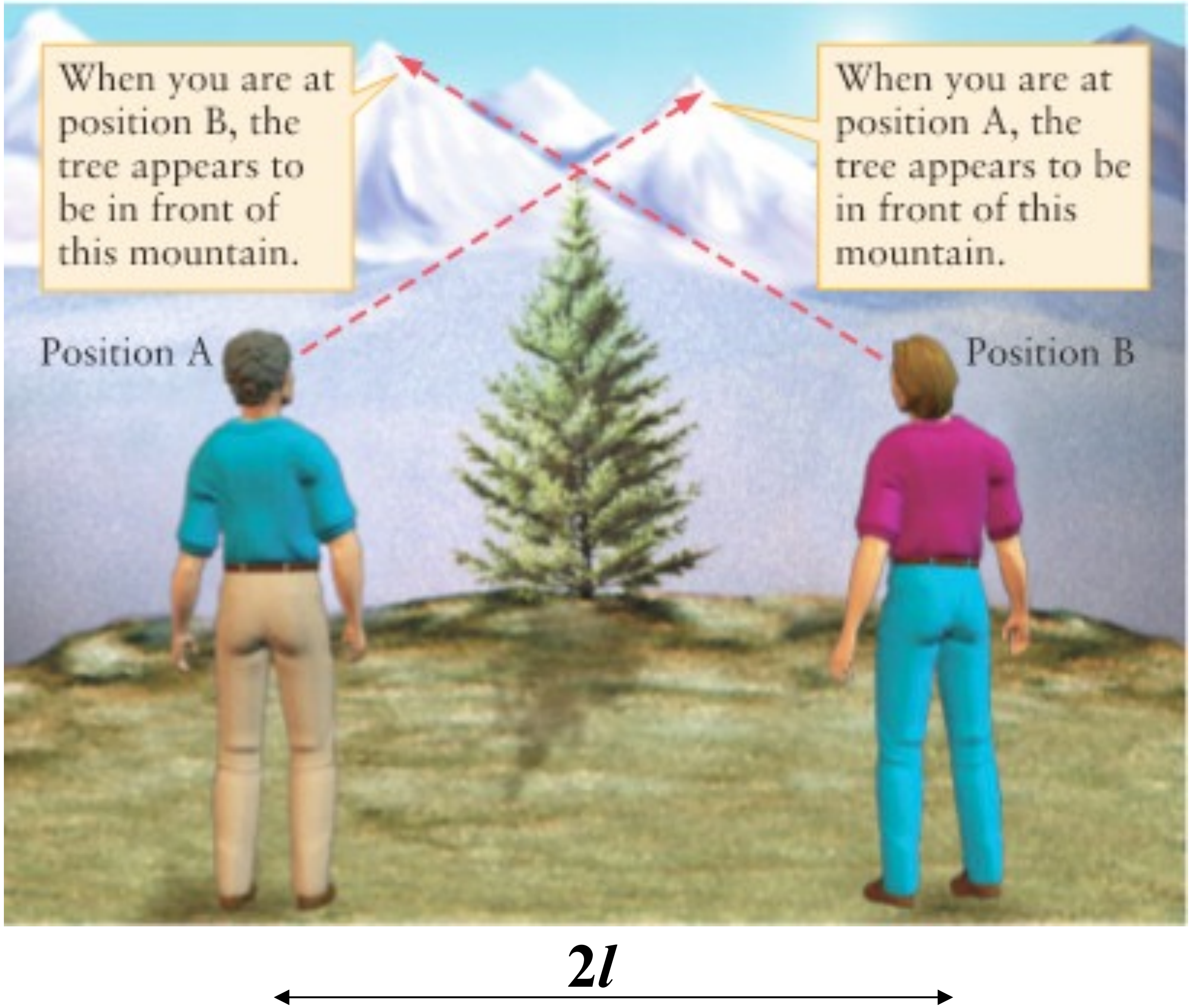
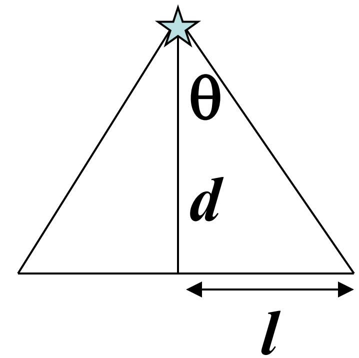
- So how far away are these stars?

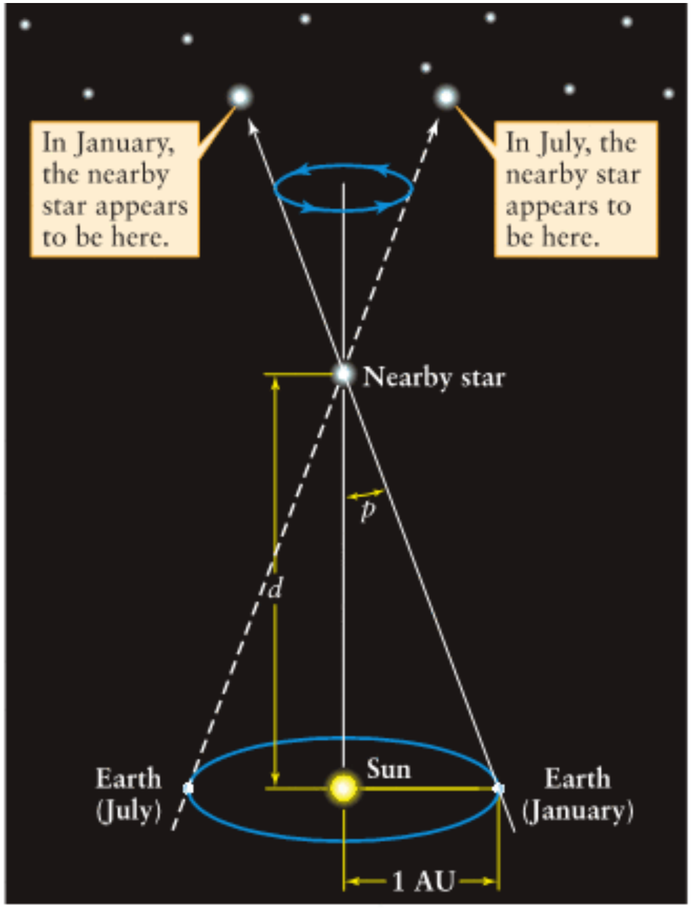
Measuring Distances



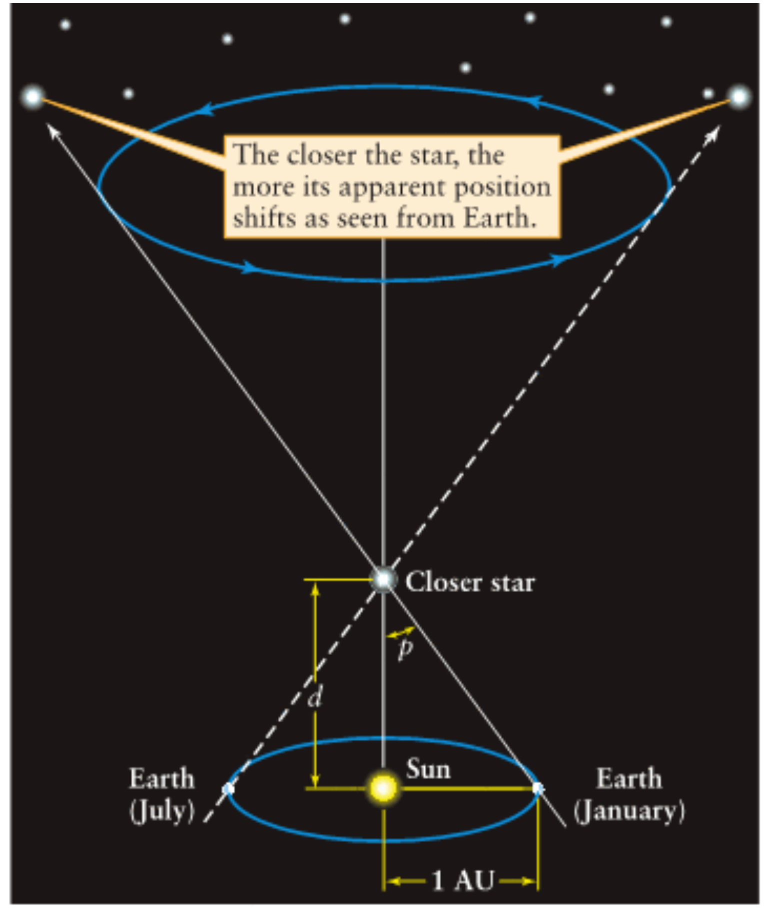


$\tan(\theta) = l/d \rightarrow d \sim l/\theta$ (θ in radians)

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 = parallax angle

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

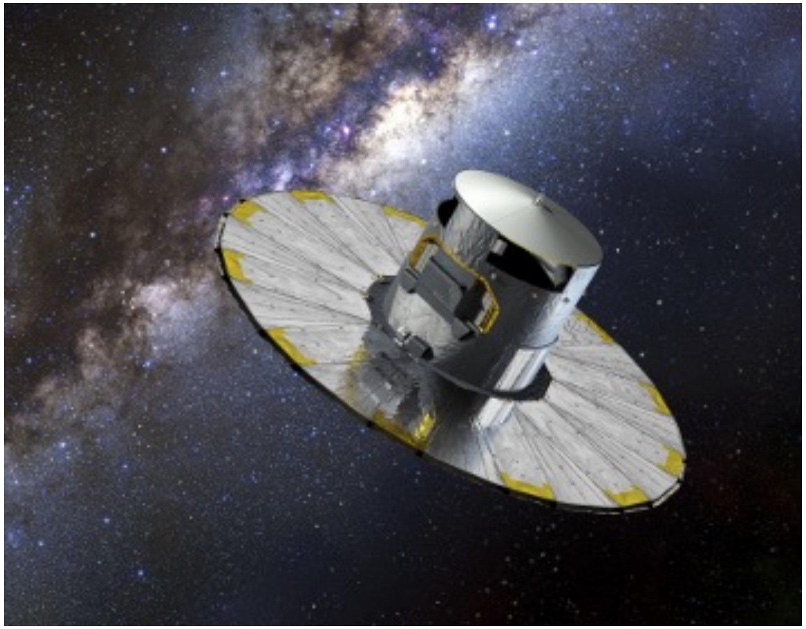
Example:
The parallax angle of a star is p = 0.01 arcsec, what is the stars distance in parsec (pc).

$$d = \frac{1}{p}\, pc = \frac{1}{0.01}\, pc = 100\, pc$$

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

How does our Sun's Luminosity Compare with other stars?

- 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 m = 6 magnitude star is a factor of 100 times fainter in brightness than a m = 1 magnitude star

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

$\mathrm{m}_1, \mathrm{m}_2$ = 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

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If a star has an apparent magnitude of m = 2.5 and an absolute magnitude of M = – 2.5 what is its distance?

Magnitude Scale: Absolute Magnitude

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If a star has an apparent magnitude of m = 2.5 and an absolute magnitude of M = − 2.5 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 $m - M + 5 = 10$ we obtain: $d = 10^{\frac{10}{5}} pc = 100\, pc$

Examples

$$d(pc) = \frac{1}{p(arcsec)}$$

Example: if $p = 0.1$ arcsec then $d(pc) = \frac{1}{0.1\ arcsec} = 10pc$

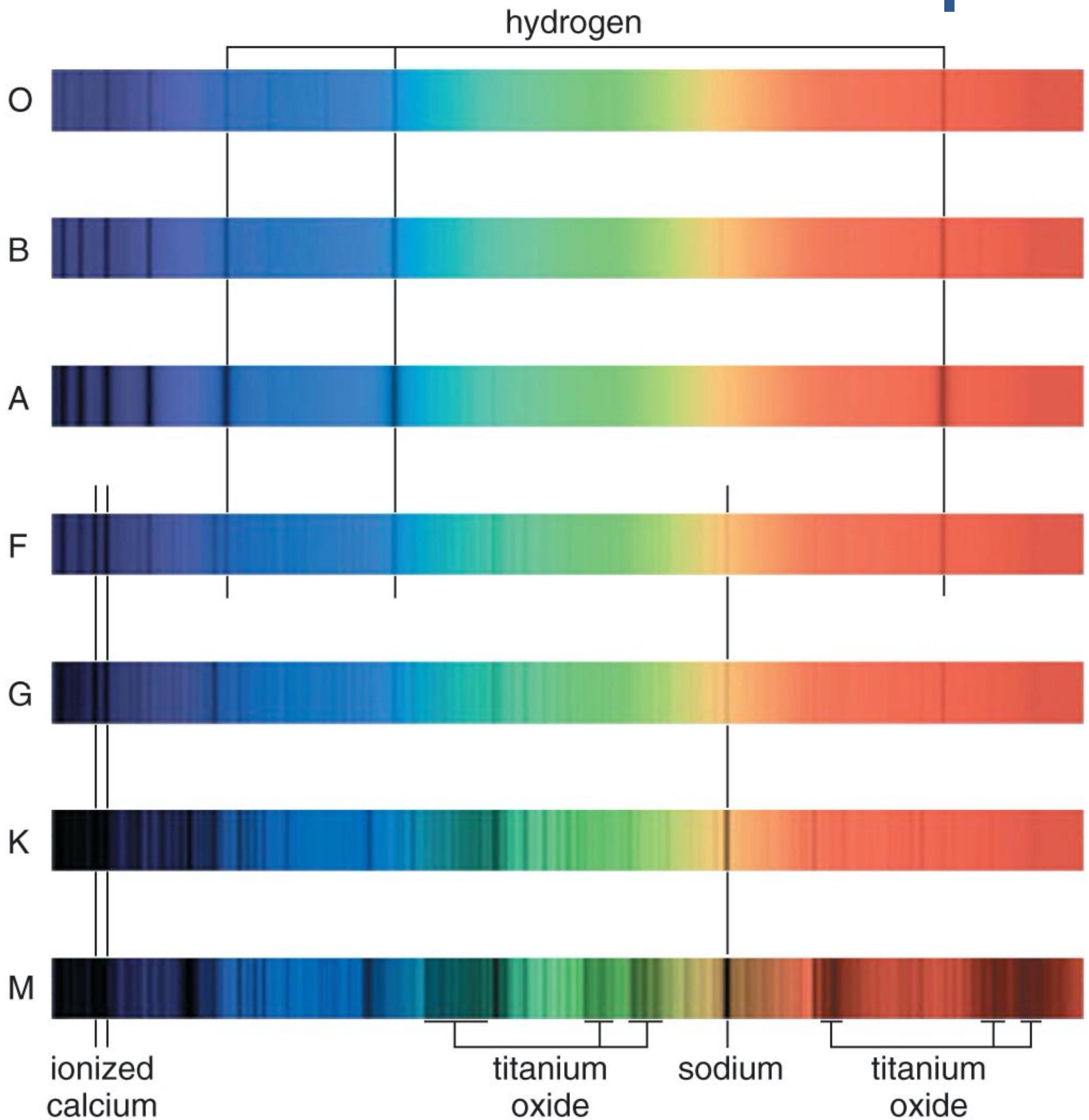
$$m_1 - m_2 = 2.5 \log \frac{F_2}{F_1} \rightarrow \frac{F_2}{F_1} = 10^{\frac{m_1 - m_2}{2.5}}$$

Example: $if\ m_1 - m_2$=10 then $\frac{F_2}{F_1} = 10^{\frac{10}{2.5}} = 10^4$=10000

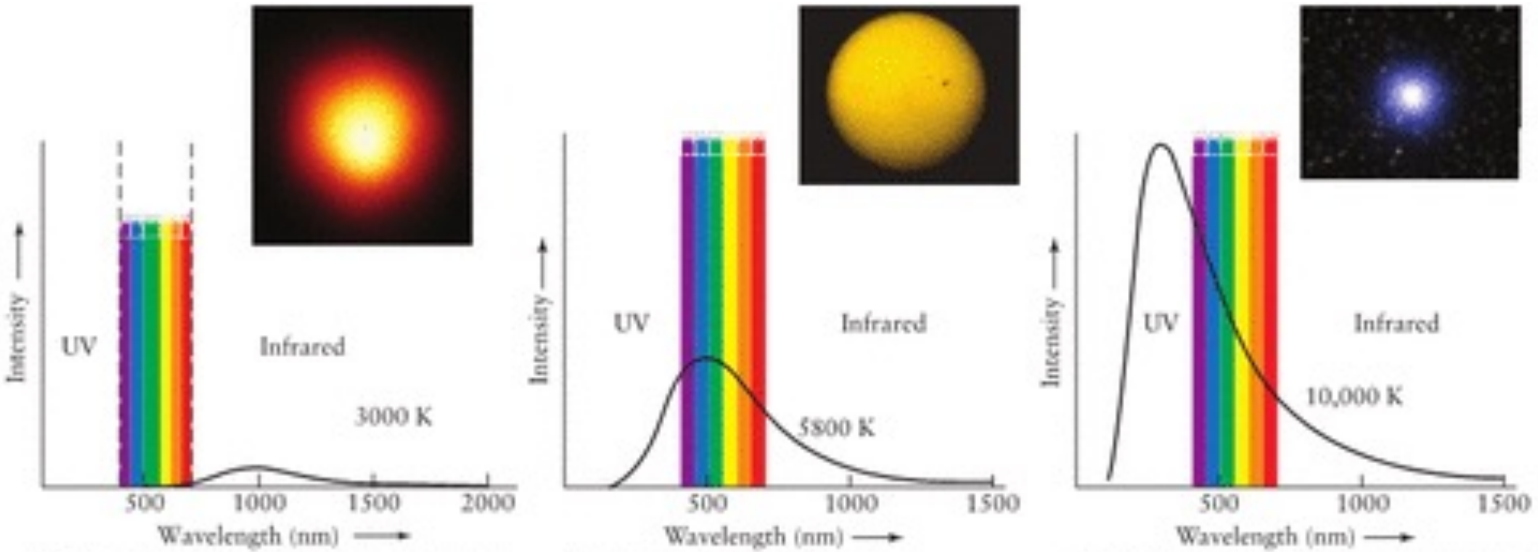
$$m - M = 5 \log d - 5 \rightarrow d = 10^{\frac{m-M+5}{5}} pc$$

Example: if m-M=10 then $d = 10^{\frac{m-M+5}{5}} pc$=$10^{\frac{15}{5}} pc = 10^3 pc = 1000pc$

How do we measure stellar temperatures?



Colors and Temperature



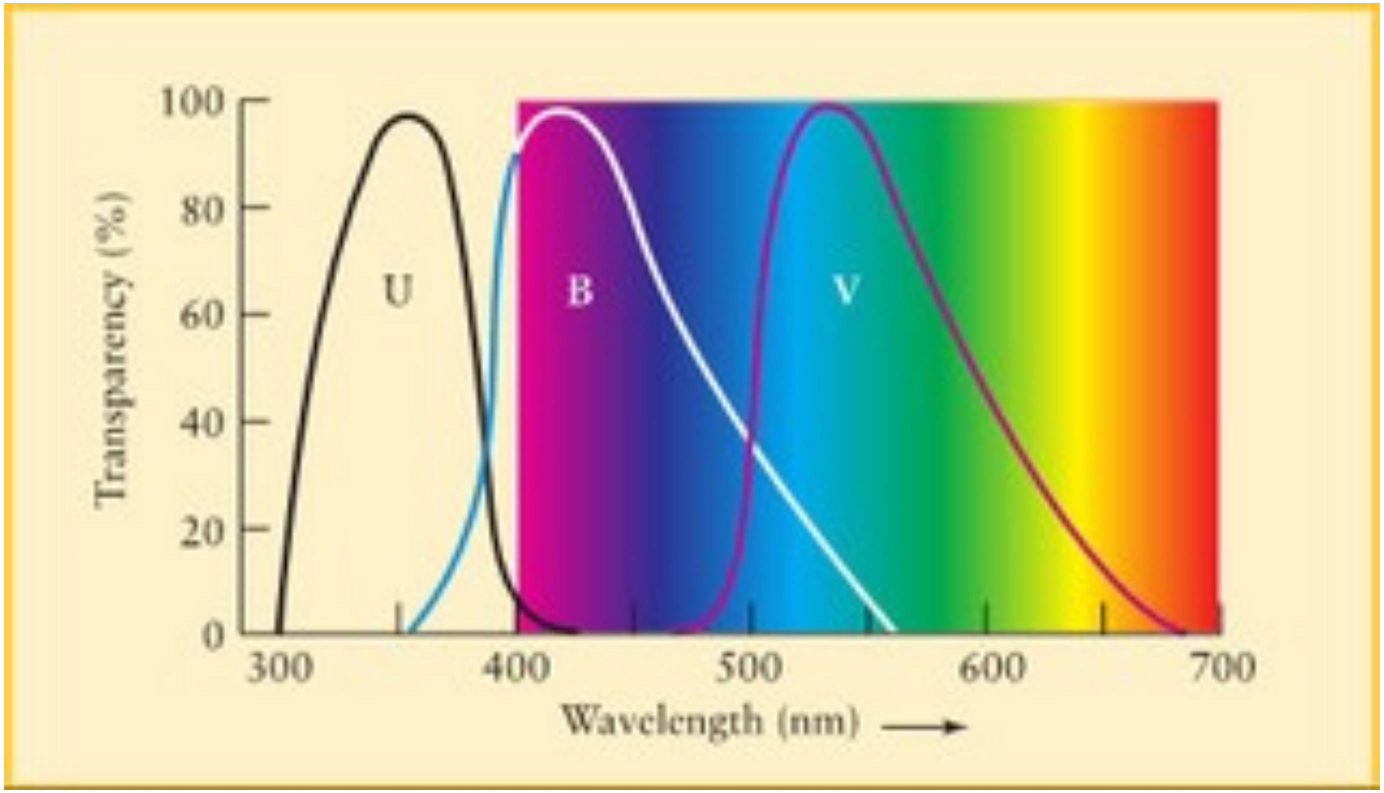
(a) A **cool star** with surface temperature 3000 K emits much more red light than blue light, and so appears red.

(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.

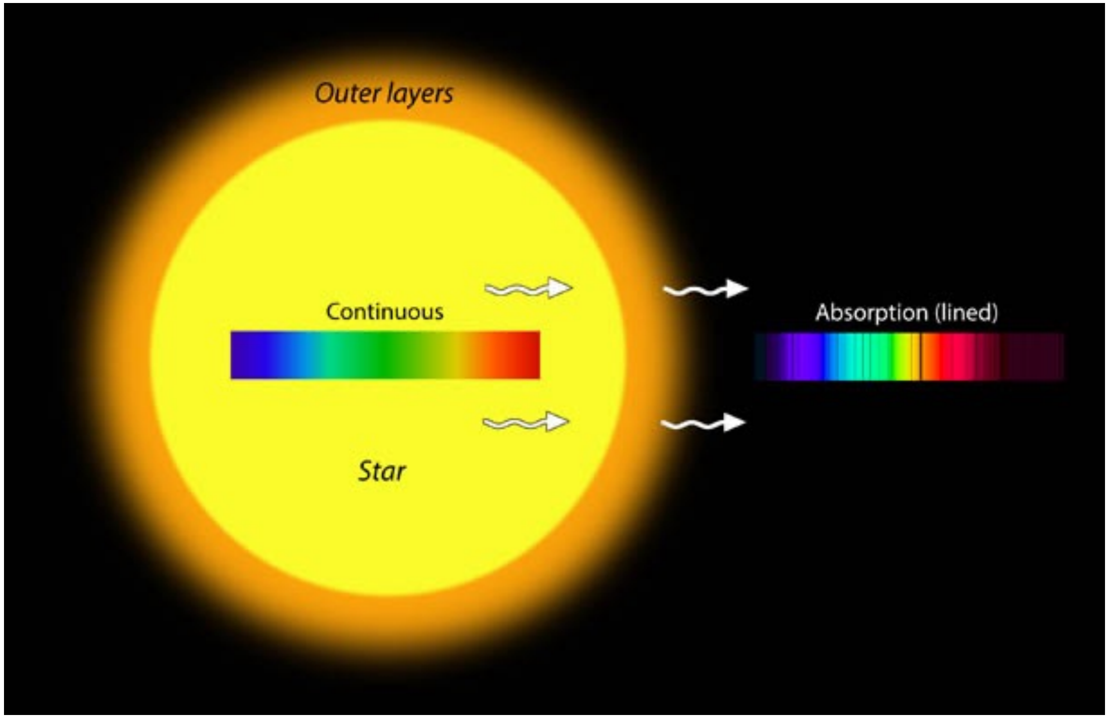
Then compare the relative fluxes by taking the ratios b_V/b_B and b_B/b_U. These ratios indicate the temperature of the stars surface.

