Chapter 15
Surveying the Stars

Agenda

- Announce:
  – Test in 2.5 weeks
  – Masteringastronomy.com issues
- Relativity review
- Review our sun
- Ch. 15 Surveying the Stars
- Lab

Special vs. General Relativity

- Applies only to constant motion
- Constant speed of light (in vacuum)
- Same laws in all inertial frames of ref.
- Observers at same speed can share frame
- Unites space w/ time in flat space

- Allows for accelerated motion
- Ditto..constant speed of light
- Same laws in local frames
- Observers must be near each other (curvature)
- Describes curved spacetime

More on General Relativity

- Time runs slower where curvature deeper
- Energy/matter curves spacetime
- Gravity/curvature bends light: grav. lenses
- Acceleration equivalent to gravity
- Allows for black holes
- Allows for different shapes for the universe
- Predicts gravitational waves
- Fixes Newtonian gravity:
  – Time dependent
  – No action at a distance

General relativity is based on the *equivalence principle* that states

- Nothing can travel faster than the speed of light
- The effects of gravity are the same as the effects of acceleration
- The laws of physics are equivalent for all observers
- None of the above

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If you are in a spaceship that is accelerating, and don't look out

- You can "feel" that you are accelerating
- You could not tell by performing experiments inside your spaceship
- You will feel as if you have weight
- All of the above
- #1 and #3

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- The way it appears today
- The way it looked 25 years ago
- Neither of the above

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Has any evidence been found that the predictions of general relativity are true?

- We've seen gravitational lensing caused by the sun, stars, and galaxies
- The spectrum of white dwarf stars shows a redshift due to time slowing down
- The perihelion of Mercury's orbit precesses
- All of the above
- All except #2

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Are there such things as "gravitational waves"?

- Yes, they are like electromagnetic waves except made by moving masses rather than moving charges.
- They are ripples in spacetime
- Some close binary stars appear to radiate them
- All of the above
- All except #1

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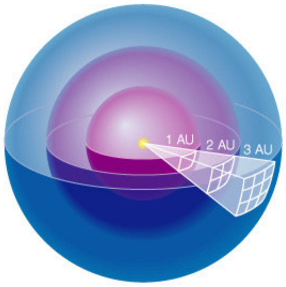
Our Sun

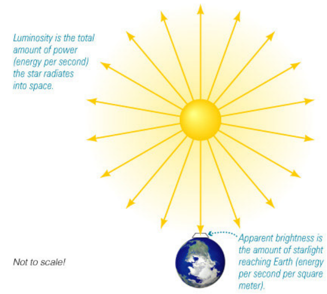
- Why does the Sun shine?
- Why isn't the Sun changing (significantly)…getting bigger or smaller?

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 stellar luminosities?





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)

Thought Question

These two stars have about the same luminosity -- which one appears brighter?

A. Alpha Centauri
B. The Sun

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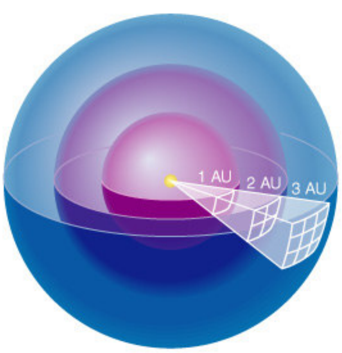

Luminosity passing through each sphere is the same

Area of sphere:

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

Divide luminosity by area to get brightness

The relationship between apparent brightness and luminosity depends on distance:

$$\text{Brightness} = \frac{\text{Luminosity}}{4\pi\ (\text{distance})^2}$$

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

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

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

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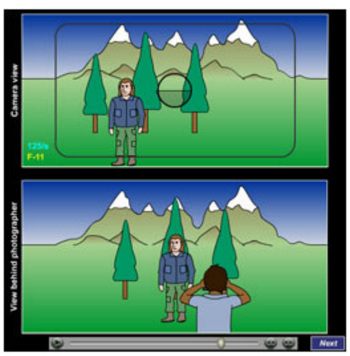
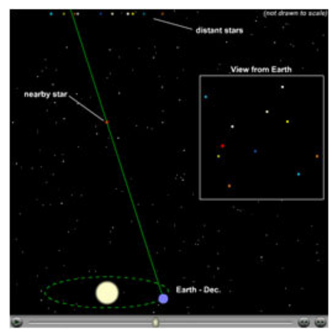
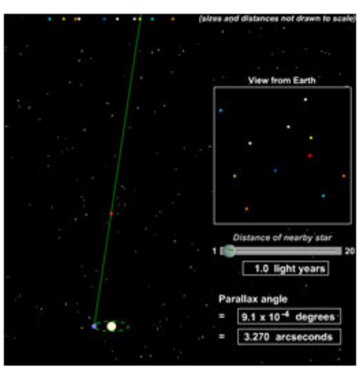