Spectra of Stars

Absorption spectra in stars are produced in the following way:

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

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**.

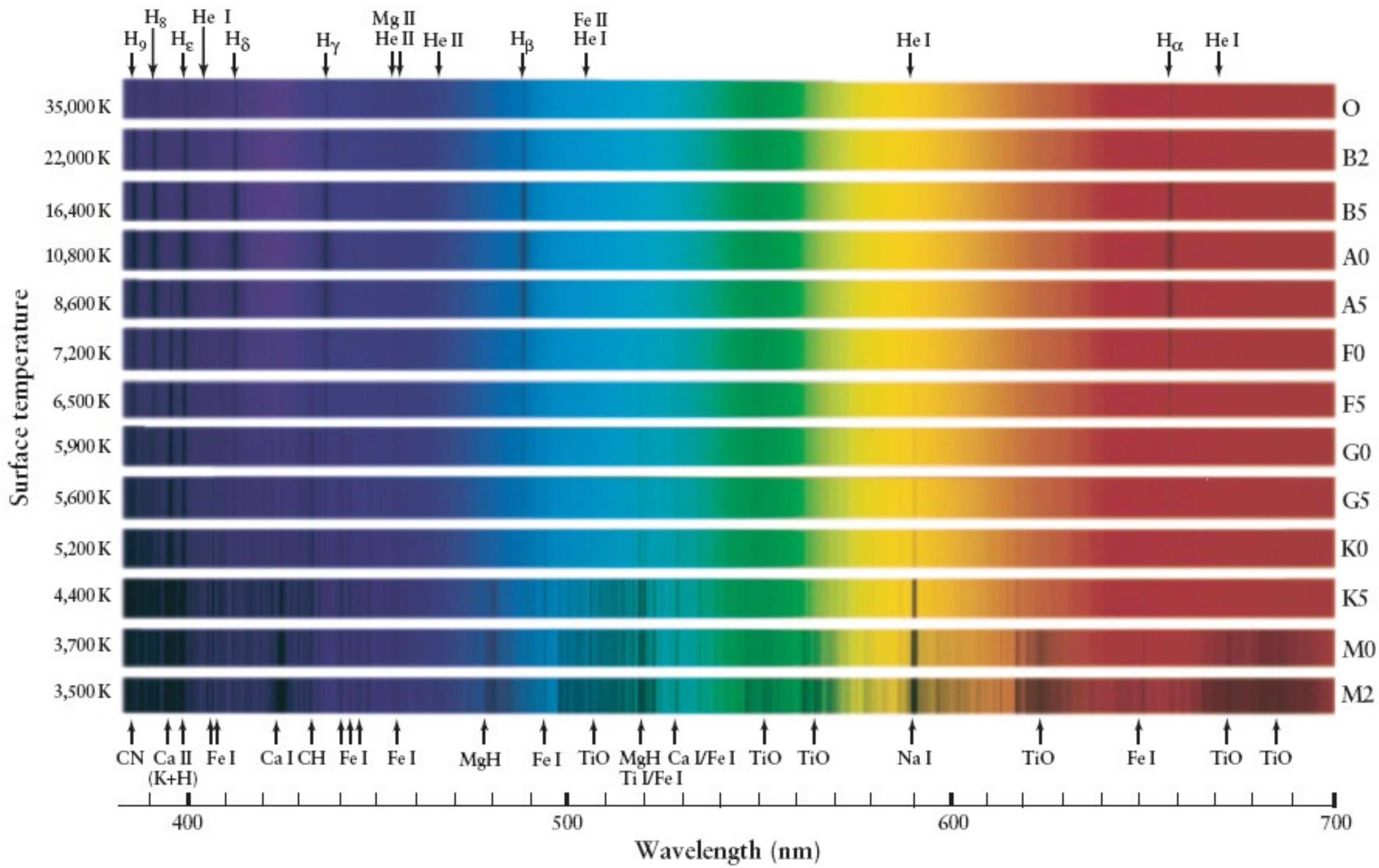
The **spectral classes** are labeled:

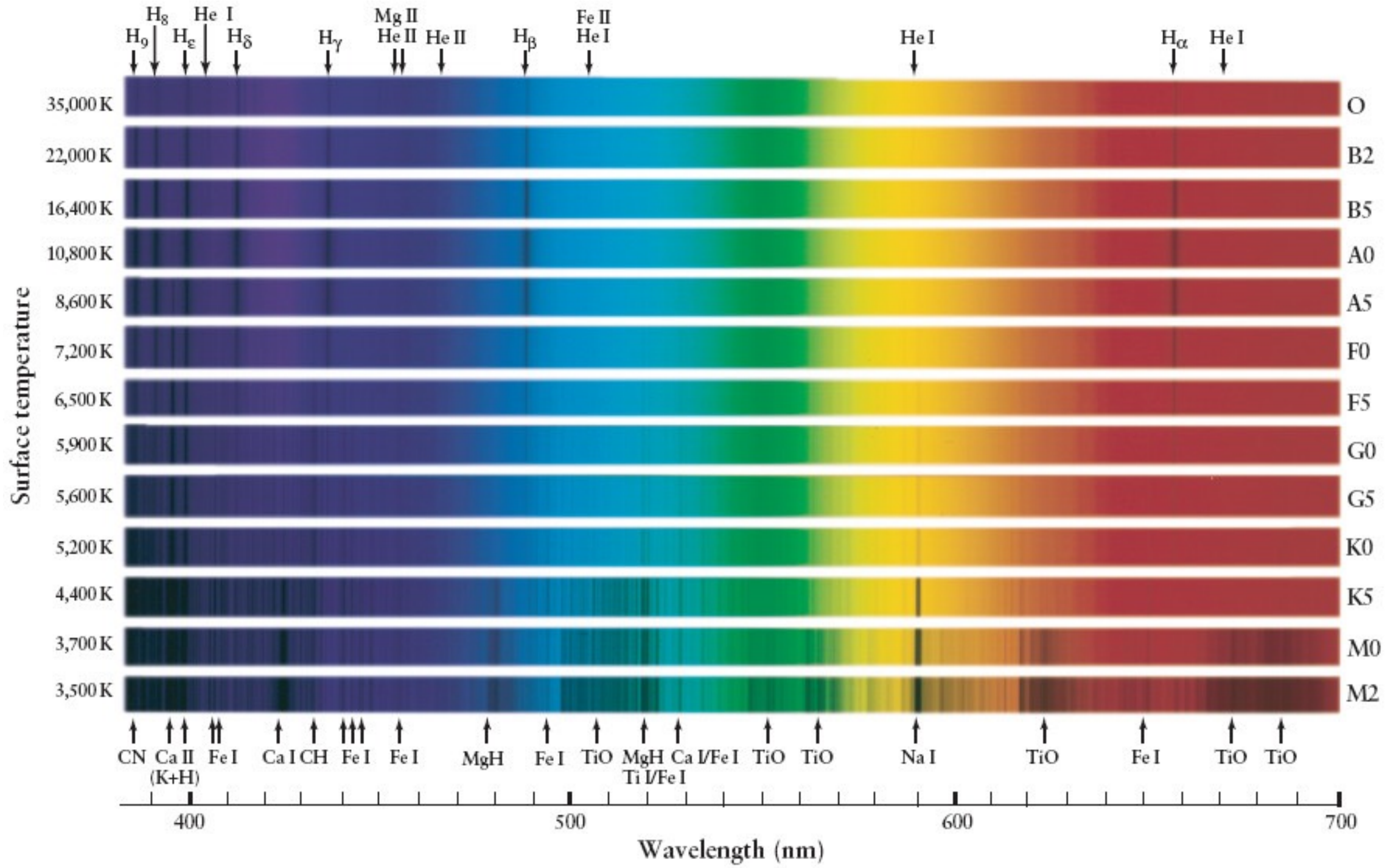
O B A F G K M L T

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

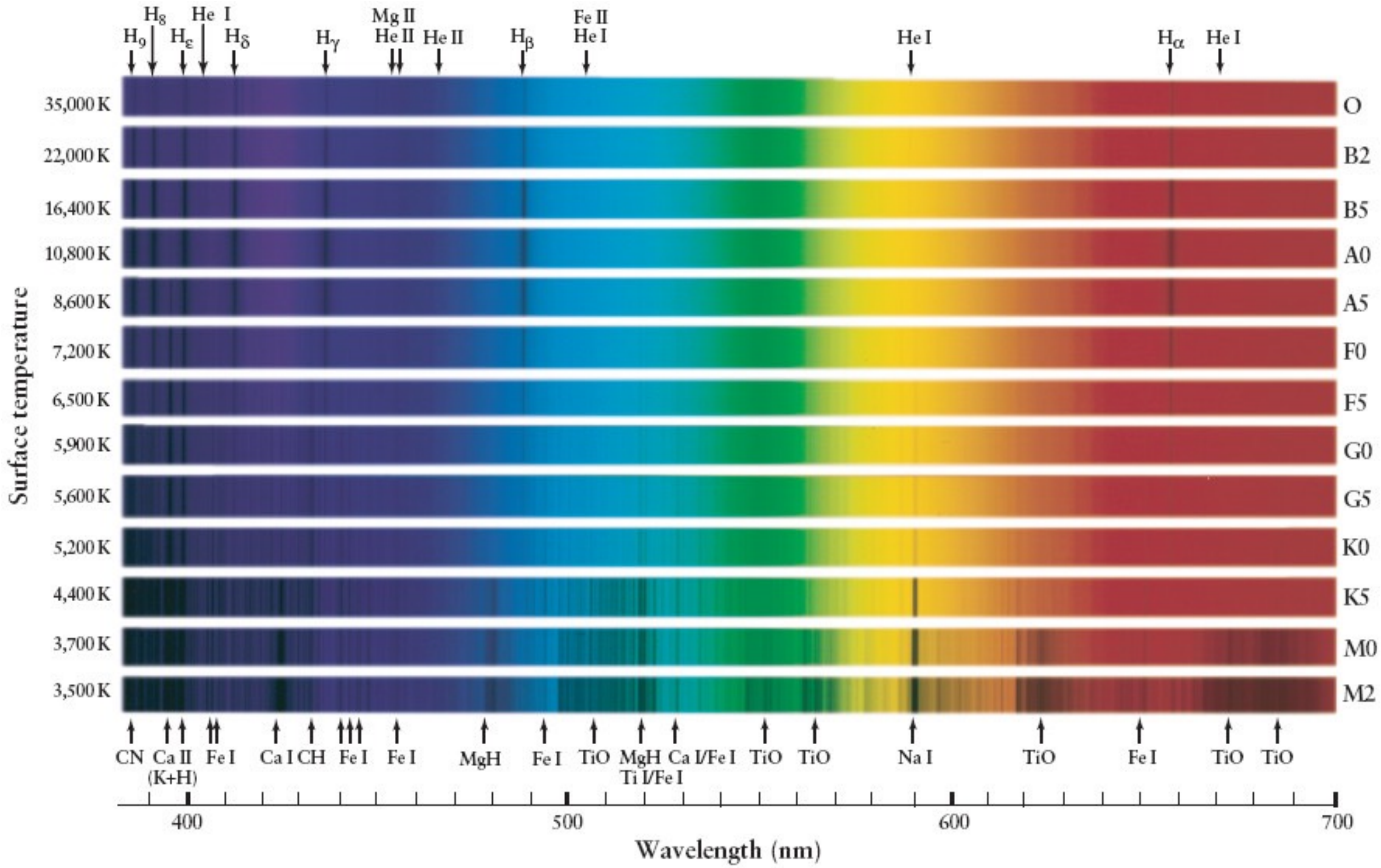
In the late 1800's a team of women at the Harvard College Observatory undertook the task of classifying the spectra of hundreds of thousands of stellar spectra.

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

The spectral classes are labeled:

O B A F G K M L T

Thought Question

Which kind of star is hottest?

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

The spectral classes are labeled:

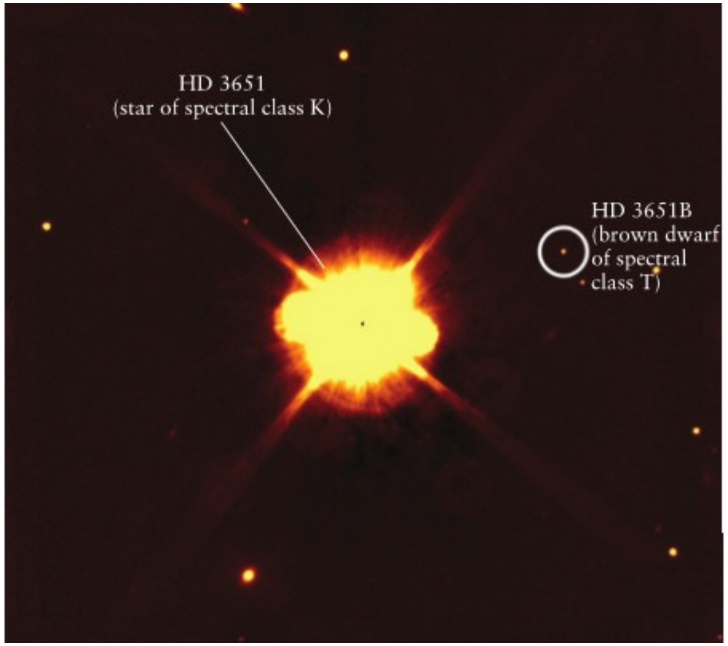
O B A F G K M L T

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 (class T).

Stellar Radii from Temperature and Luminosity

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 from Temperature and Luminosity

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

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

Dividing equation 1 by equation 2 we have:

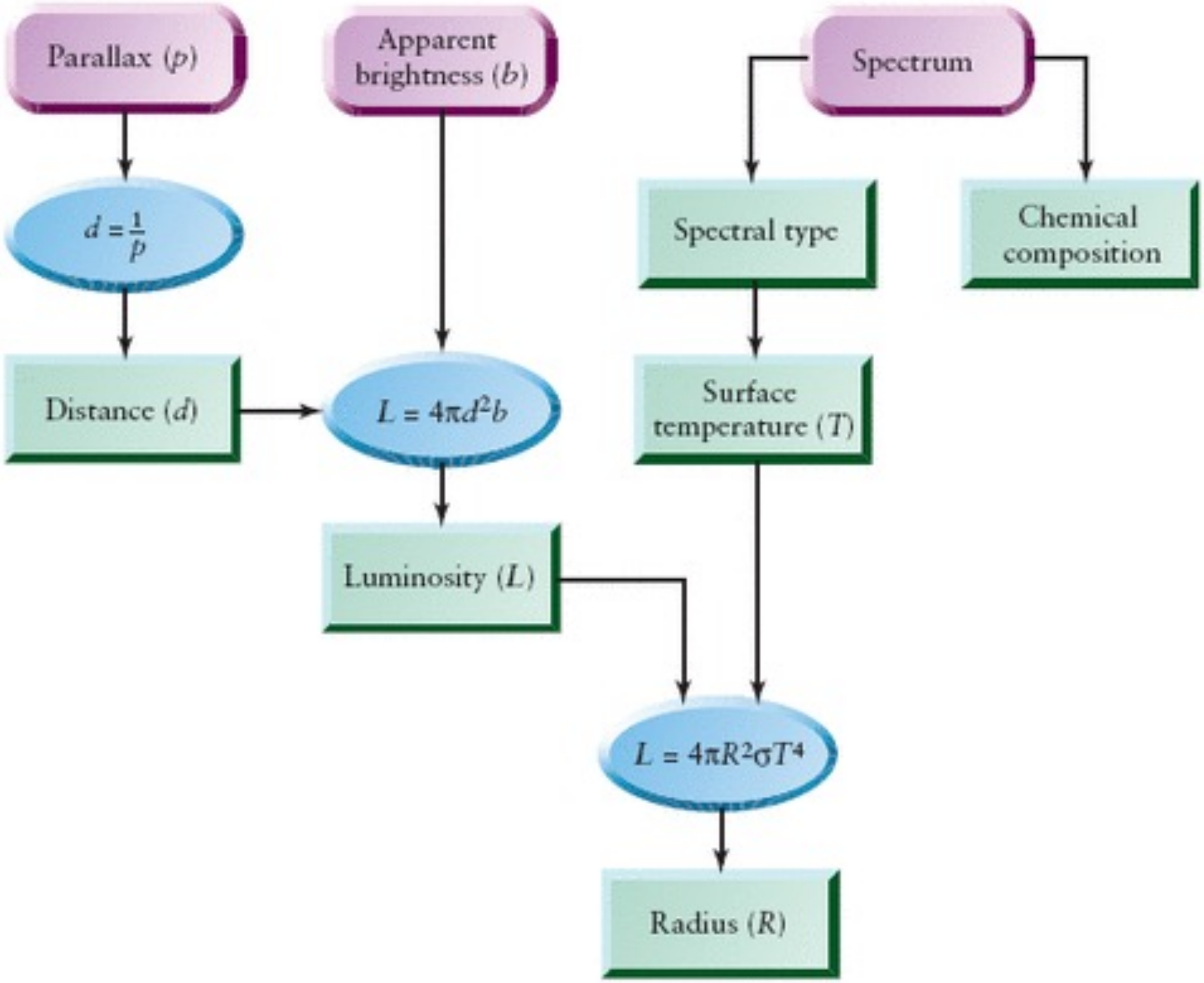
$L/L_\odot = (R/R_\odot)^2 (T/T_\odot)^4$ Equation (3)

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

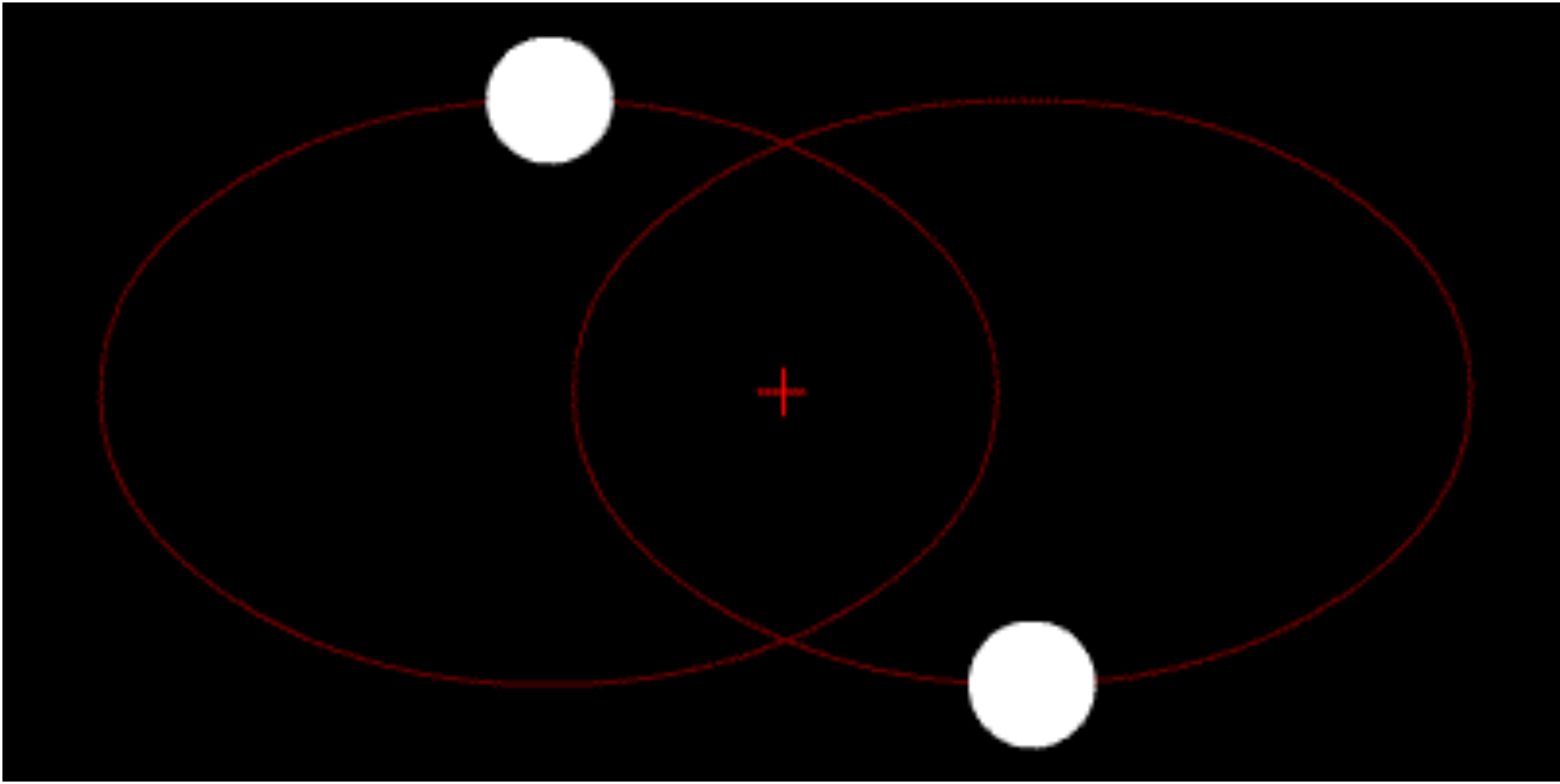
$R/R_\odot = \sqrt{L/L_\odot}(T_\odot/T)^2$ Equation (4)

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

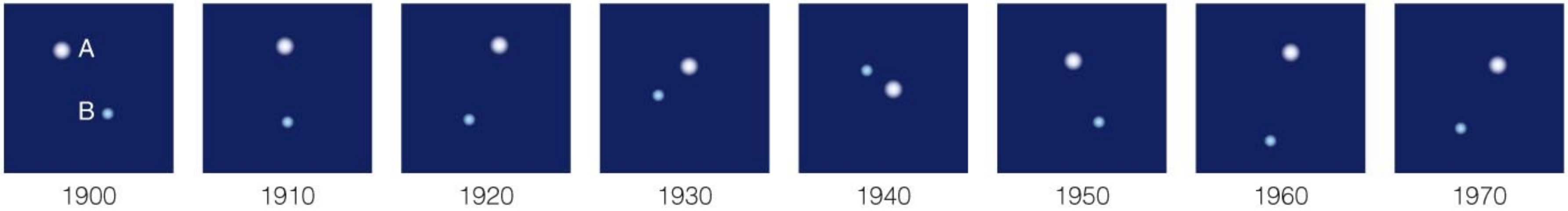


Types of Binary Star Systems

- Visual binary
- Spectroscopic binary
- Eclipsing binary

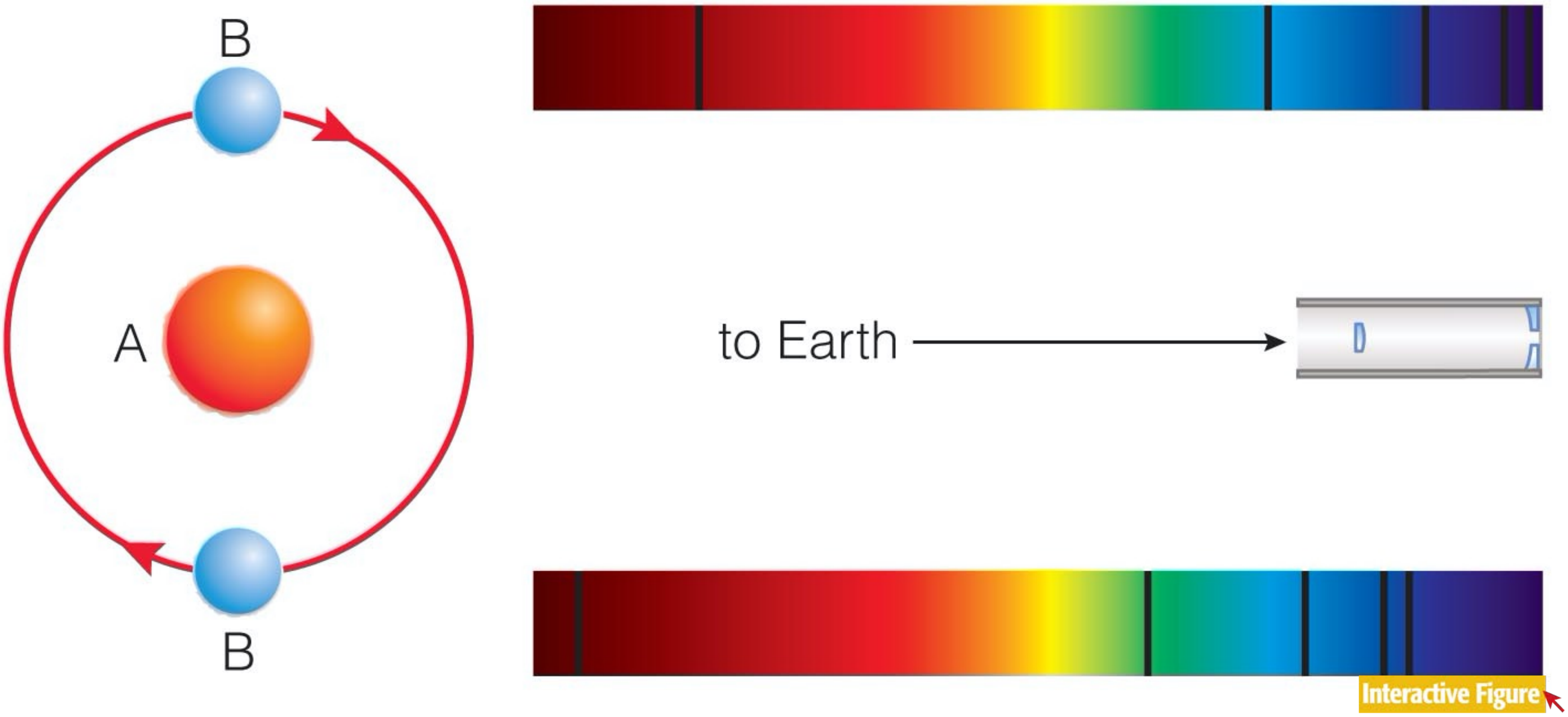
About half of all stars are in binary systems.

Visual Binary



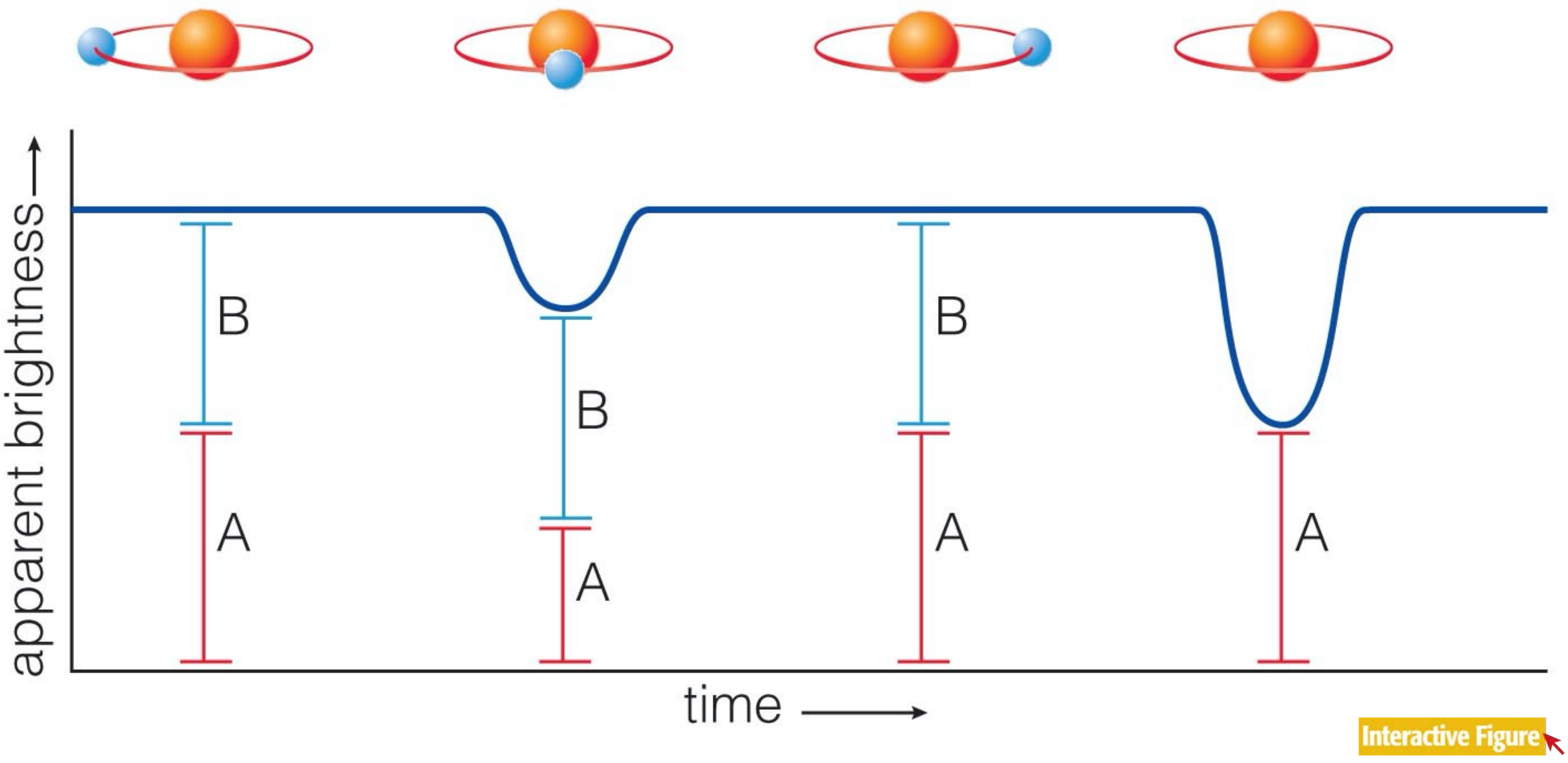
- We can directly observe the orbital motions of these stars.

Spectroscopic Binary



- We determine the orbit by measuring Doppler shifts.

Eclipsing Binary

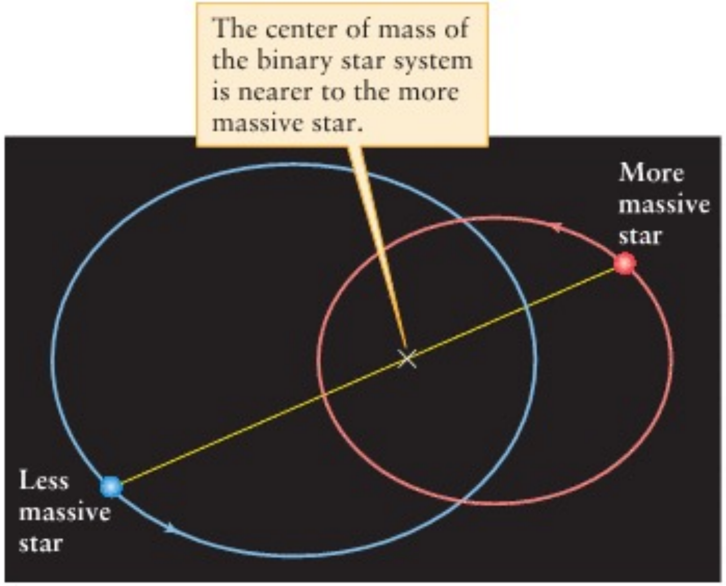


- We can measure periodic eclipses.

Masses of Stars in Binary Systems

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

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



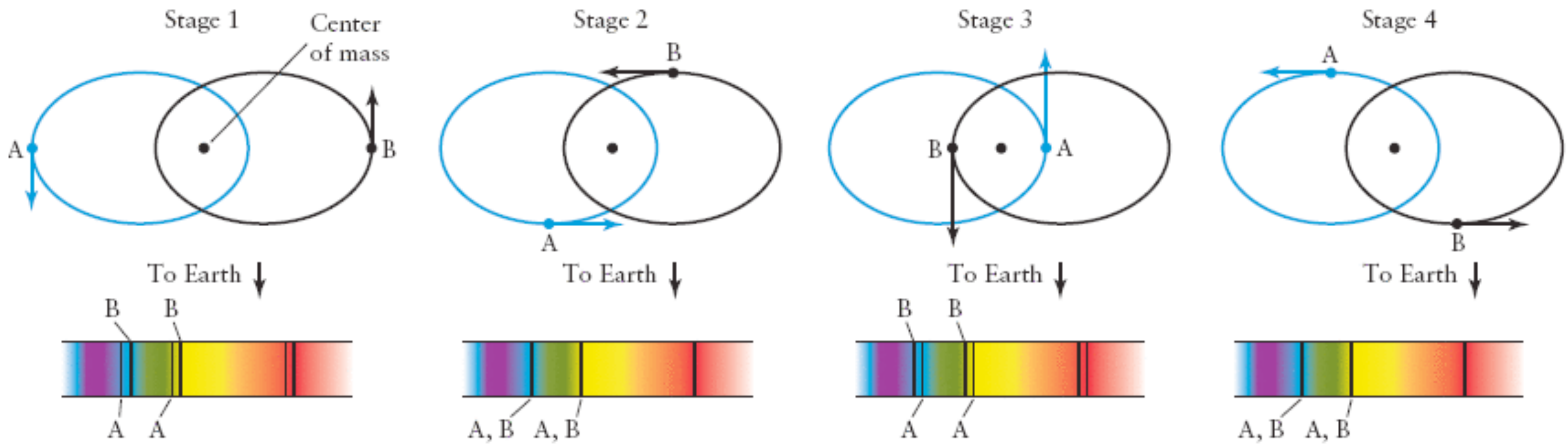
(b) A binary star system

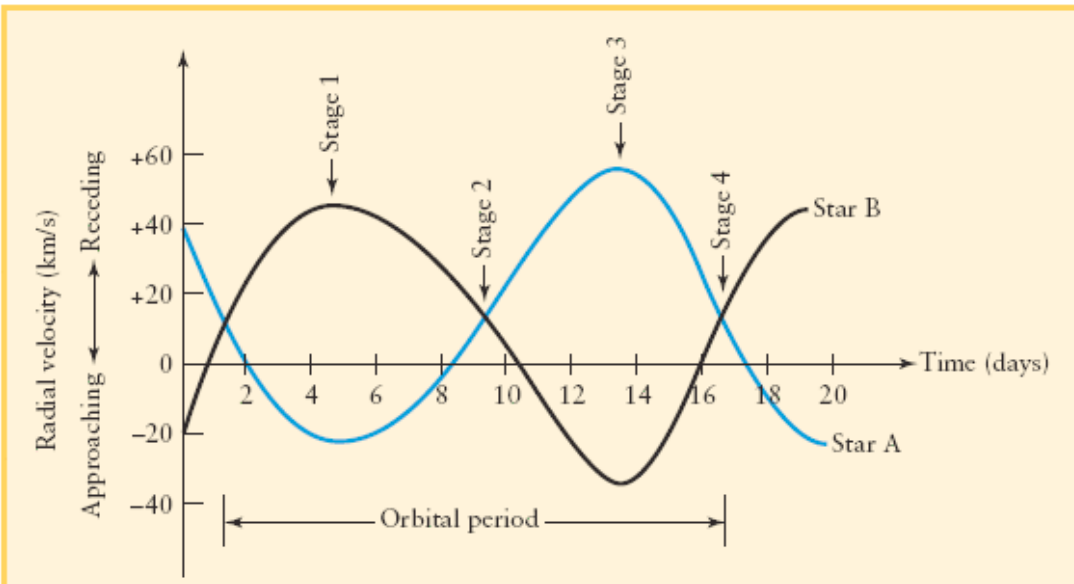
P = period of orbit, in years

$a = a_1 + a_2$, 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

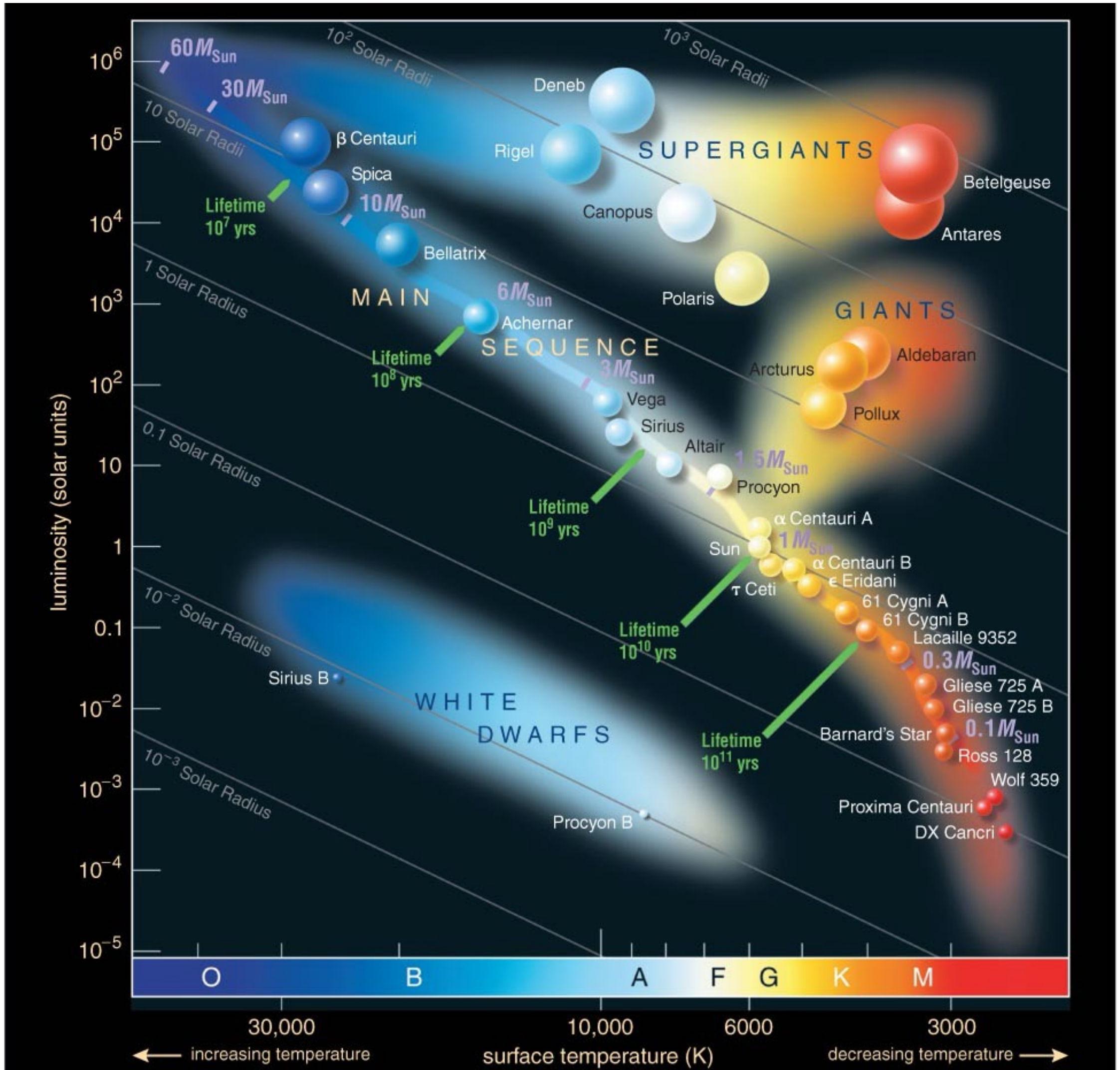




Radial Velocity Curves of Spectroscopic binary system HD 171978

15.2 Patterns Among Stars

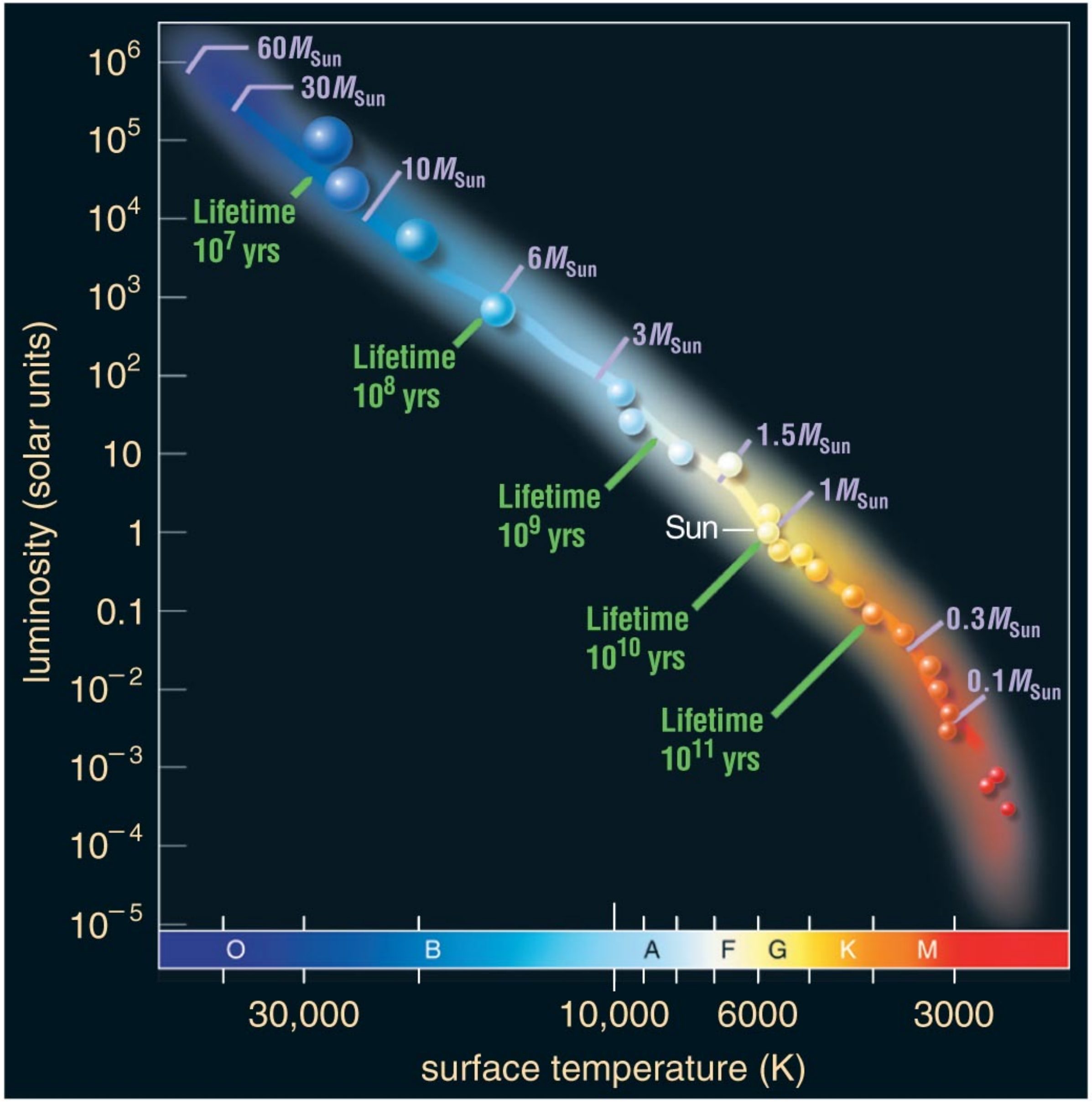
- Our goals for learning:
  - **What is a Hertzsprung-Russell diagram?**
  - **What is the significance of the main sequence?**
  - **What are giants, supergiants, and white dwarfs?**
  - **Why do the properties of some stars vary?**