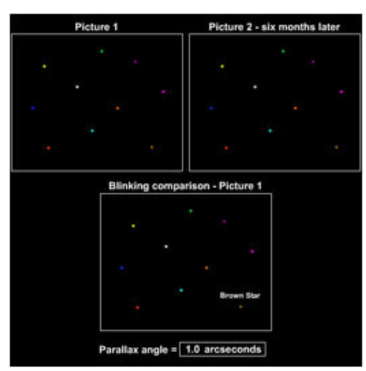
Parallax is the apparent shift in position of a nearby object against a background of more distant objects



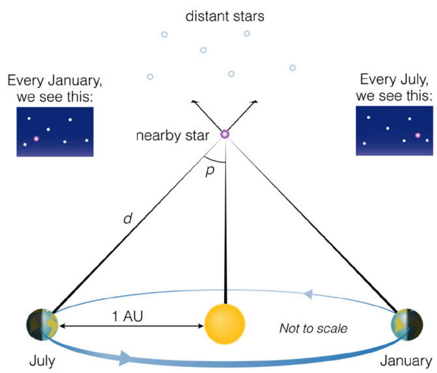
Apparent positions of nearest stars shift by about an arcsecond as Earth orbits Sun



Parallax angle depends on distance



Parallax is measured by comparing snapshots taken at different times and measuring the shift in angle to star



Parallax and Distance

p = parallax angle

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

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

Most luminous stars:

10^6 L_{Sun}

Least luminous stars:

10^{-4} L_{Sun}

(L_{Sun} is luminosity of Sun)

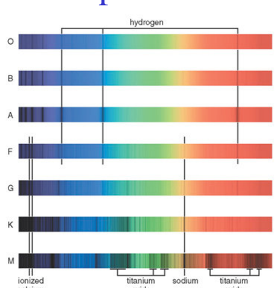
The Magnitude Scale

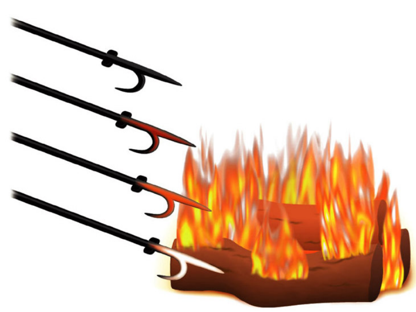
m = apparent magnitude , M = absolute magnitude

$$\frac{\text{apparent brightness of Star 1}}{\text{apparent brightness of Star 2}} = (100^{1/5})^{m_1 - m_2}$$

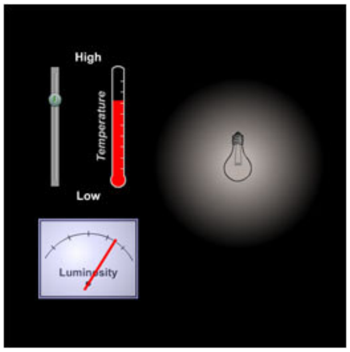
$$\frac{\text{luminosity of Star 1}}{\text{luminosity of Star 2}} = (100^{1/5})^{M_1 - M_2}$$

How do we measure stellar temperatures?





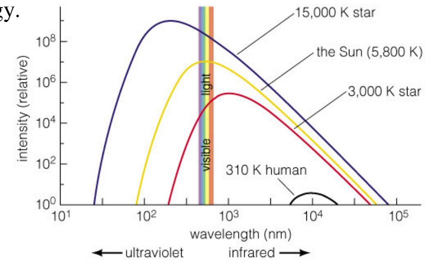
Every object emits ***thermal radiation*** with a spectrum that depends on its temperature



An object of fixed size grows more luminous as its temperature rises

Properties of Thermal Radiation

1. Hotter objects emit more light per unit area at all frequencies.
2. Hotter objects emit photons with a higher average energy.