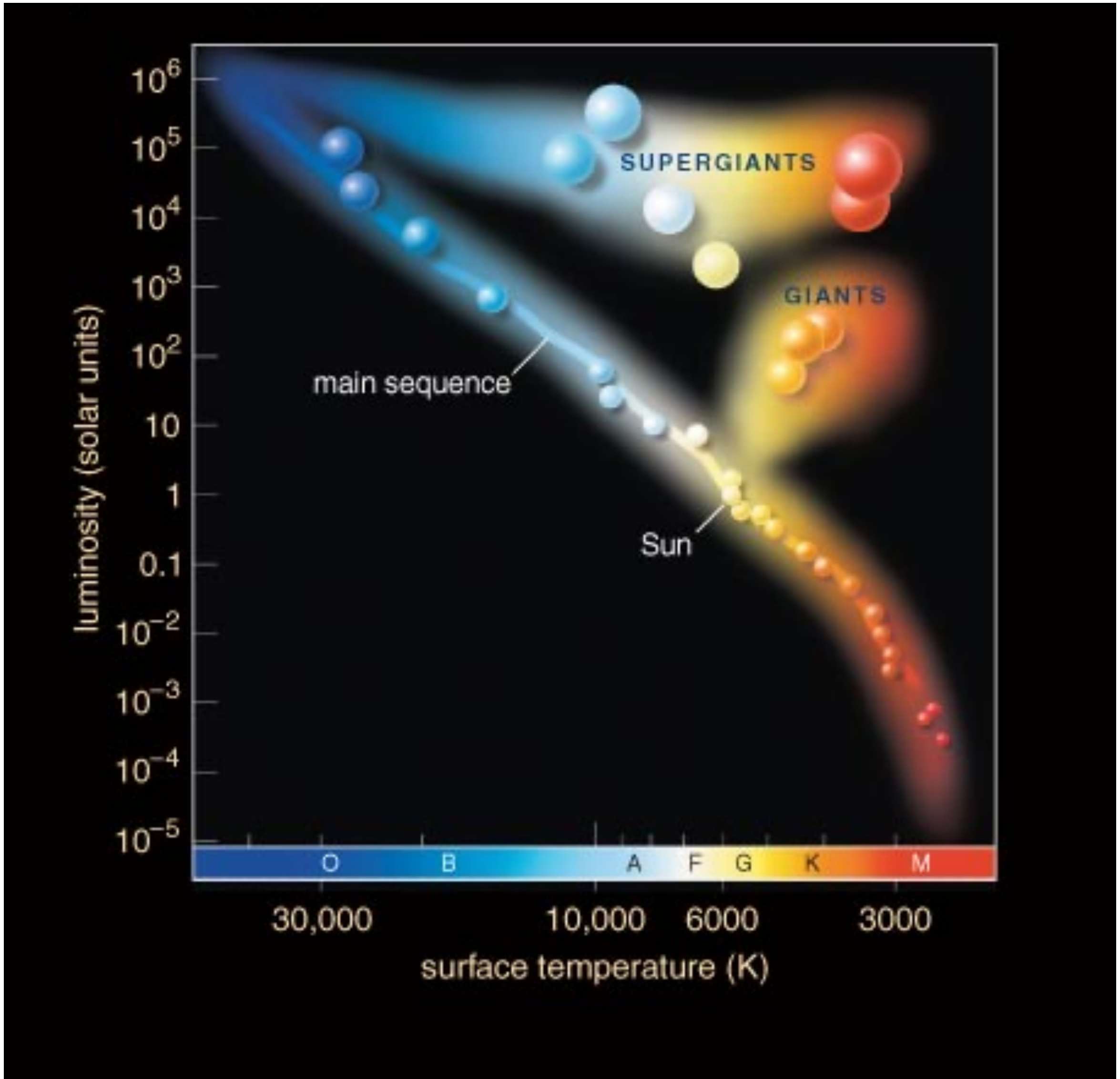
Luminosity

Temperature

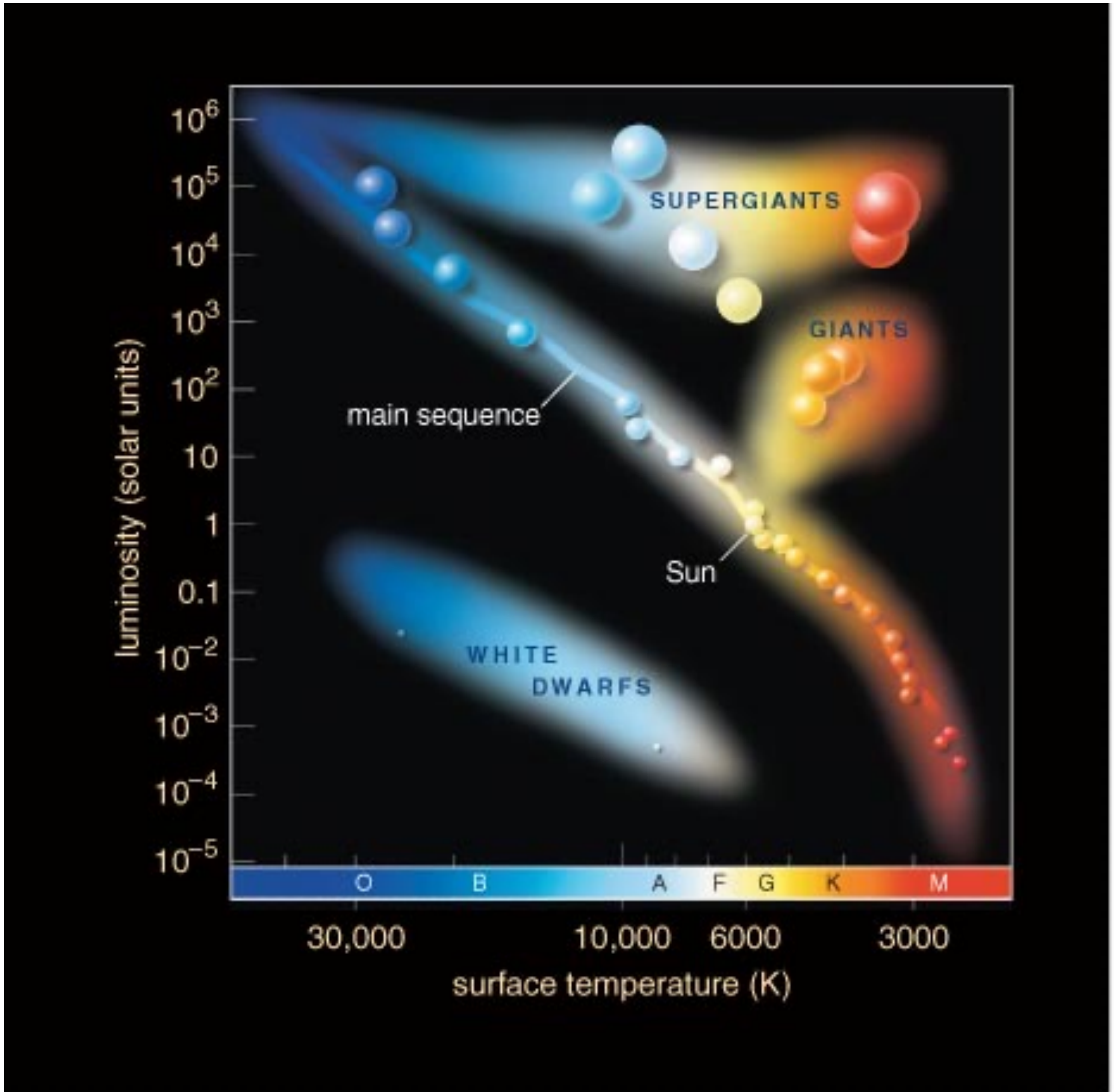
- An H-R diagram plots the luminosity and temperature of stars.



- 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.

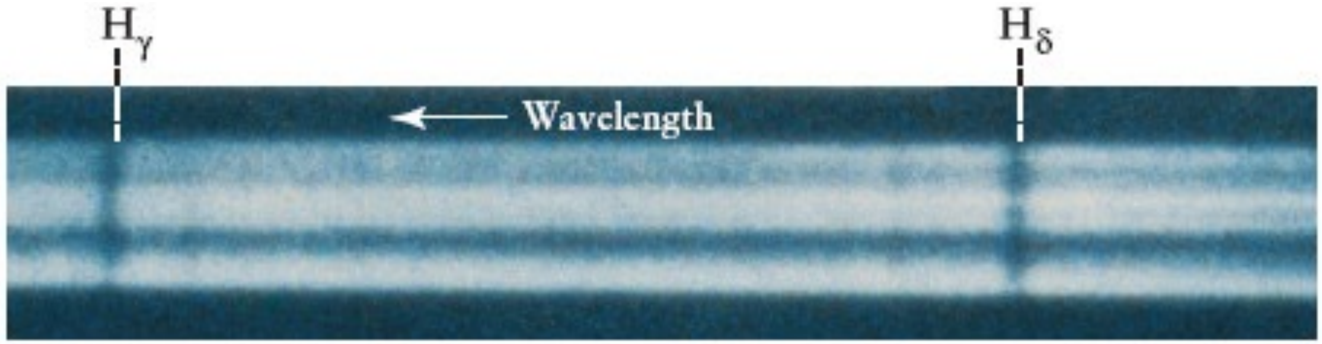
Giant stars: luminosities of 100–1000 $L_\odot$ and temperatures of 3000–6000 K. Red giants have T : 3000–5000 K.

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

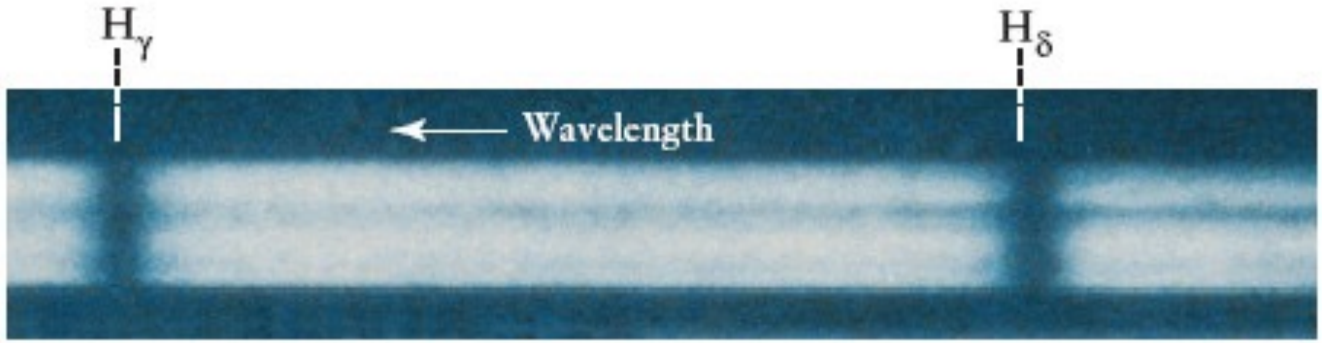
White Dwarfs: A low-mass star that has exhausted all its thermonuclear fuel and contracted to a size roughly equal to the size of the Earth (*has-been star*).

Brown Dwarfs: Starlike ($M < 0.08 M_\odot$) 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

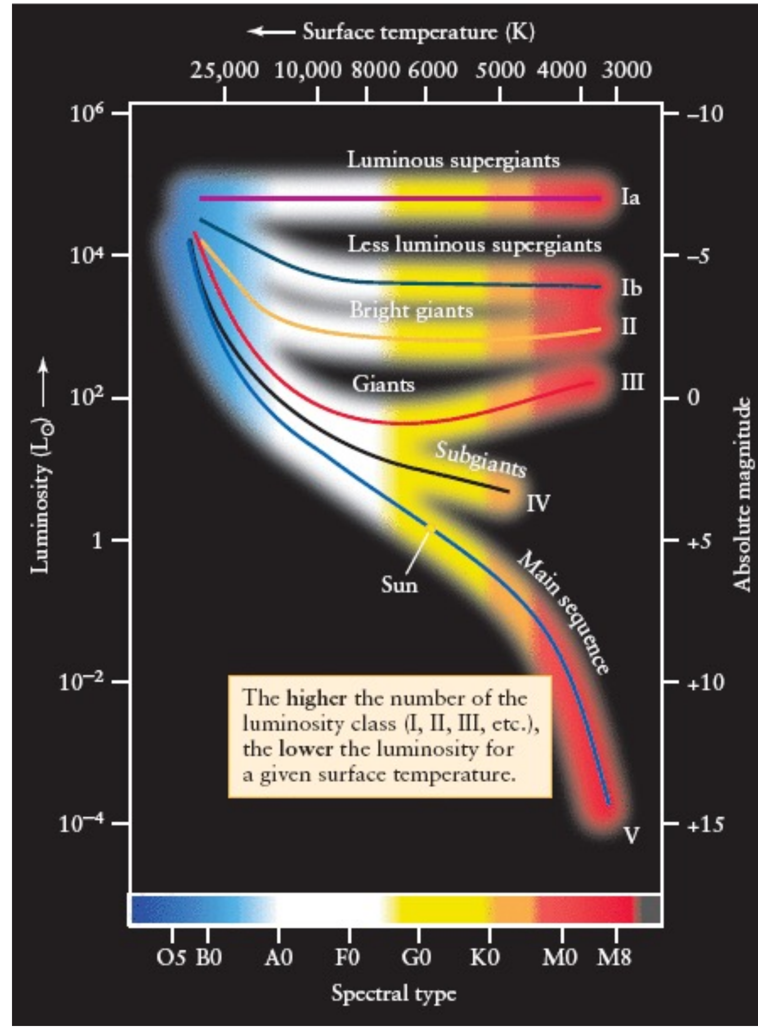
  Examples: Sun - G2 V
  Sirius - A1 V
  Proxima Centauri - M5.5 V
  Betelgeuse - M2 I

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.

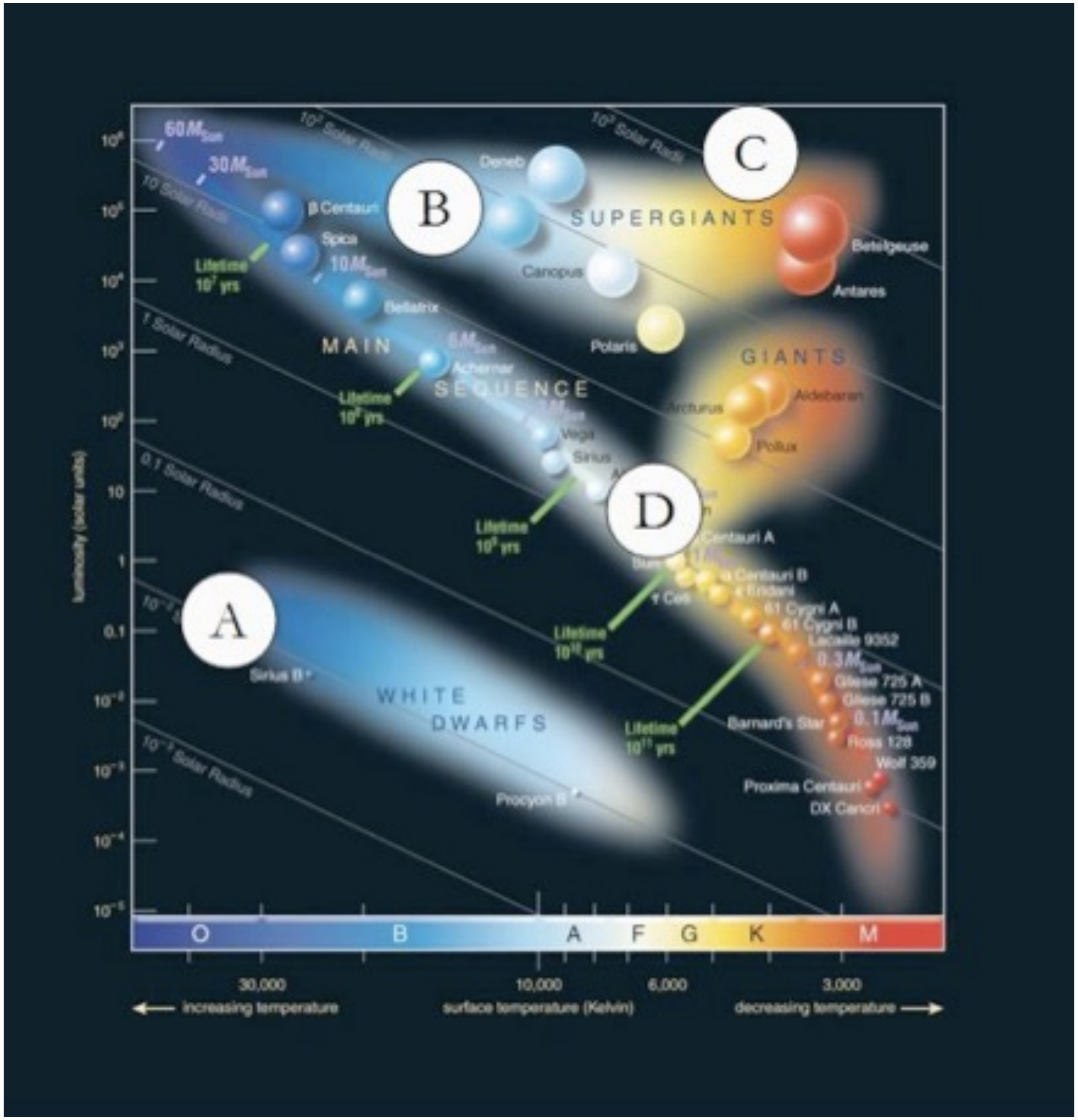
Examples: What is the luminosity of

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



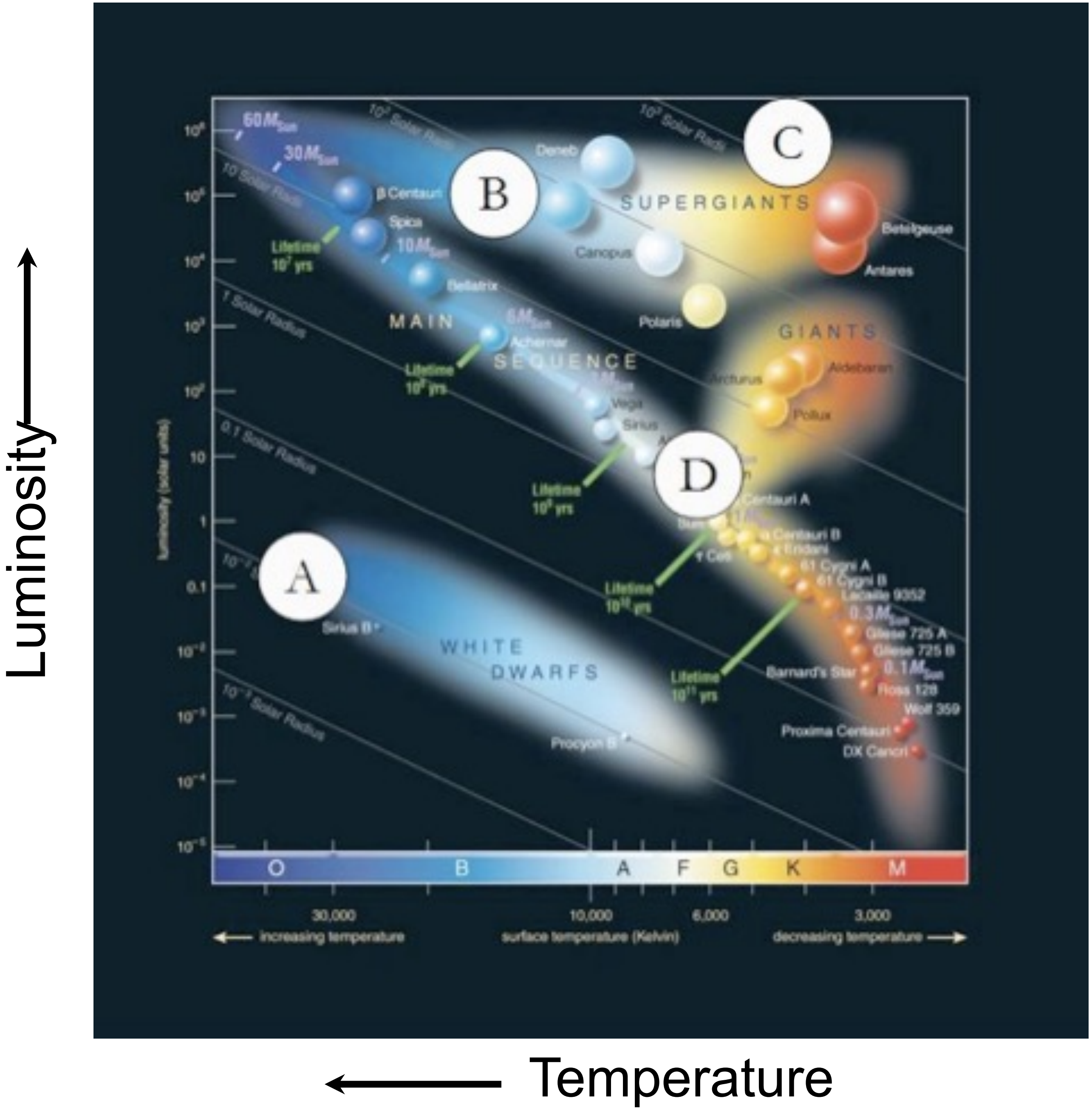
H-R diagram with Luminosity Classes..

- Which star is the hottest?



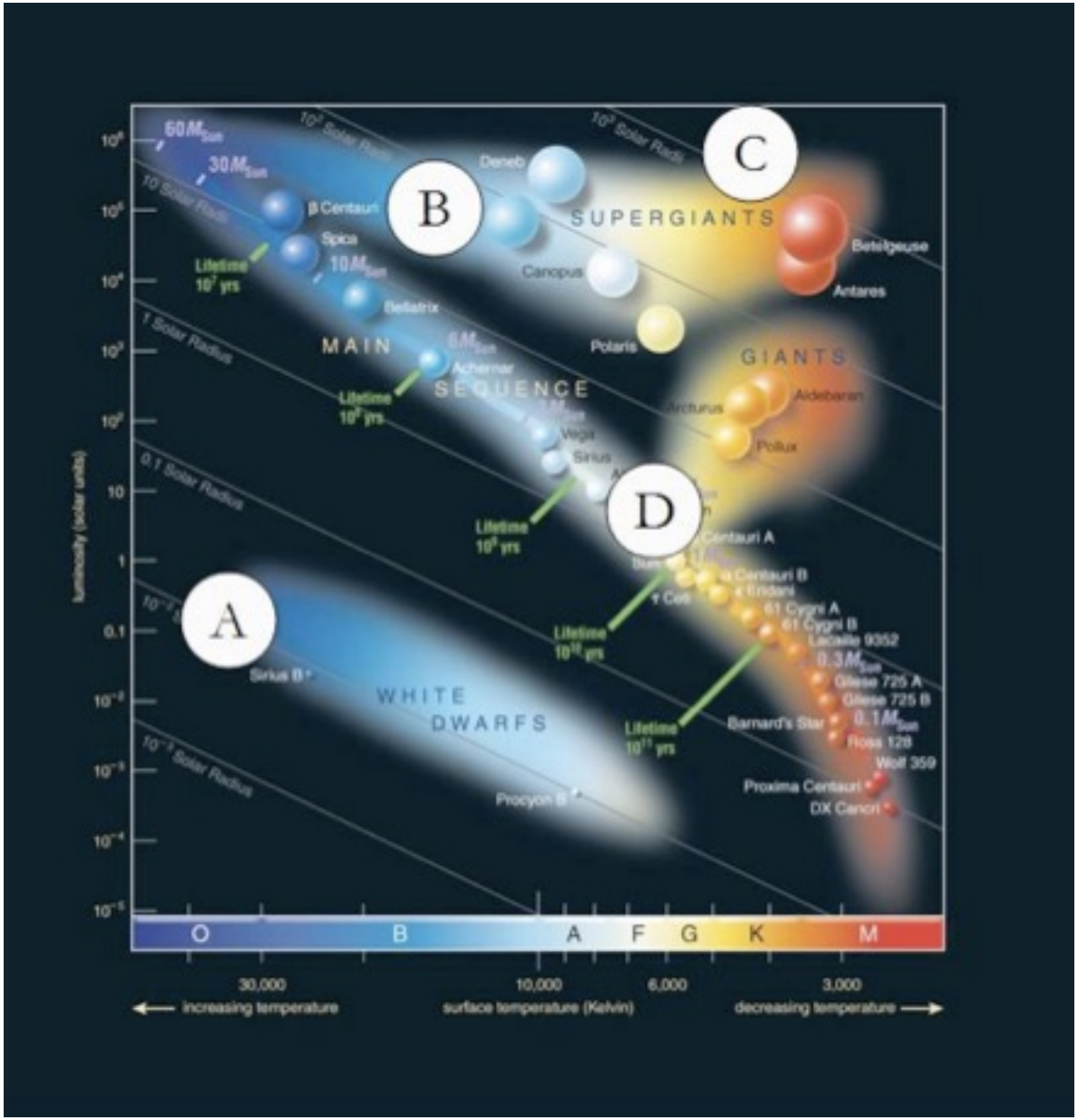
Luminosity

Temperature



- Which star is the hottest?

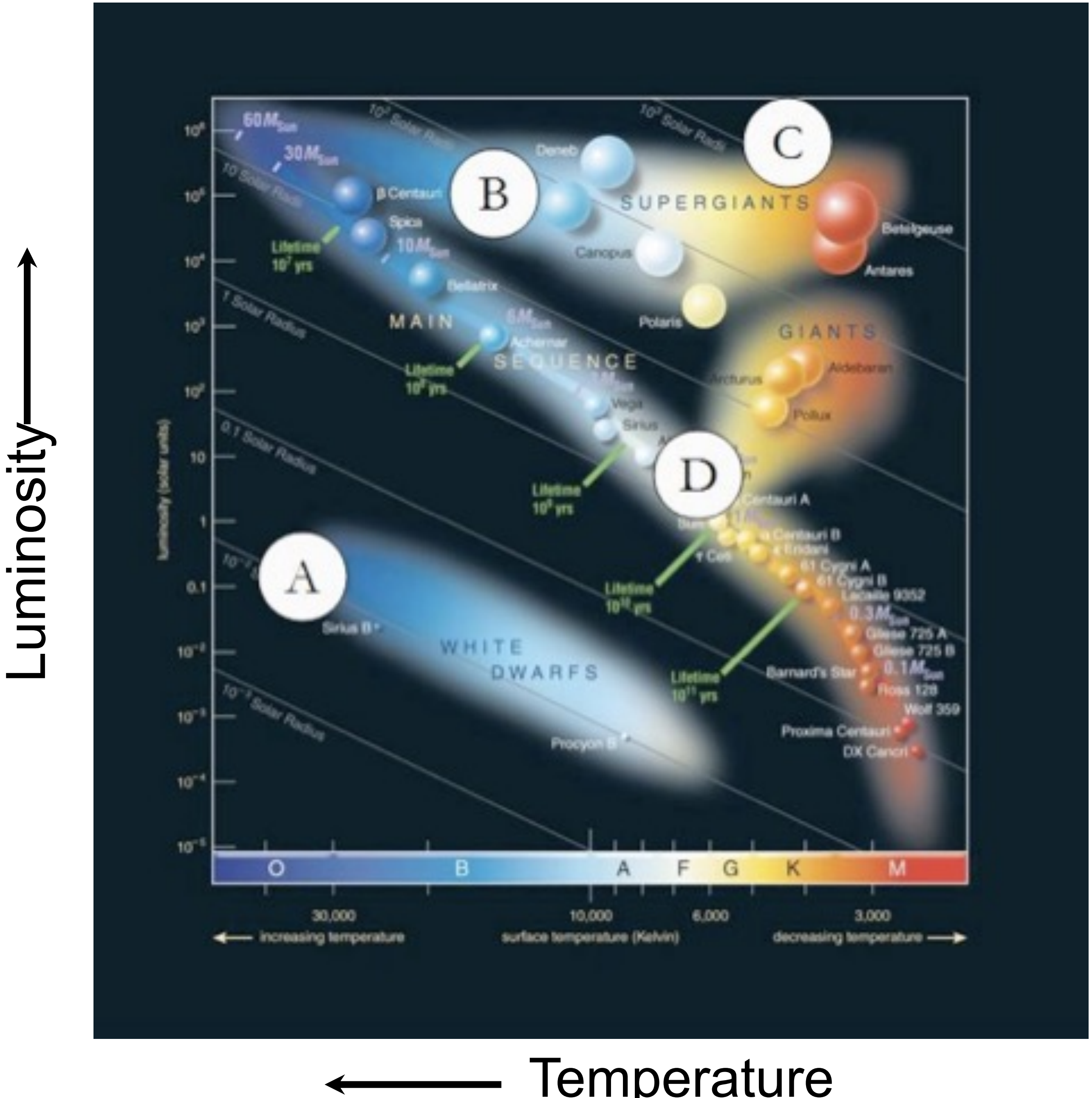
A



Luminosity

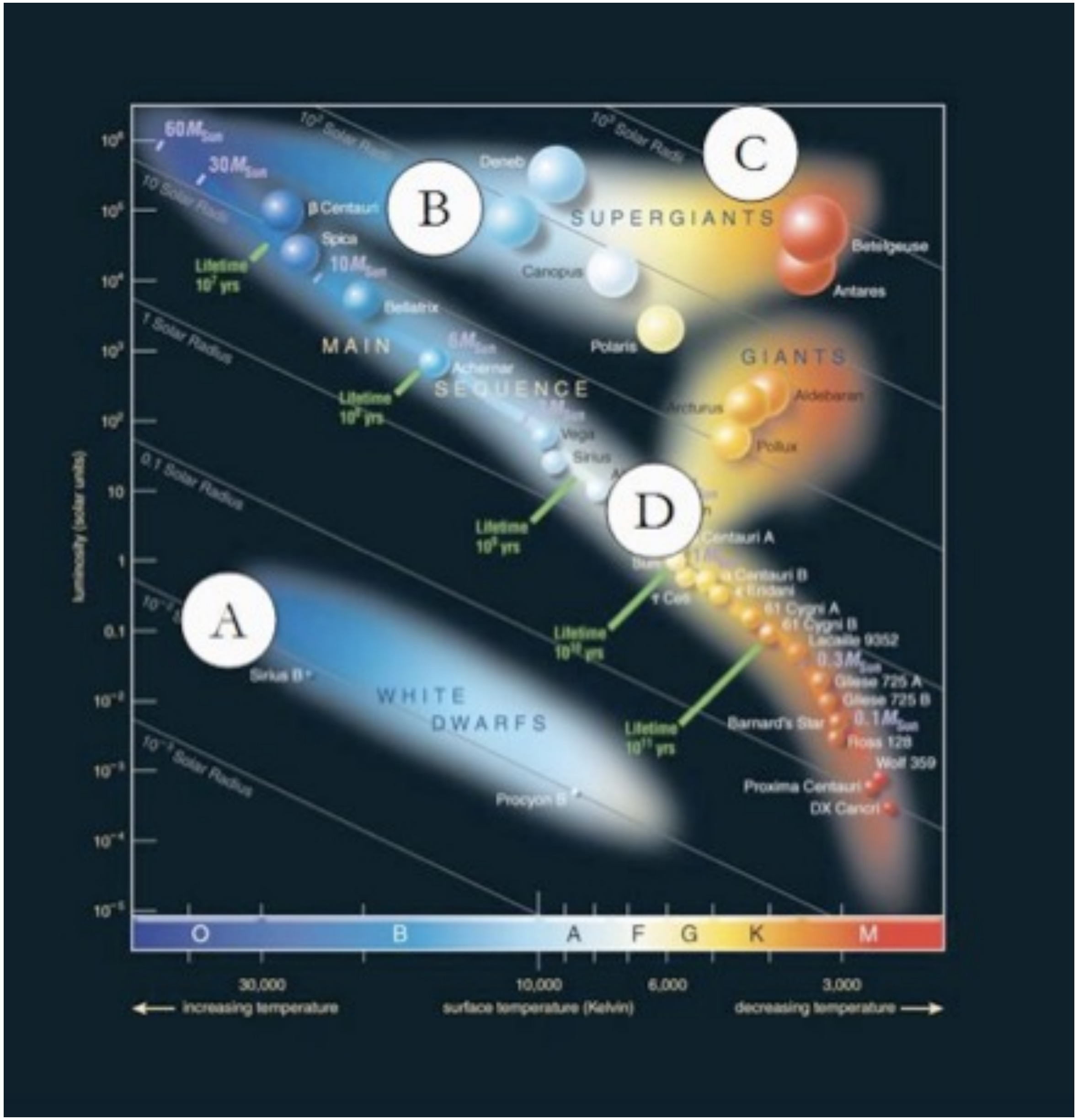
Temperature

- Which star is the most luminous?



- Which star is the most luminous?

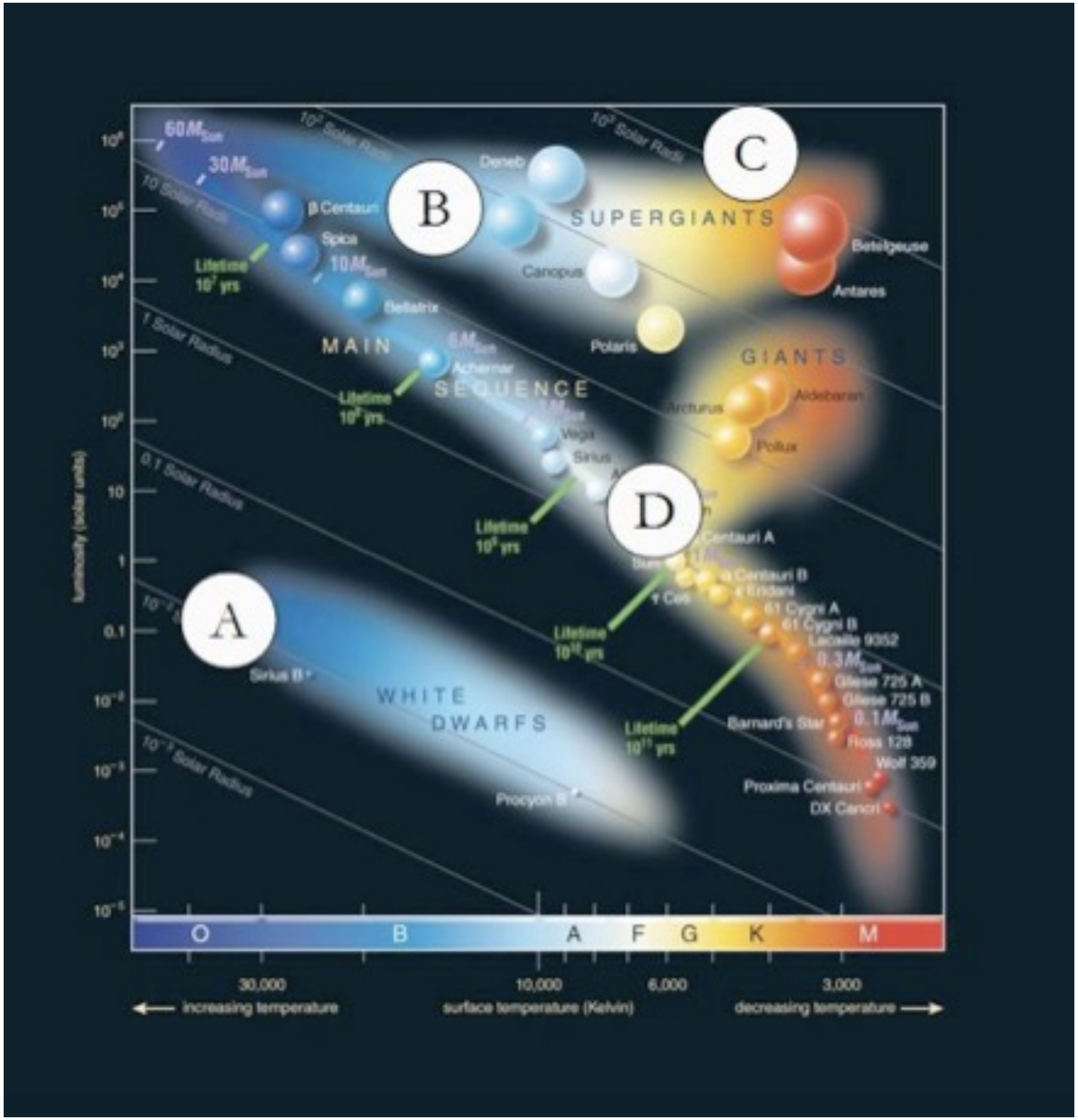
C



Luminosity

Temperature

- Which star is a main-sequence star?

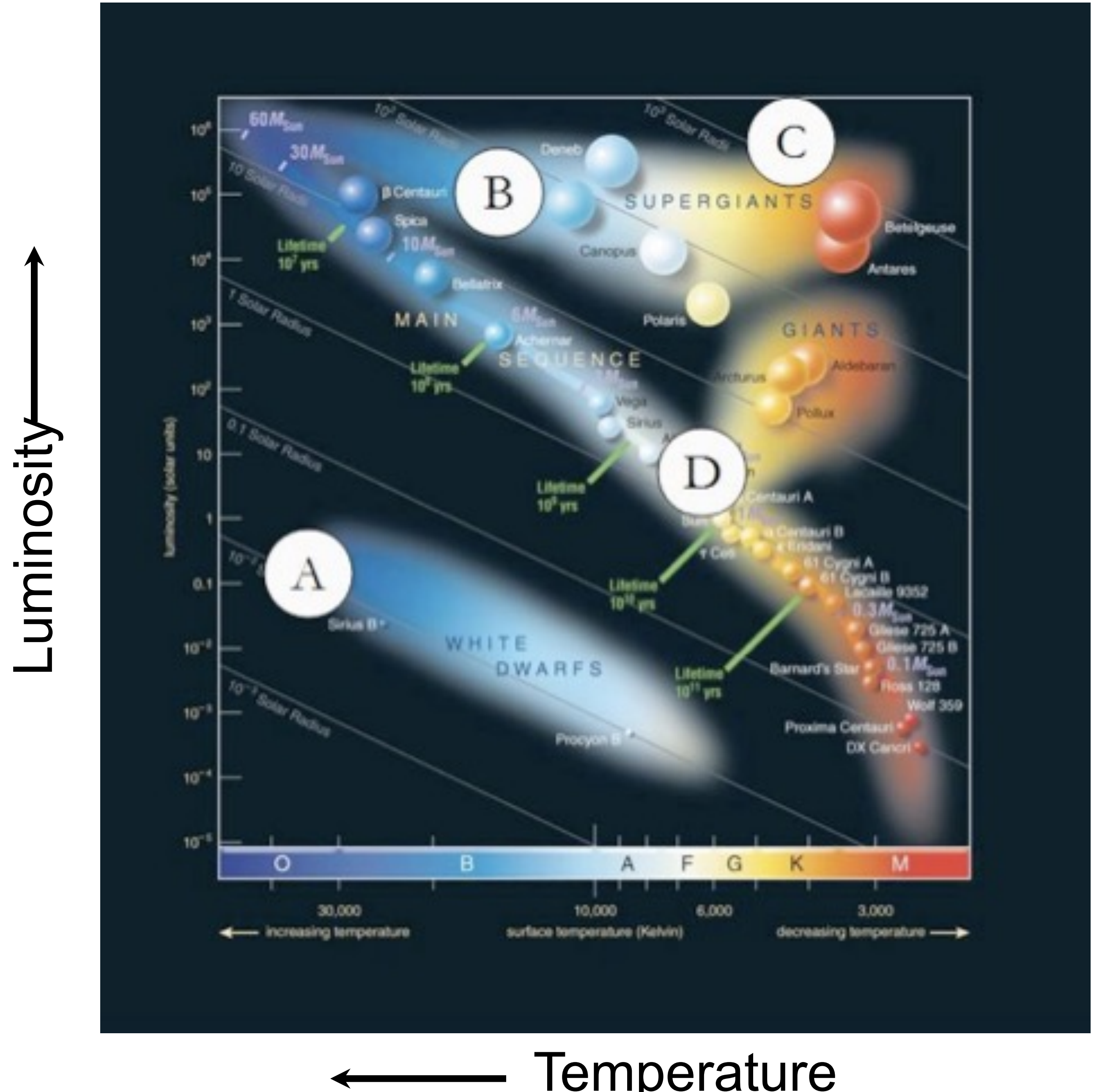


Luminosity

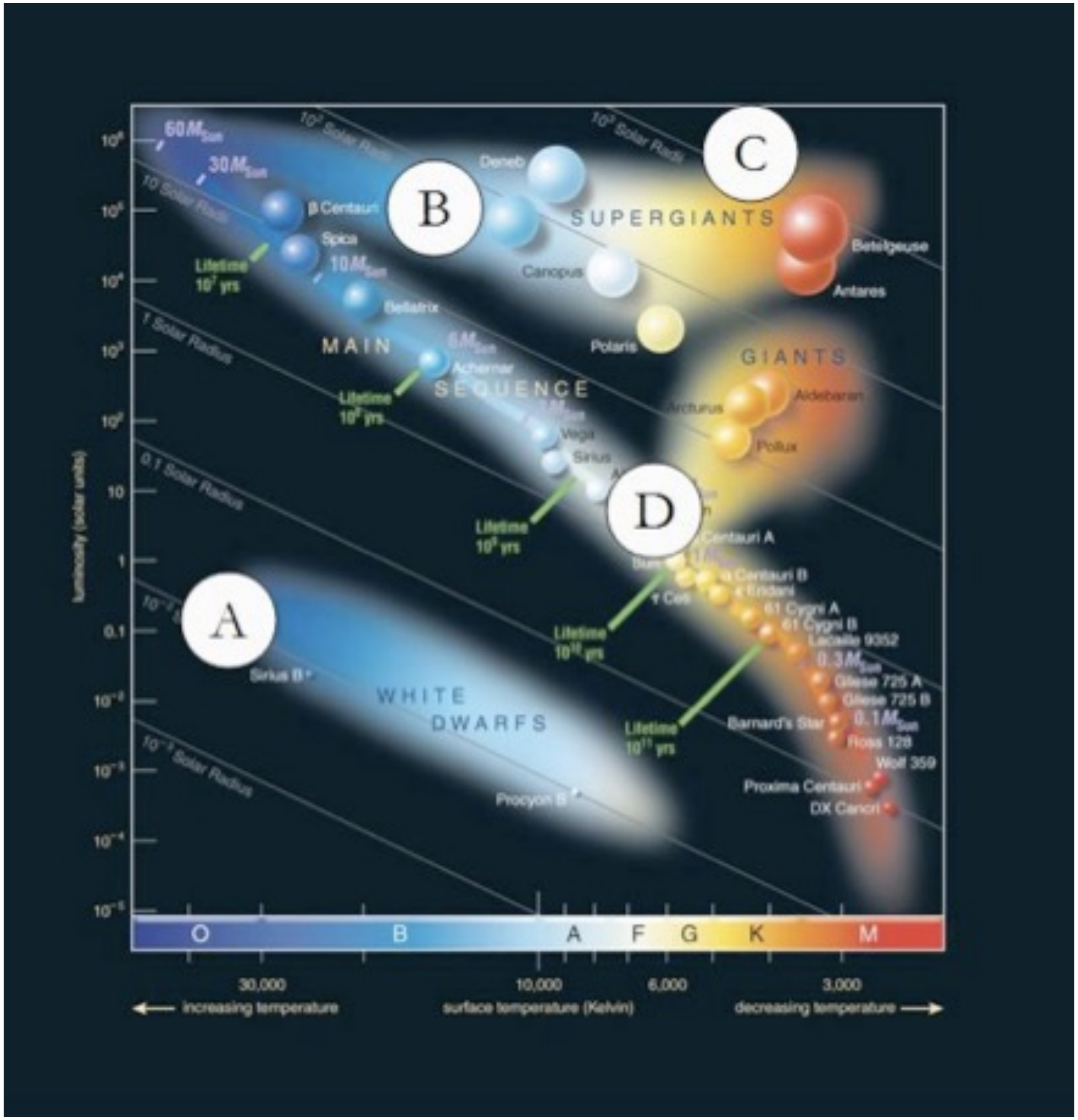
Temperature

- Which star is a main-sequence star?

D



- Which star has the largest radius?



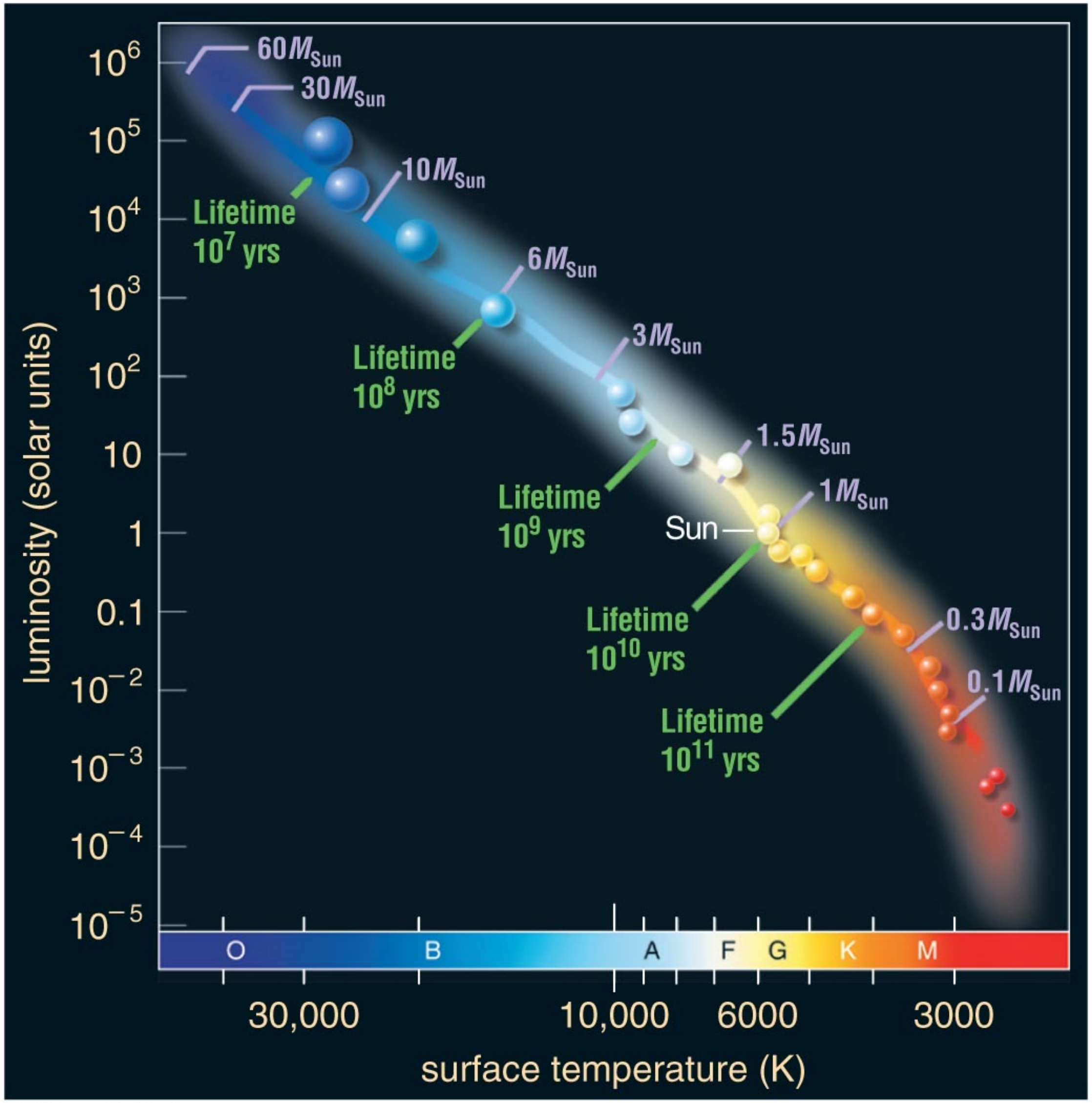
Luminosity

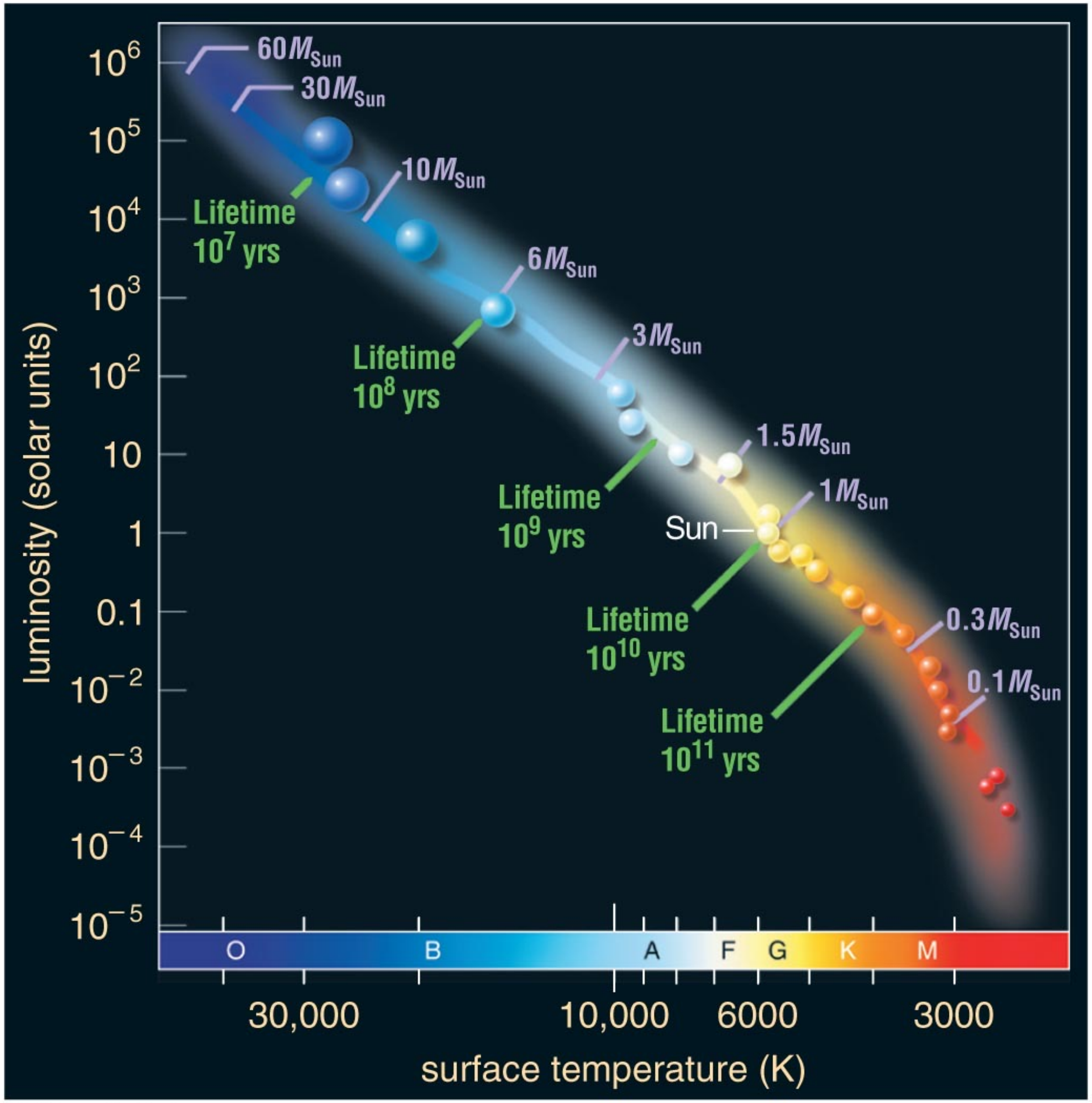
Temperature

- Which star has the largest radius?