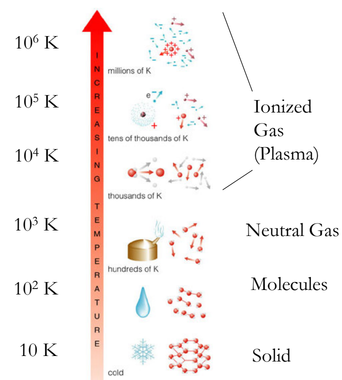
Hottest stars:

50,000 K

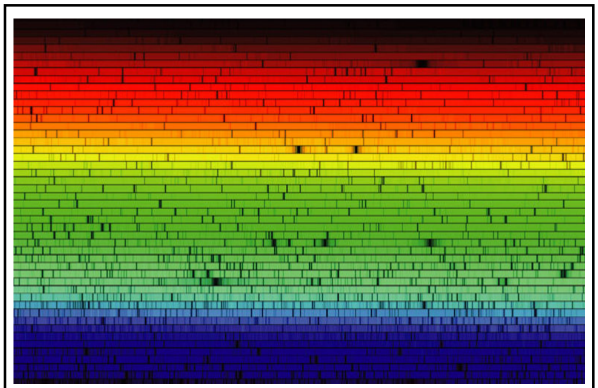
Coolest stars:

3,000 K

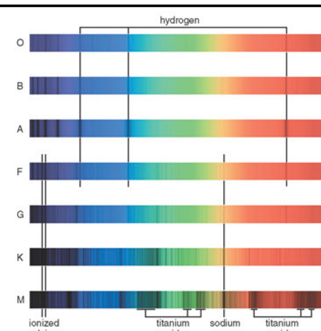
(Sun's surface is 5,800 K)



Level of ionization also reveals a star's temperature



Absorption lines in star's spectrum tell us ionization level



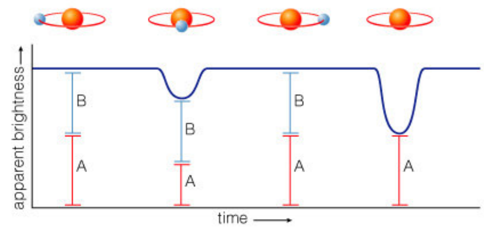
Lines in a star's spectrum correspond to a ***spectral type*** that reveals its temperature

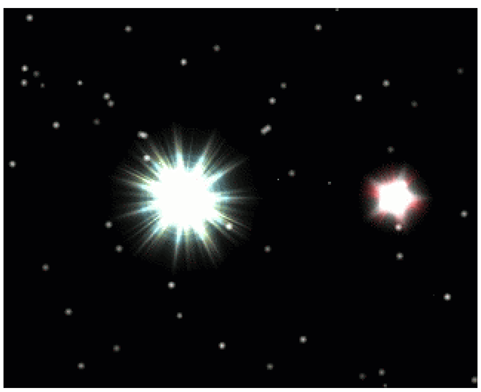
(Hottest) O B A F G K M (Coolest)

Pioneers of Stellar Classification

- Annie Jump Cannon and the “calculators” at Harvard laid the foundation of modern stellar classification

How do we measure stellar masses?





The orbit of a binary star system depends on strength of gravity

Types of Binary Star Systems

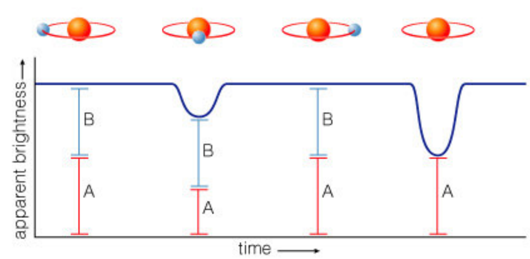
- Visual Binary
- Eclipsing Binary
- Spectroscopic Binary

About half of all stars are in binary systems

Visual Binary

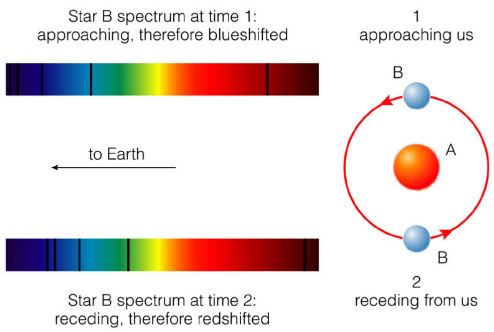
We can directly observe the orbital motions of these stars

Eclipsing Binary



We can measure periodic eclipses

Spectroscopic Binary



We determine the orbit by measuring Doppler shifts

Isaac Newton

We measure mass using gravity

Direct mass measurements are possible only for stars in binary star systems

$$p^2 = \frac{4\pi^2}{G\,(M_1 + M_2)}\,a^3$$

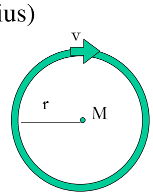
p = period

a = average separation

Need 2 out of 3 observables to measure mass:

1) Orbital Period (p)
2) Orbital Separation (a or r = radius)
3) Orbital Velocity (v)

For circular orbits, $v = 2\pi r / p$



Most massive stars:

$100\ M_{Sun}$

Least massive stars:

$0.08\ M_{Sun}$

(M_{Sun} is the mass of the Sun)

What have we learned?

- How do we measure stellar luminosities?
  - If we measure a star's apparent brightness and distance, we can compute its luminosity with the inverse square law for light
  - Parallax tells us distances to the nearest stars
- How do we measure stellar temperatures?
  - A star's color and spectral type both reflect its temperature

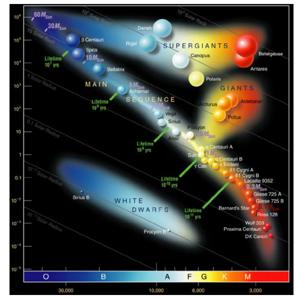
What have we learned?

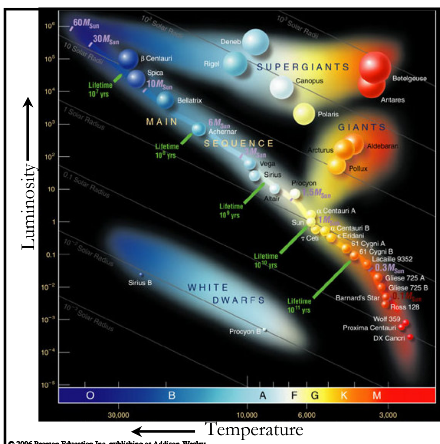
- How do we measure stellar masses?
  - Newton's version of Kepler's third law tells us the total mass of a binary system, if we can measure the orbital period (p) and average orbital separation of the system (a)

15.2 Patterns among Stars

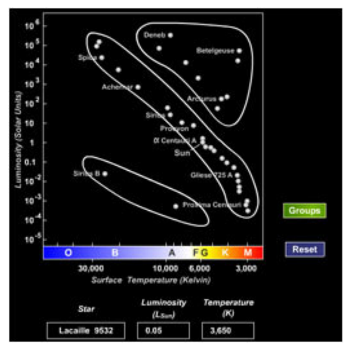
- Our goals for learning
- What is a Hertzsprung-Russell diagram?
- What is the significance of the main sequence?
- What are giants, supergiants, and white dwarfs?
- Why do the properties of some stars vary?

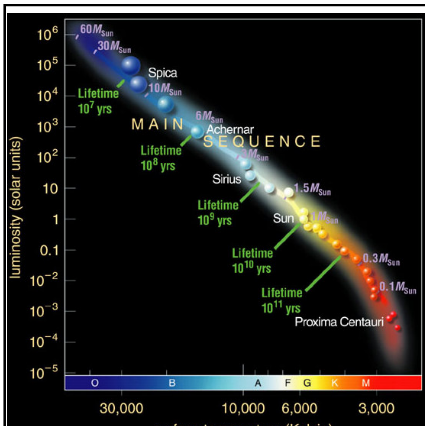
What is a Hertzsprung-Russell diagram?