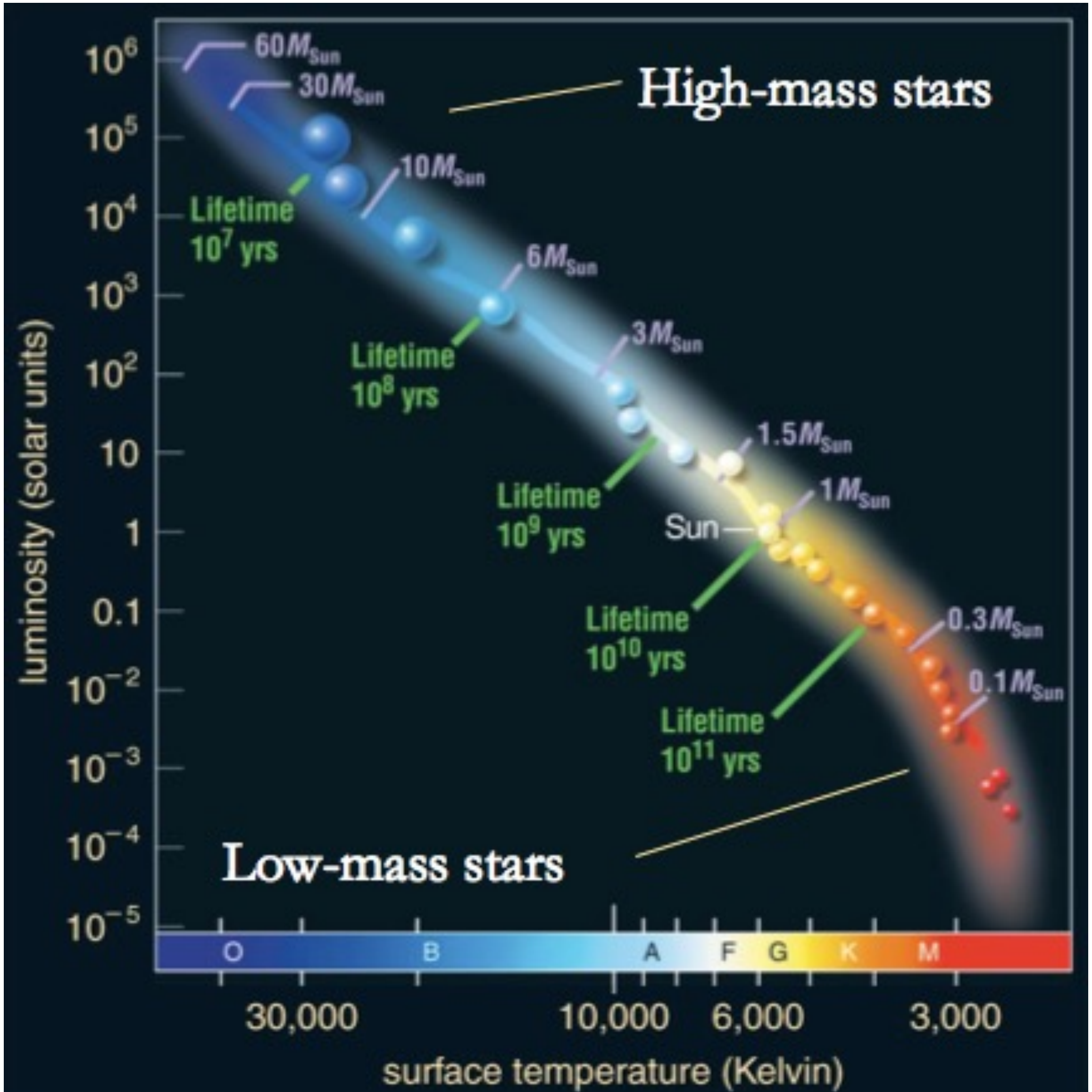
C

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.

Stellar Properties Review

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

  $10^{-4}L_{Sun}$–$10^{6}L_{Sun}$

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

  3000 K–50,000 K

- ***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

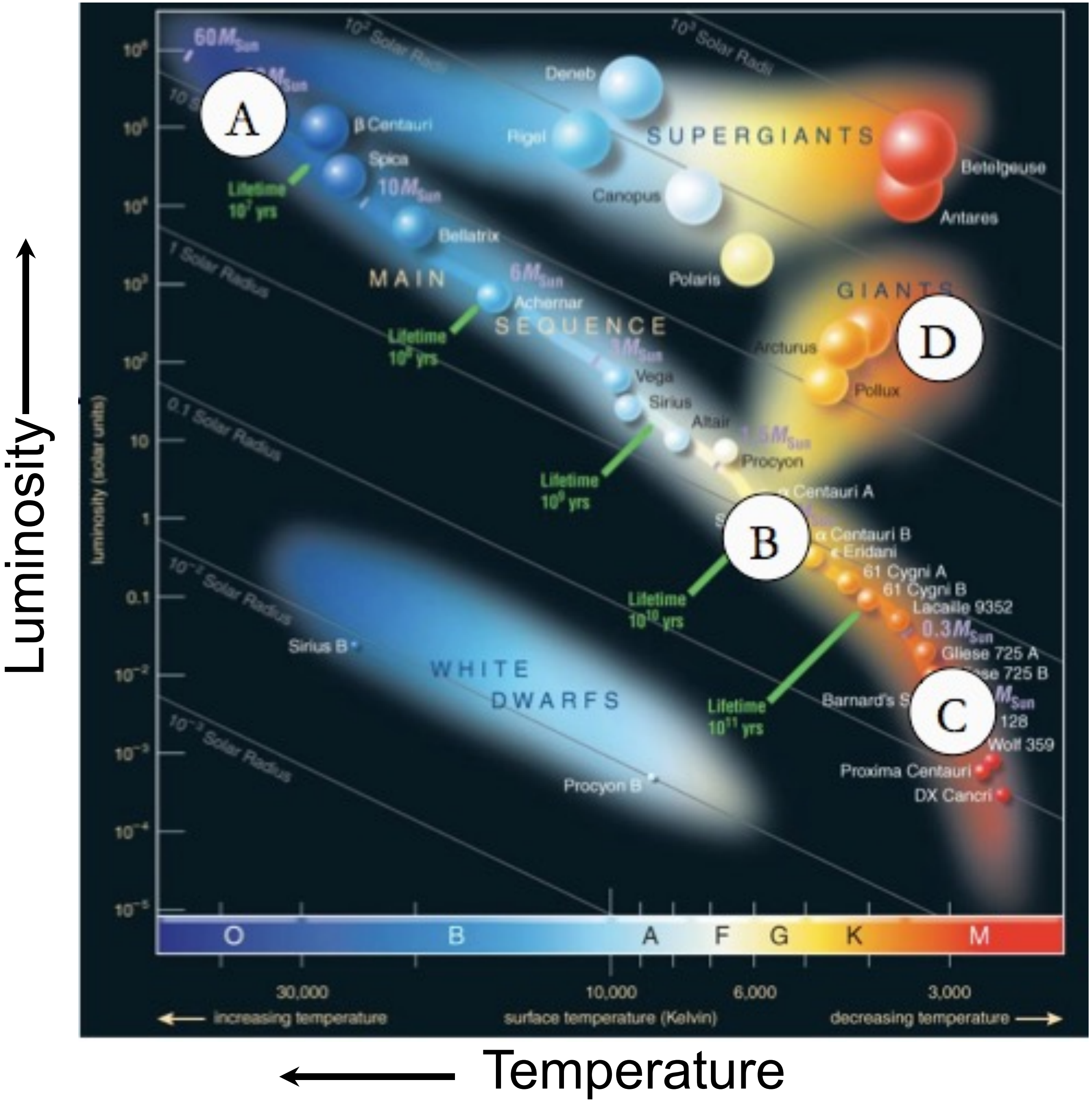
$$L = \frac{E}{t} \Rightarrow t = \frac{E}{L} = \frac{fMc^2}{L} \propto \frac{M}{M^{3.5}} = \frac{1}{M^{2.5}}$$

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

What are giants, supergiants, and white dwarfs?

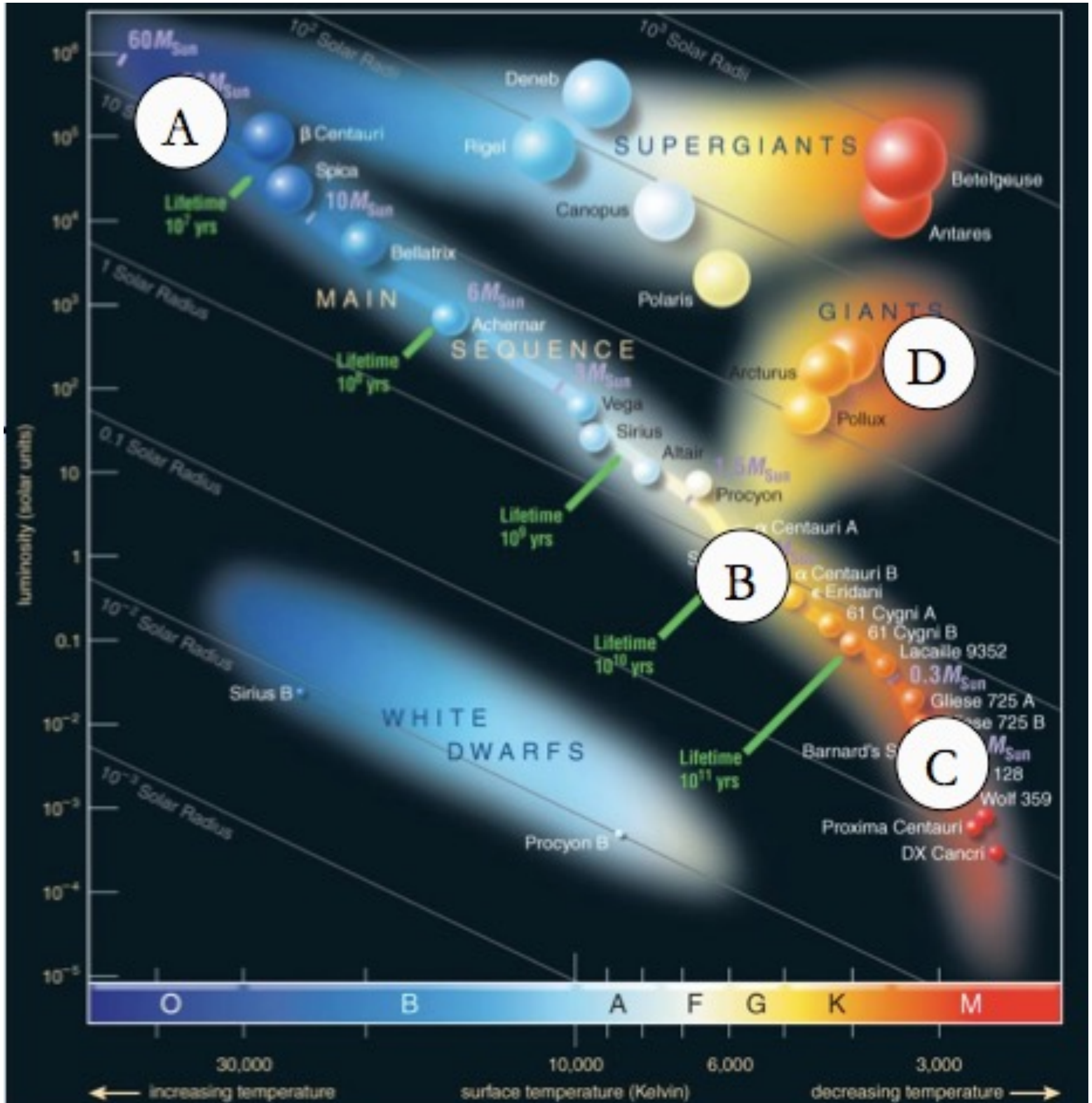
Off the Main Sequence

- 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.**



- Which star is most like our Sun?

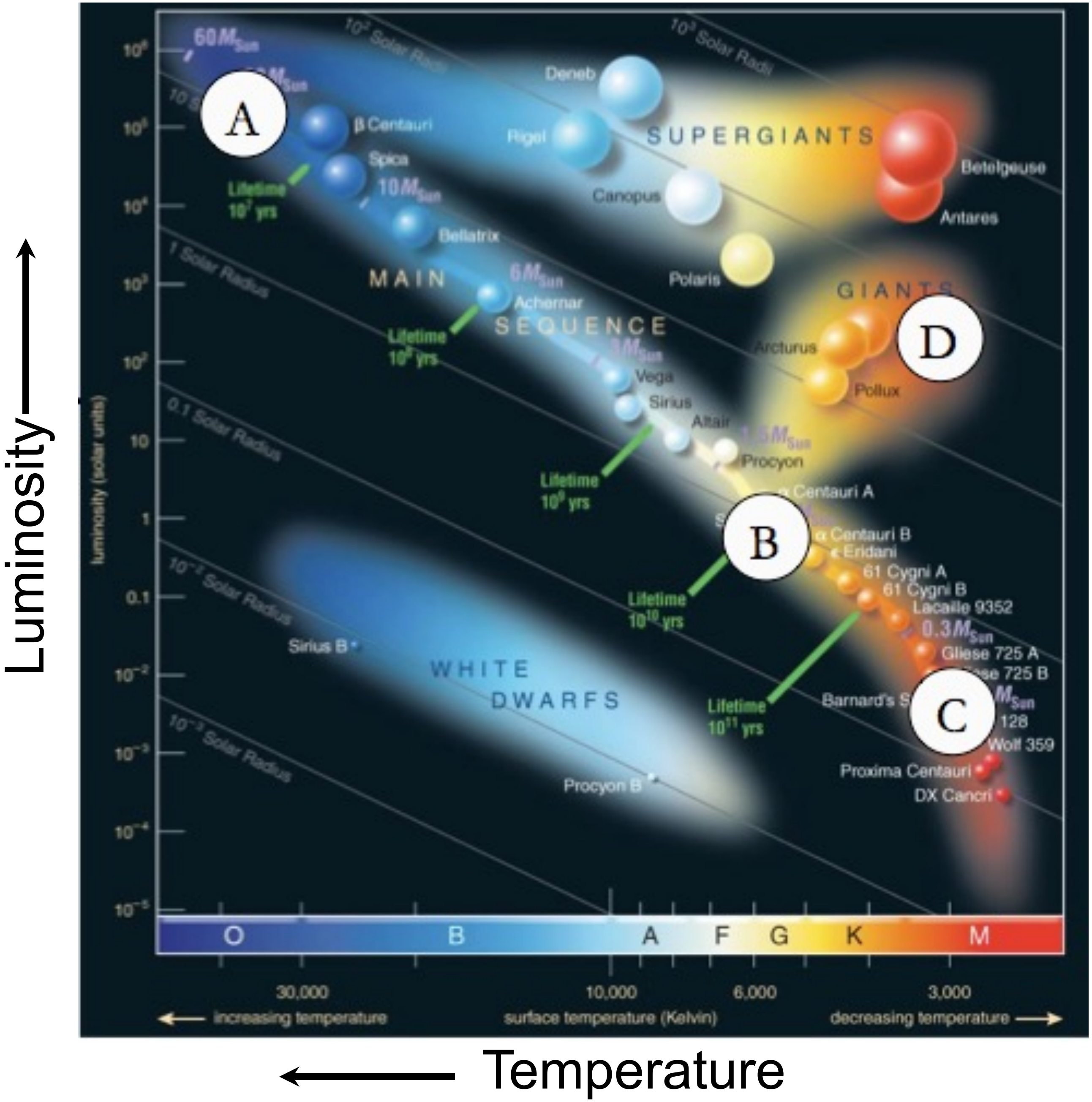
Luminosity



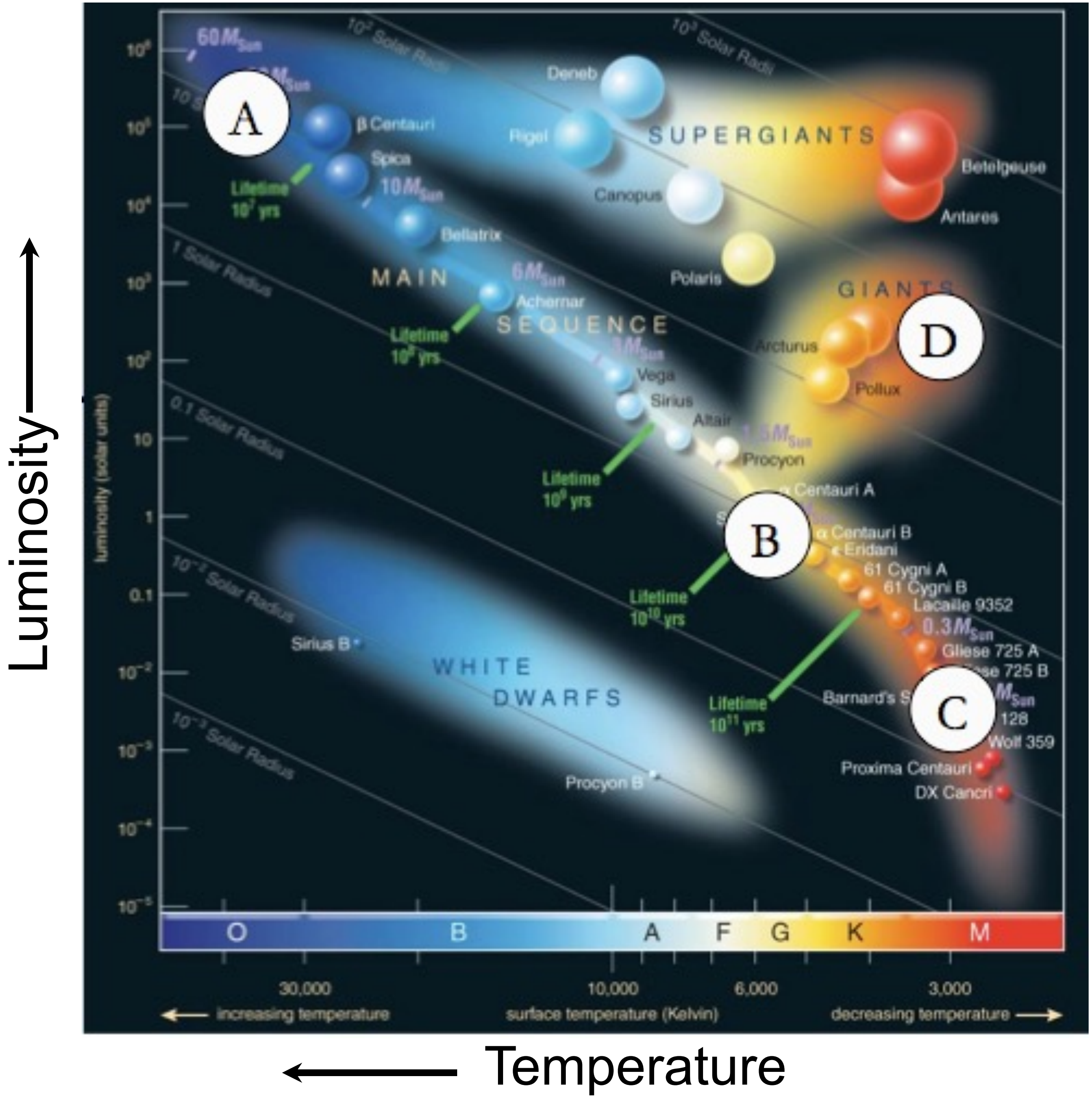
Temperature

- Which star is most like our Sun?

B

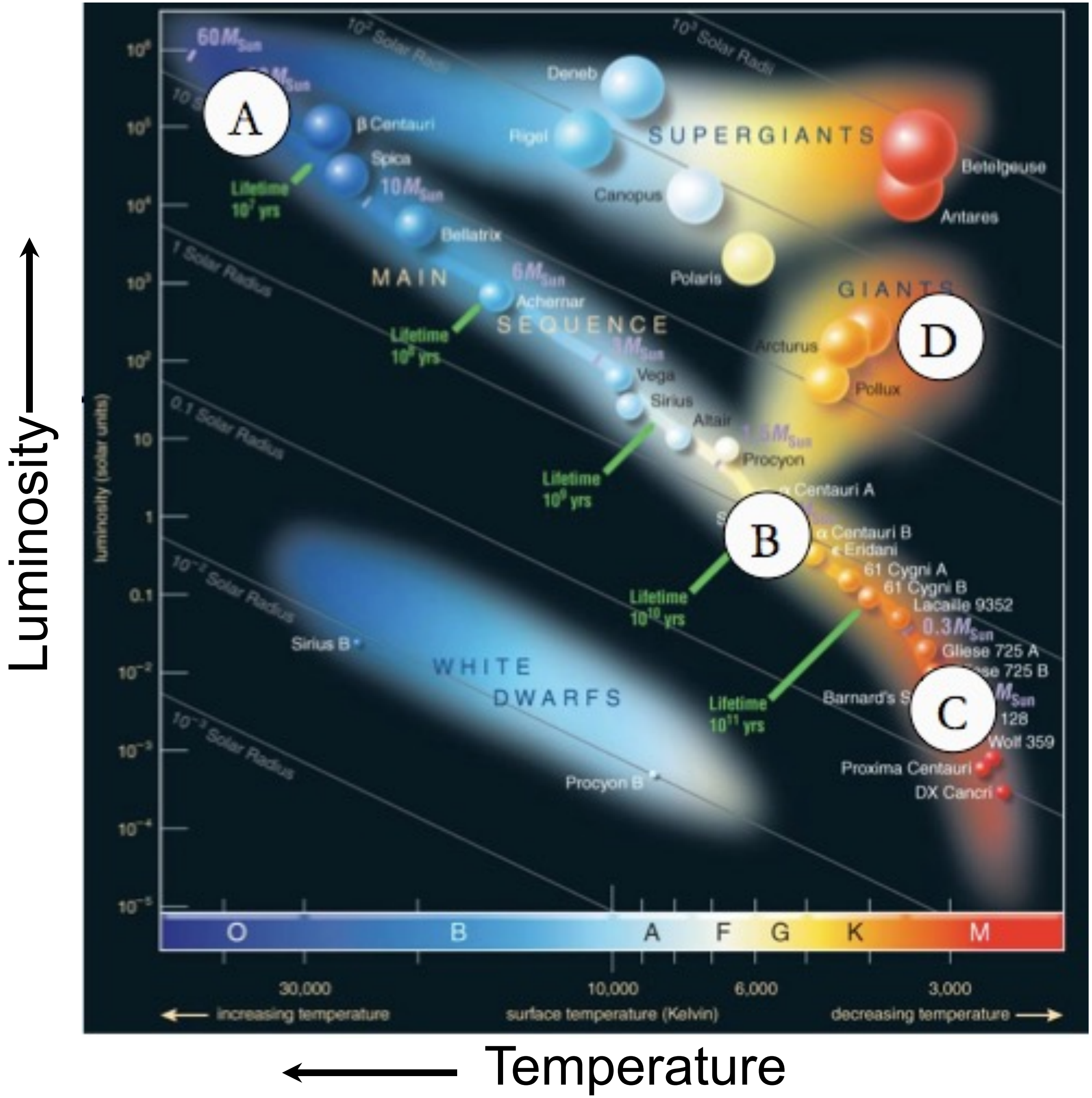


- Which of these stars will have changed the least 10 billion years from now?