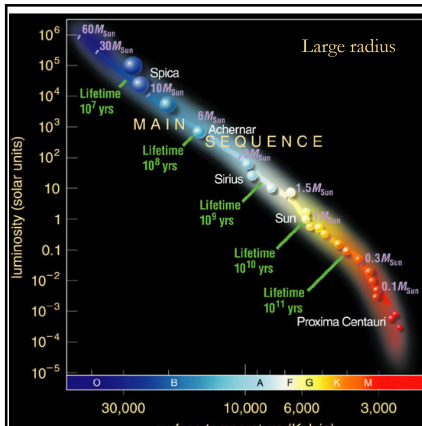


An H-R diagram plots the luminosity and temperature of stars



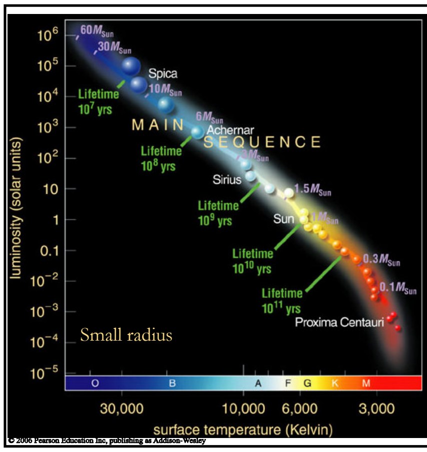


Most stars fall somewhere on the ***main sequence*** of the H-R diagram



Stars with lower *T* and higher *L* than main-sequence stars must have larger radii:

giants and ***supergiants***



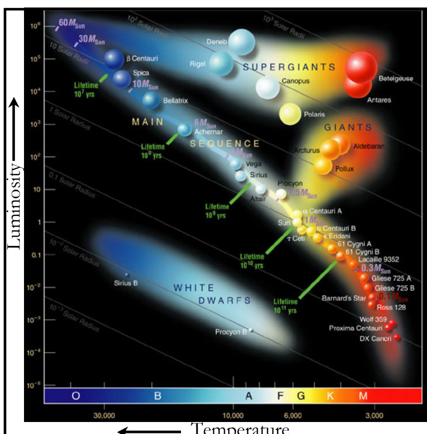
Stars with higher T and lower L than main-sequence stars must have smaller radii:

white dwarfs

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

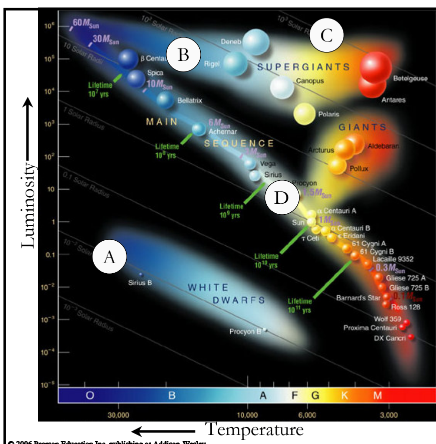
I - supergiant
II - bright giant
III - giant
IV - subgiant
V - main sequence

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

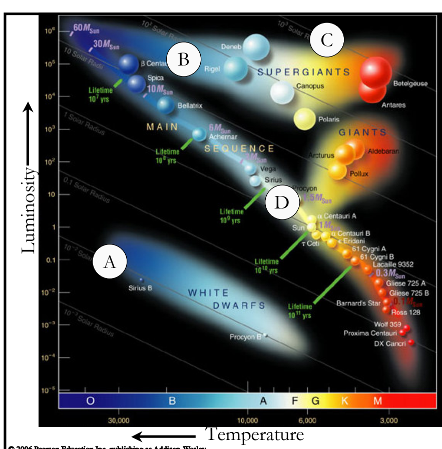


H-R diagram depicts:

Temperature
Color
Spectral Type
Luminosity
Radius

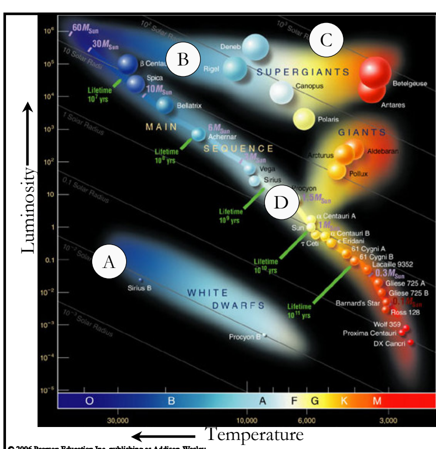


Which star is the hottest?

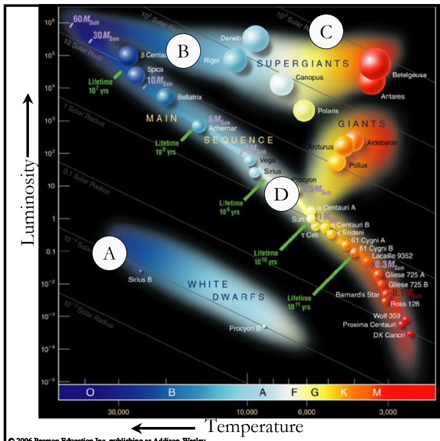


Which star is the hottest?

A

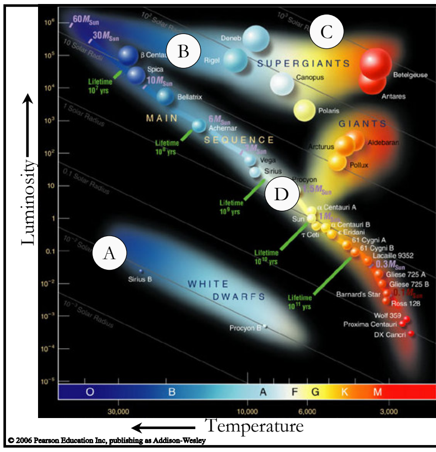


Which star is the most luminous?

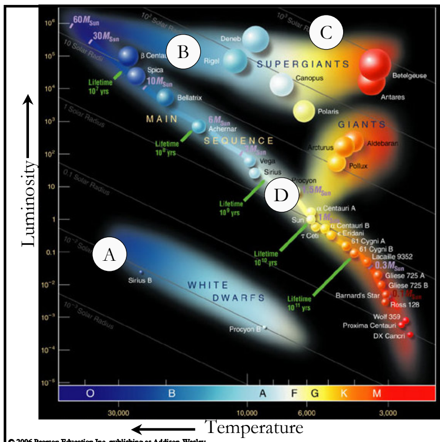


Which star is the most luminous?

C

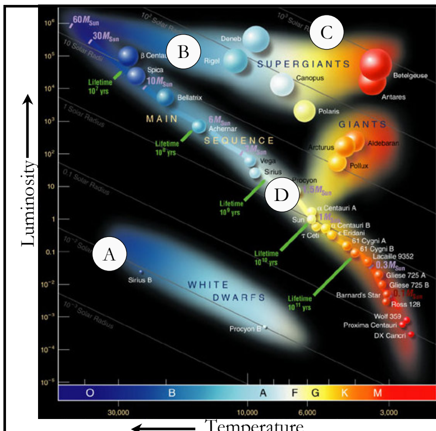


Which star is a main-sequence star?

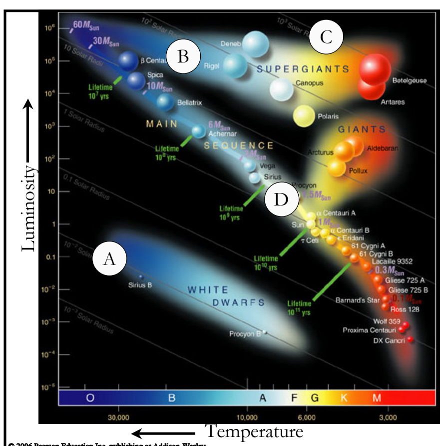


Which star is a main-sequence star?

D



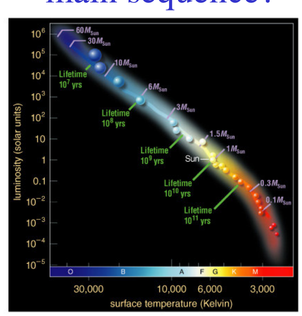
Which star has the largest radius?

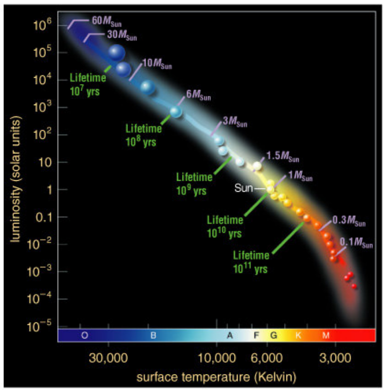


Which star has the largest radius?

C

What is the significance of the main sequence?