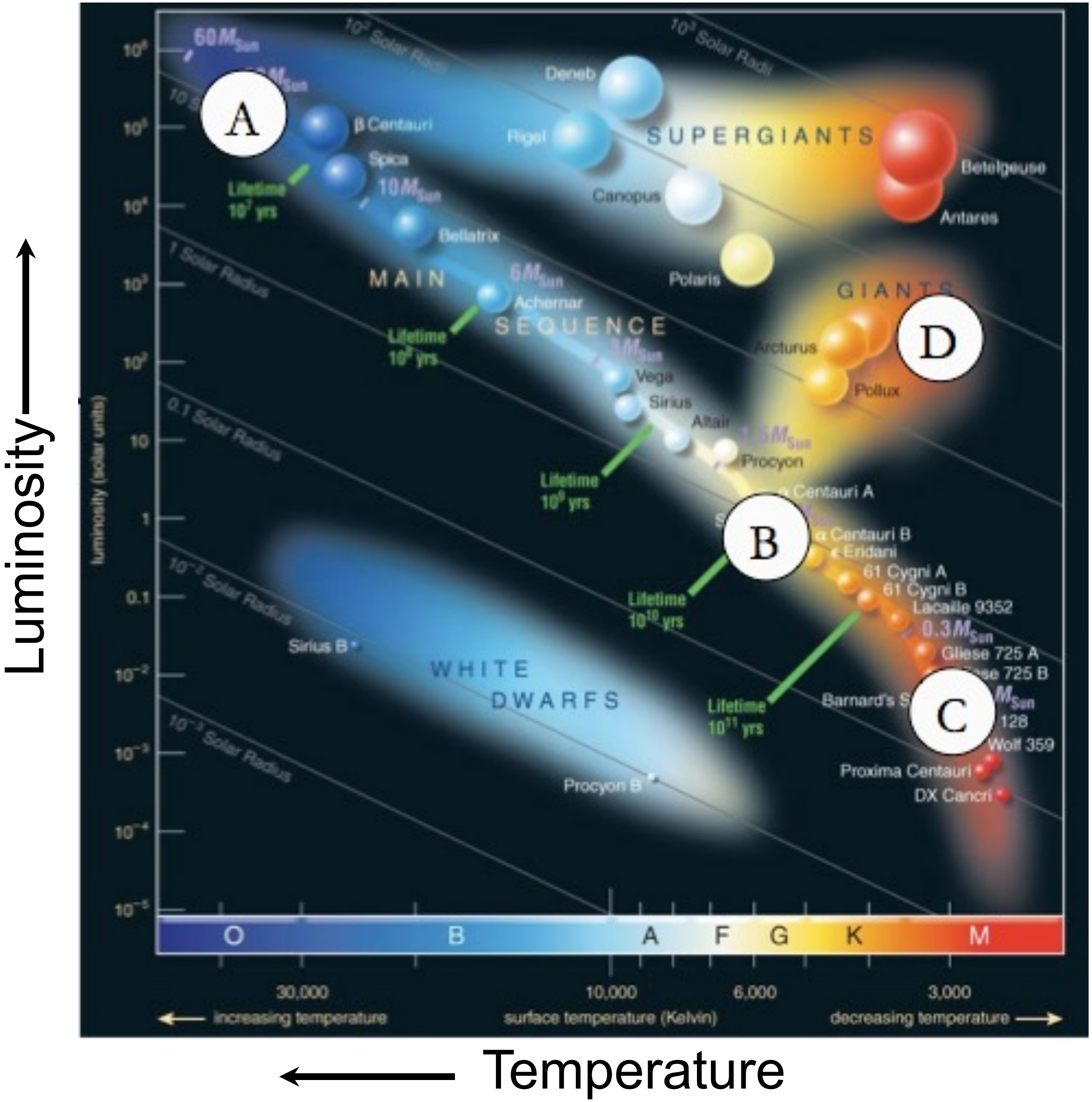


- Which of these stars will have changed the least 10 billion years from now?

C



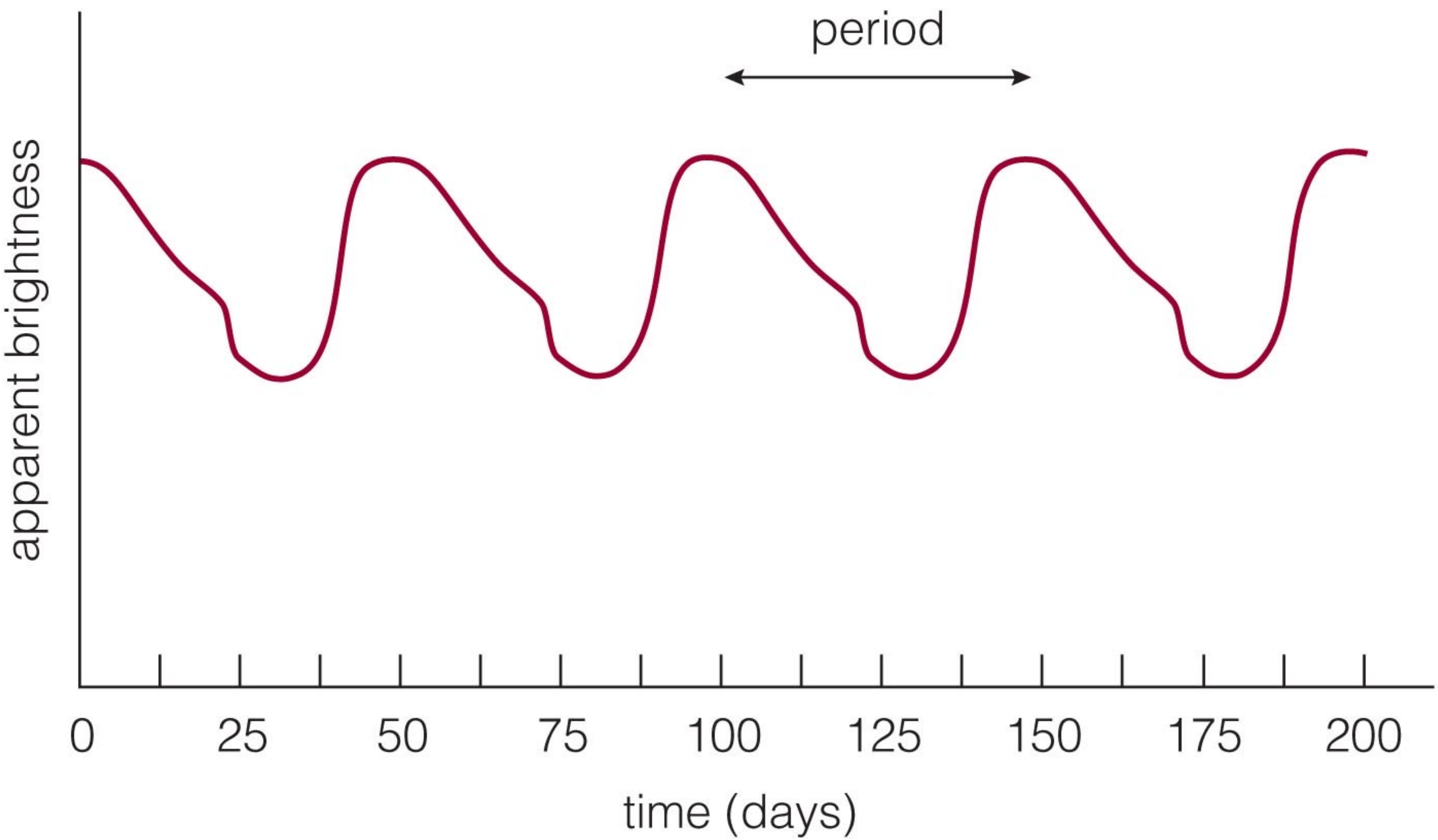
- Which of these stars can be no more than 10 million years old?



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

A

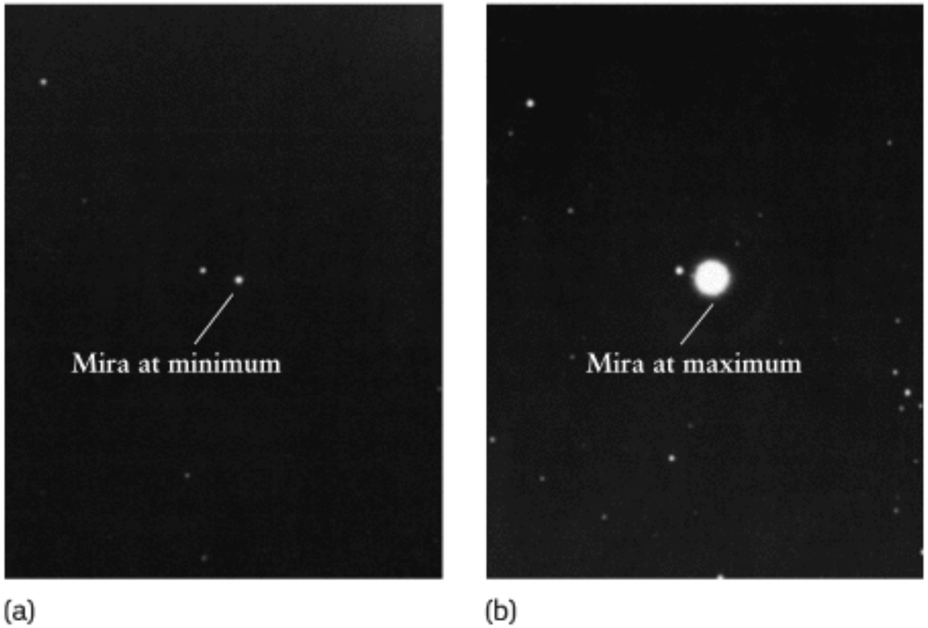
Variable Stars



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}.

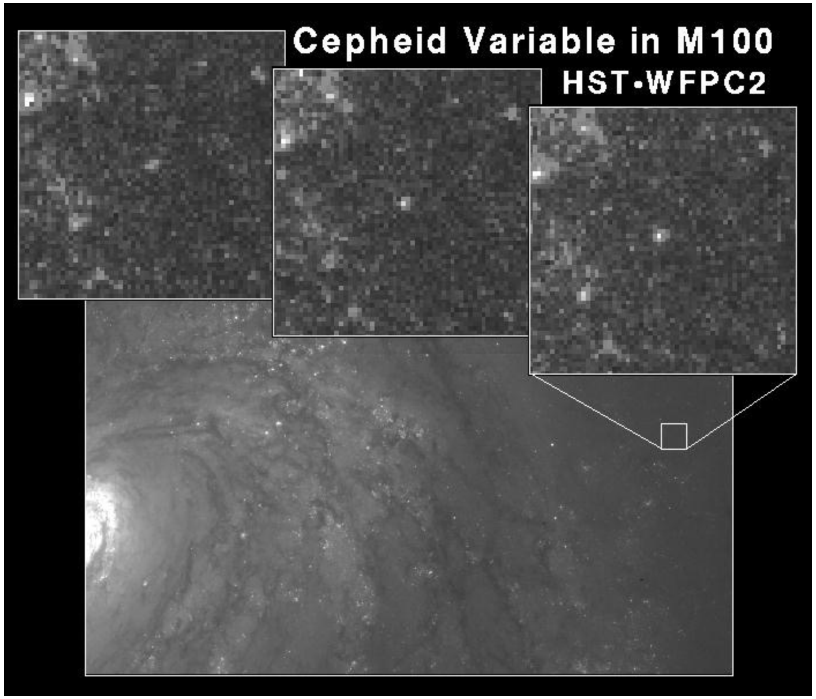


The first **long-period variable** star discovered was Mira (Period ~ 332 days).

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 (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.

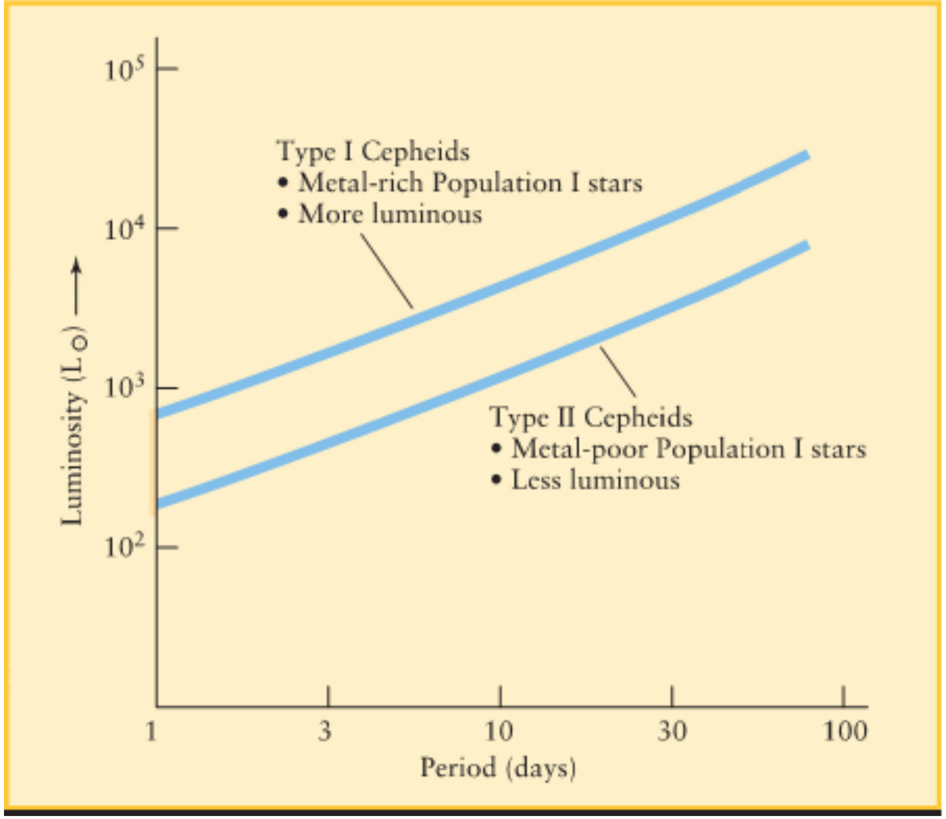
Cepheid Variables: Period-Luminosity Relation

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.

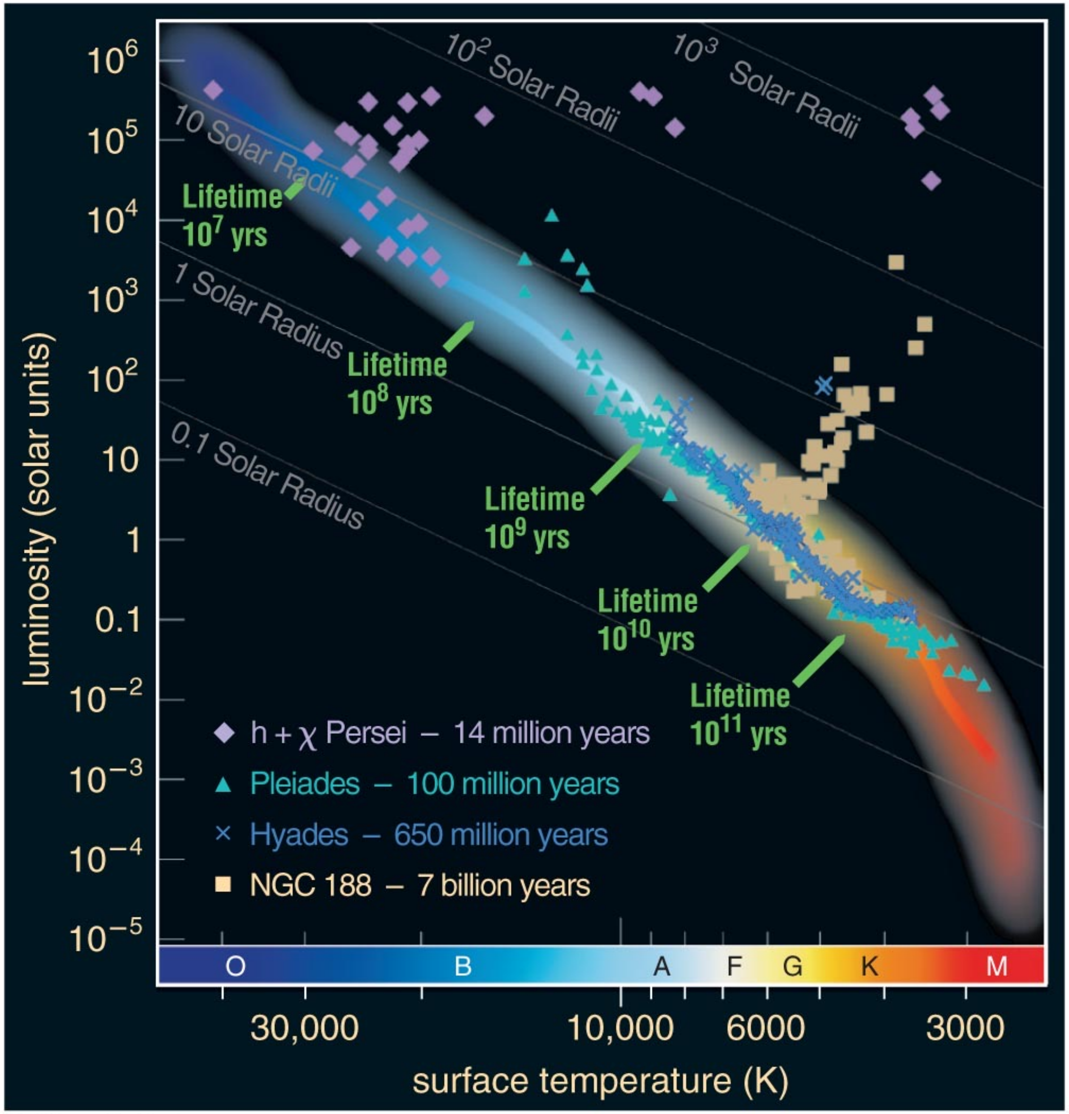
Because the stars in a star cluster were all born at roughly the same time, the different **properties of all the stars in a cluster are a function only of mass.** By studying star clusters we see how stars of different mass evolve differently.

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.

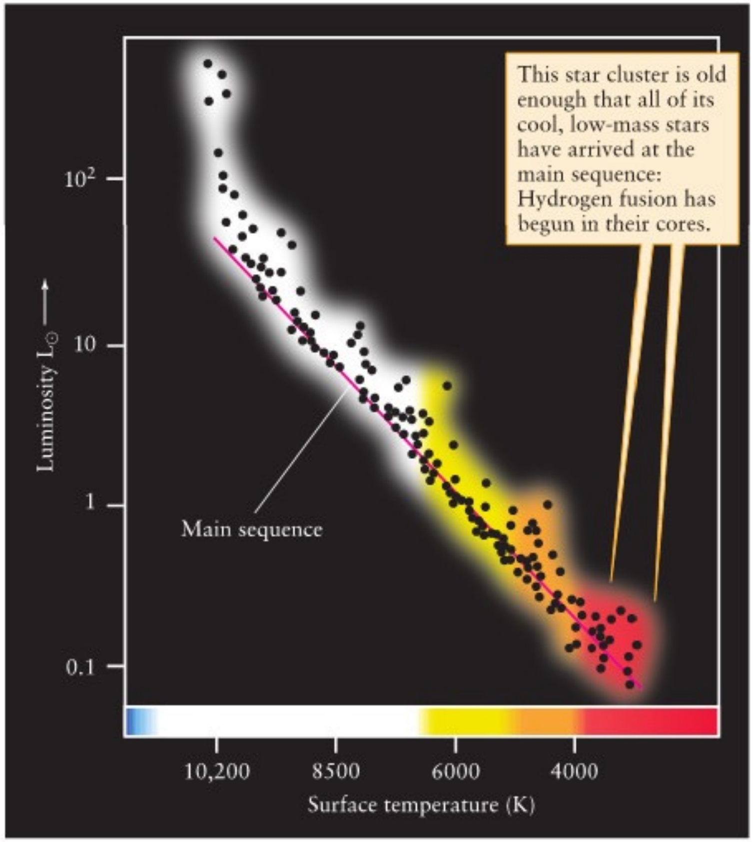
- ***Globular cluster:*** Up to a million or more stars in a dense ball tightly bound together by gravity

How do we measure the age of a star cluster?



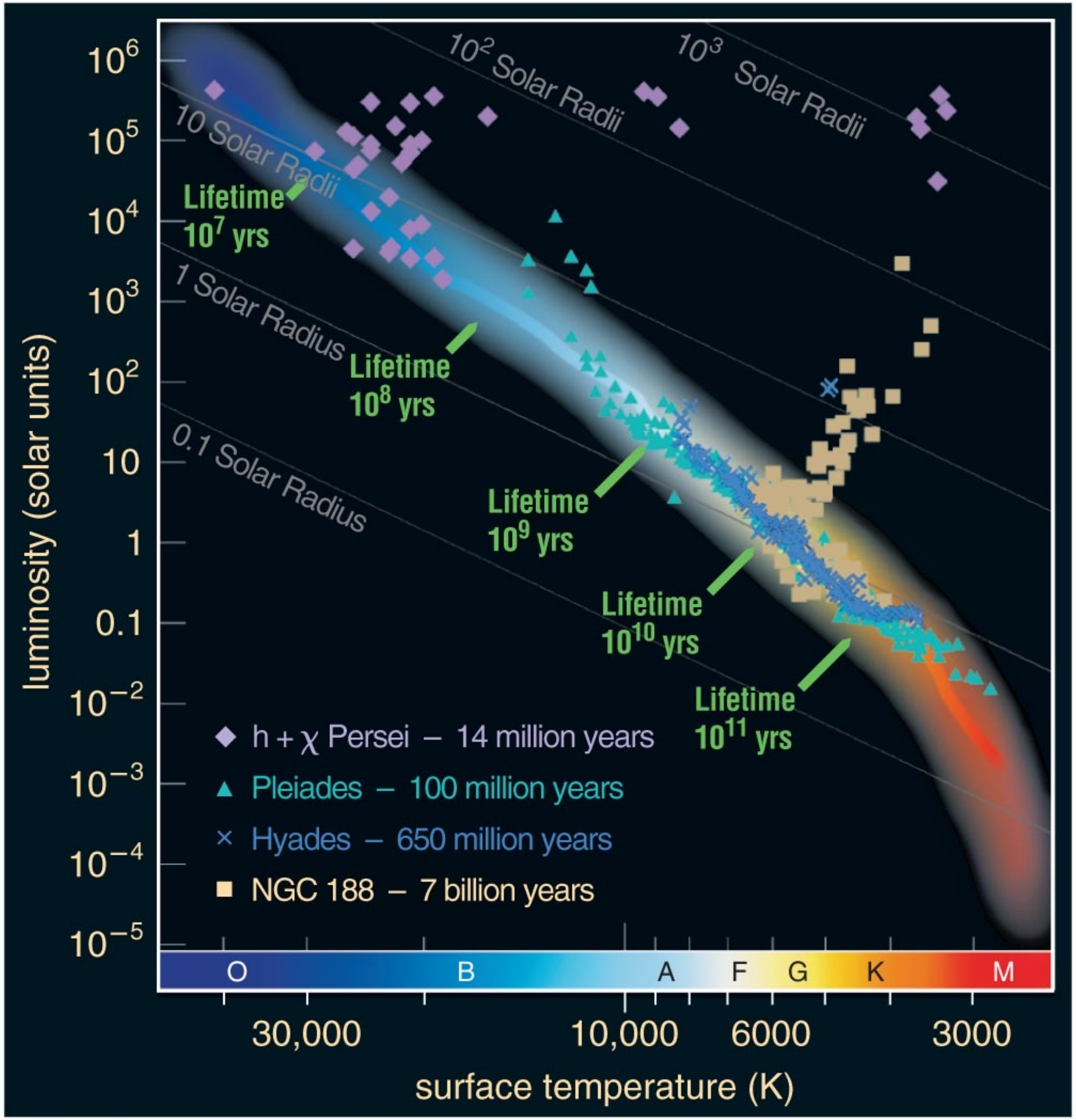
Example of Open Cluster: Pleiades

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

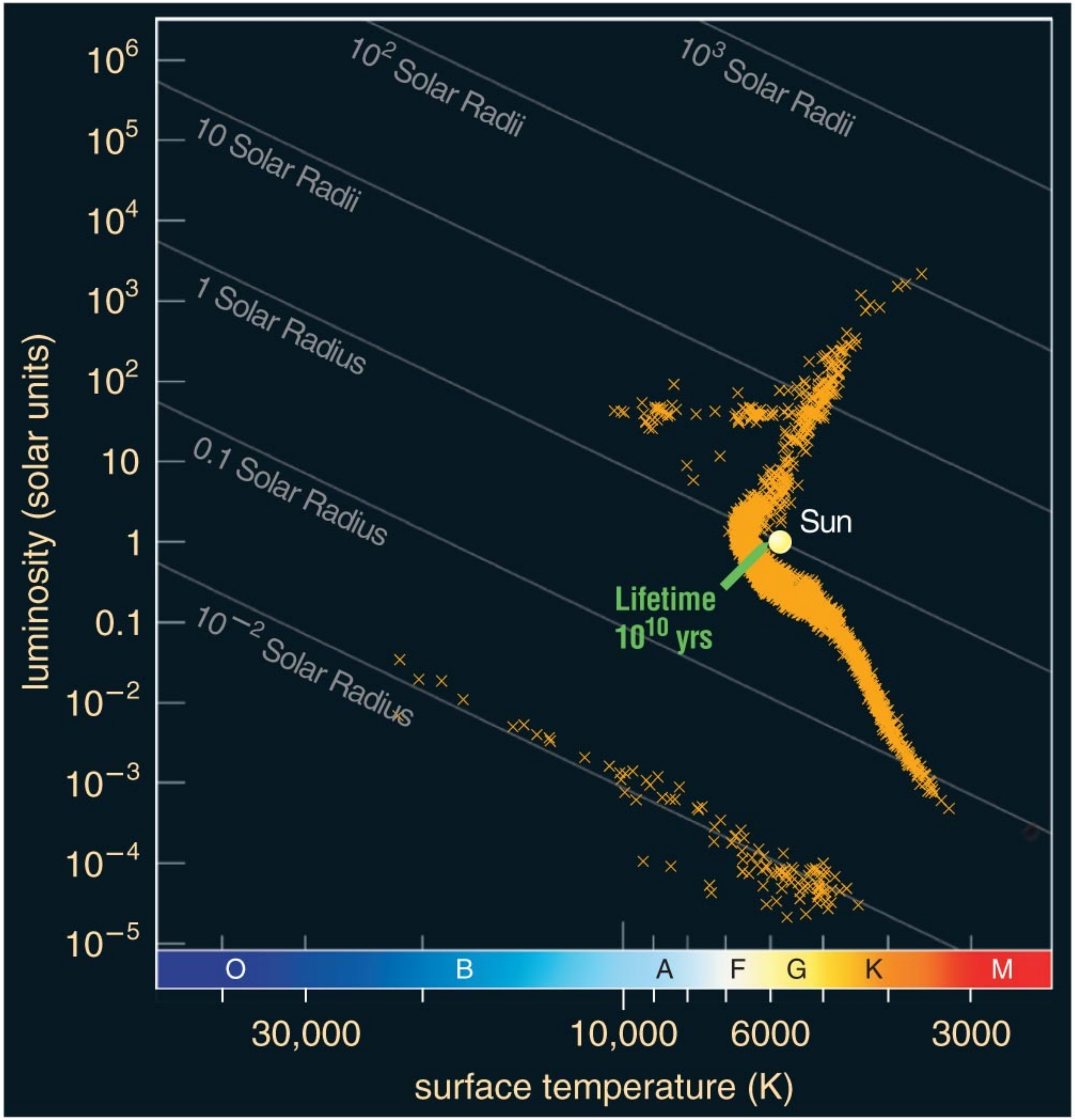


(b) An H-R diagram of the stars in the Pleiades

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 ~100×10^6 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.

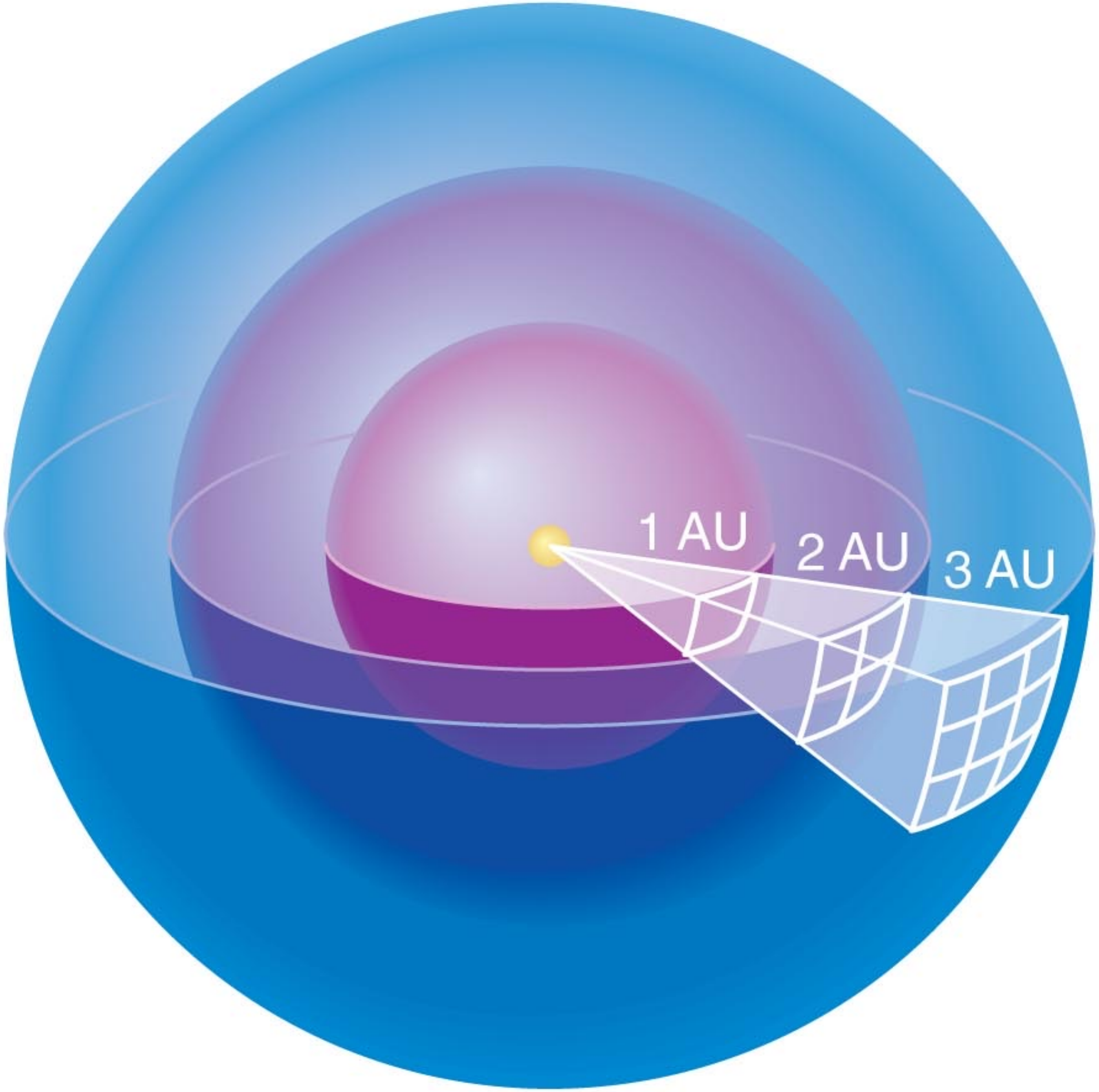


- Detailed modeling of the oldest globular clusters reveals that they are about 13 billion years old.

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.

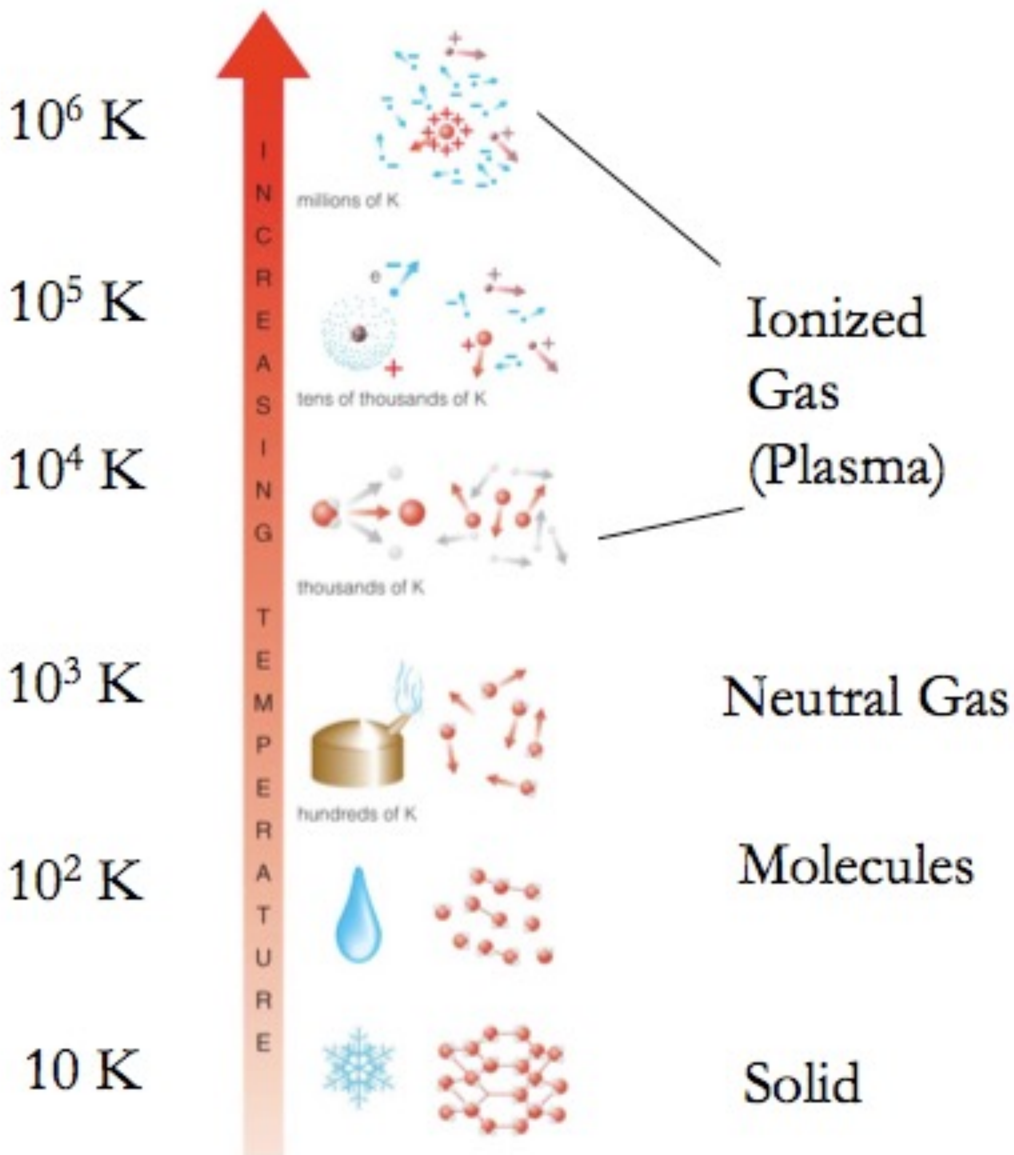
EXTRA SLIDES



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

  Area of sphere:
  4π (radius)^2

- Divide luminosity by area to get brightness.



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

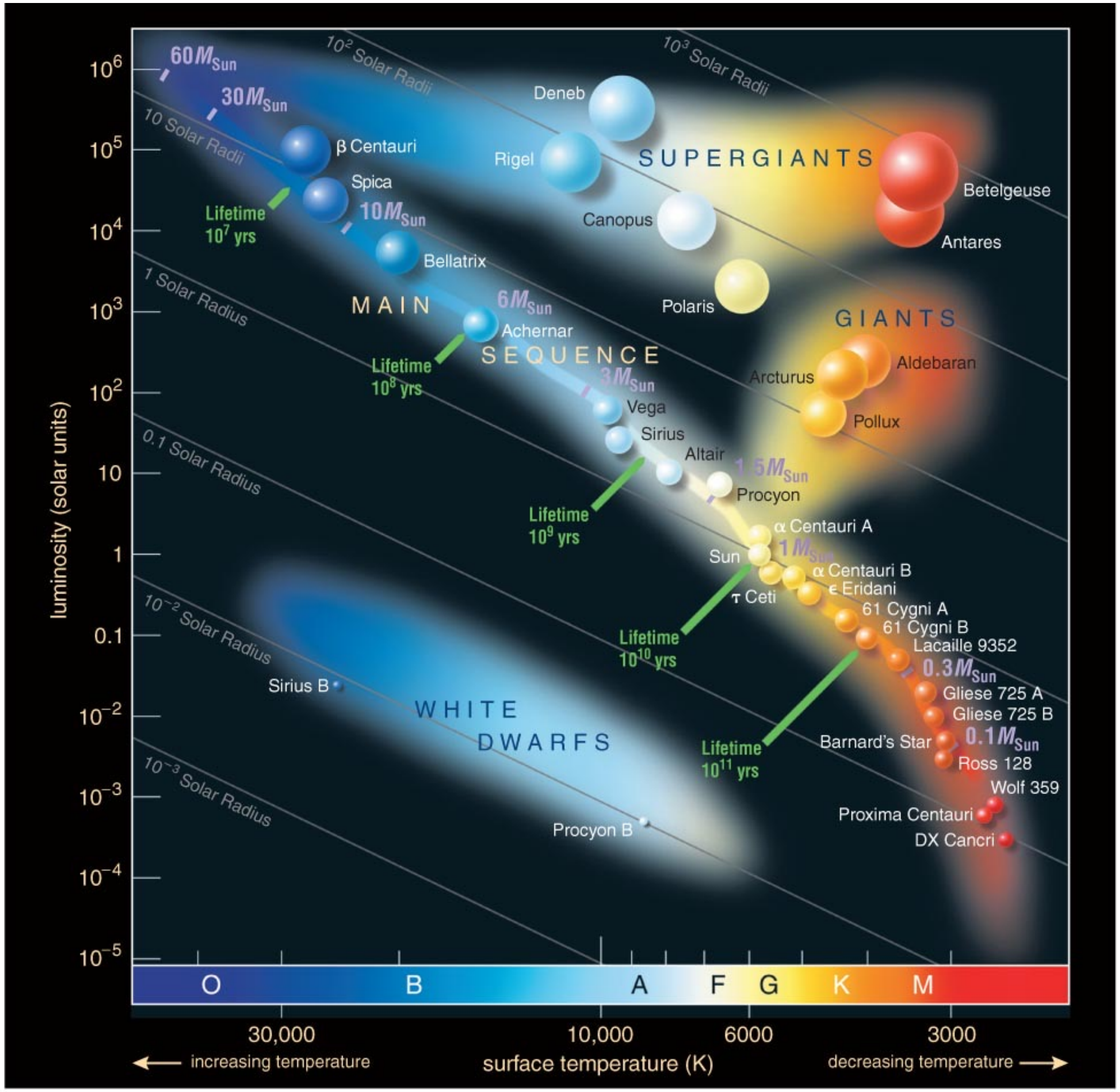
HIPPARCOS

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.

Luminosity



Temperature

- H-R diagram depicts:

Temperature

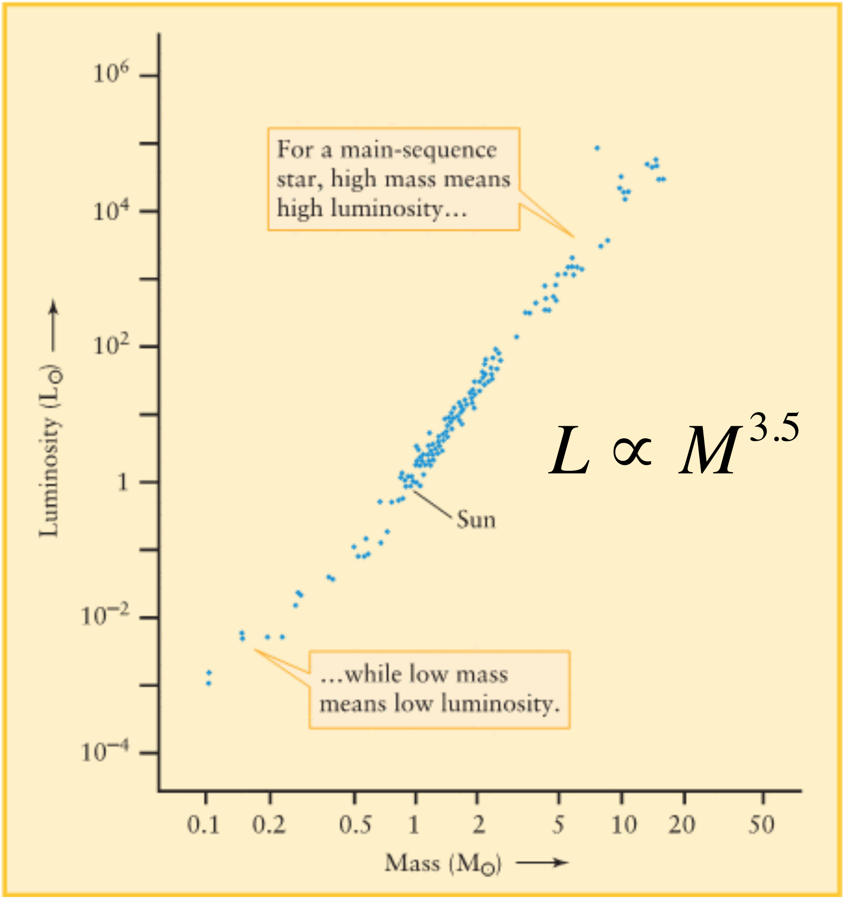
Luminosity

Luminosity Class

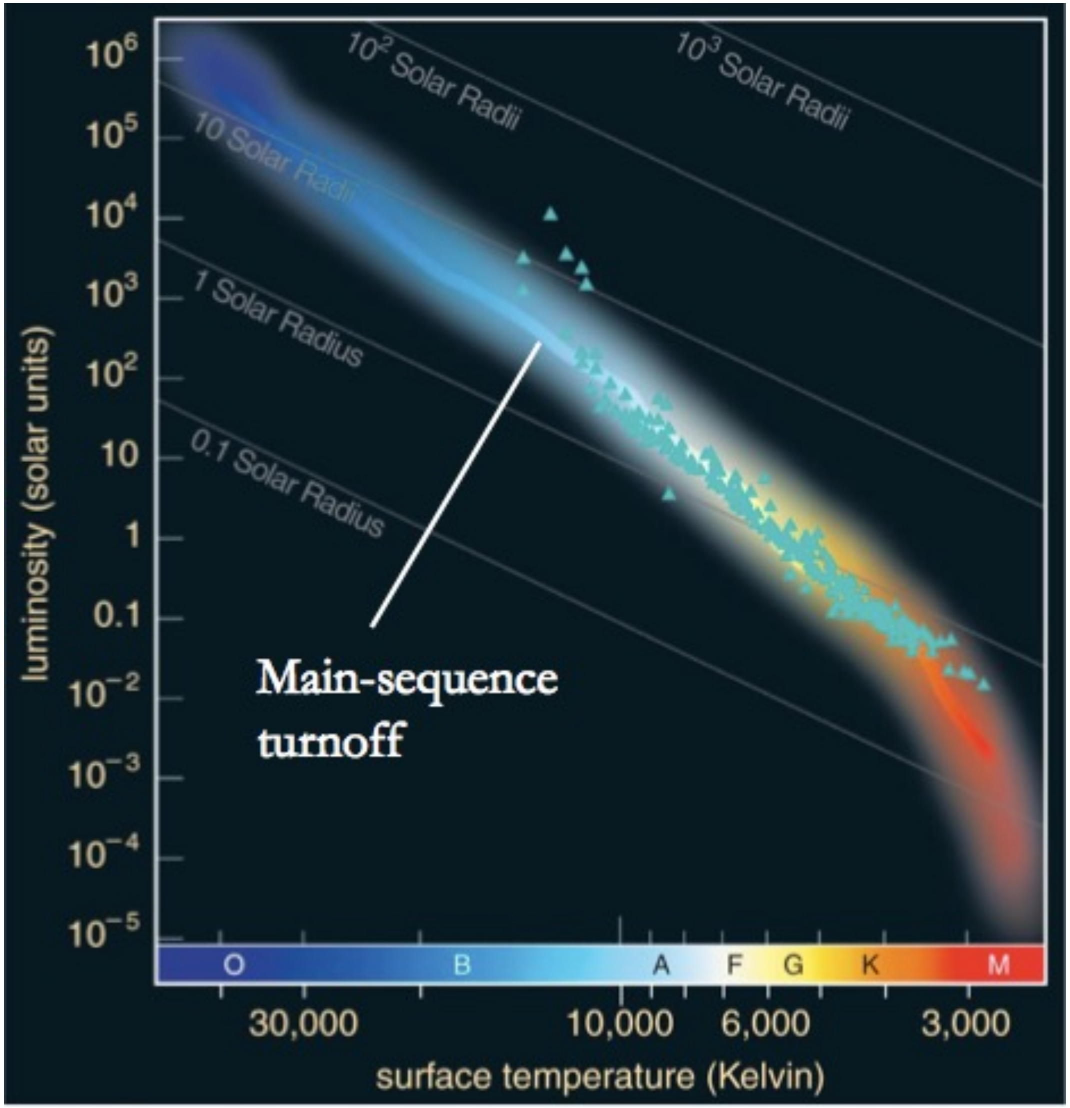
Radius

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.