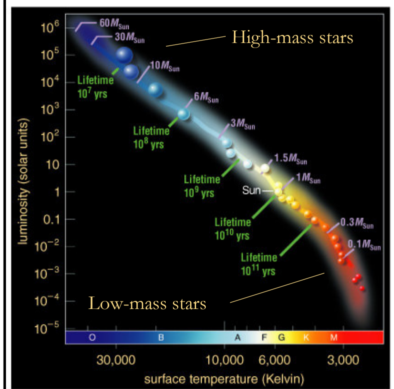




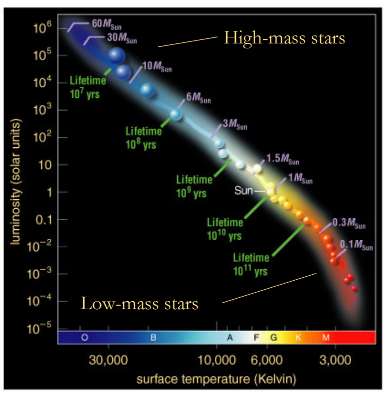
Main-sequence stars are fusing hydrogen into helium in their cores like the Sun

Luminous main-sequence stars are hot (blue)

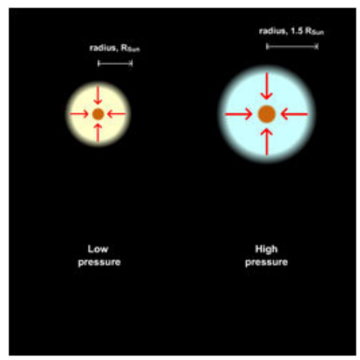
Less luminous ones are cooler (yellow or red)



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



The mass of a normal, hydrogen-burning star determines its luminosity and spectral type!



Core pressure and temperature of a higher-mass star need to be larger in order to balance gravity

Higher core temperature boosts fusion rate, leading to larger luminosity

Stellar Properties Review

Luminosity: from brightness and distance

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

Temperature: from color and spectral type

3,000 K - 50,000 K

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

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

Stellar Properties Review

Luminosity: from brightness and distance

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

Temperature: from color and spectral type

($0.08 M_{Sun}$) 3,000 K - 50,000 K ($100 M_{Sun}$)

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

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

Mass & Lifetime

Sun's life expectancy: 10 billion years

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Until core hydrogen (10% of total) is used up

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Sun's life expectancy: 10 billion years

Until core hydrogen (10% of total) is used up

Life expectancy of 10 M_{Sun} star:

10 times as much fuel, uses it 10^4 times as fast

10 million years ~ 10 billion years x 10 / 10^4

Mass & Lifetime

Sun's life expectancy: 10 billion years

Until core hydrogen (10% of total) is used up

Life expectancy of 10 M_{Sun} star:

10 times as much fuel, uses it 10^4 times as fast

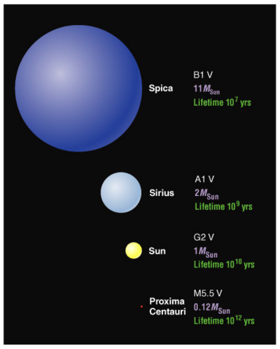
10 million years ~ 10 billion years x 10 / 10^4

Life expectancy of 0.1 M_{Sun} star:

0.1 times as much fuel, uses it 0.01 times as fast

100 billion years ~ 10 billion years x 0.1 / 0.01

Main-Sequence Star Summary



High Mass:

- High Luminosity
- Short-Lived
- Large Radius
- Blue

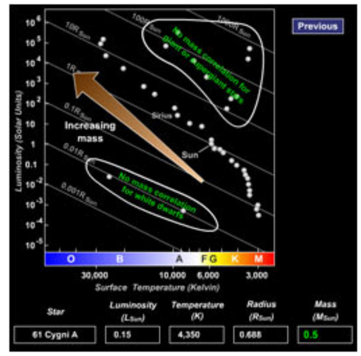
Low Mass:

- Low Luminosity
- Long-Lived
- Small Radius
- Red

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 stars end up small and white after fusion has ceased: **white dwarfs**



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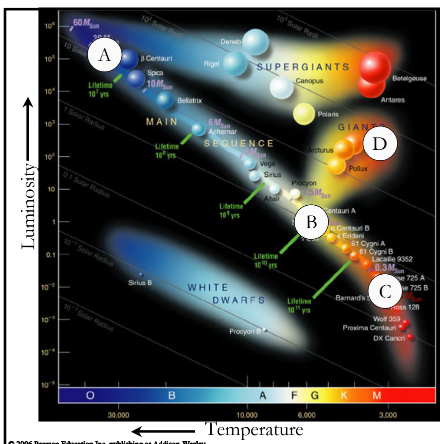

Which star is most like our Sun?

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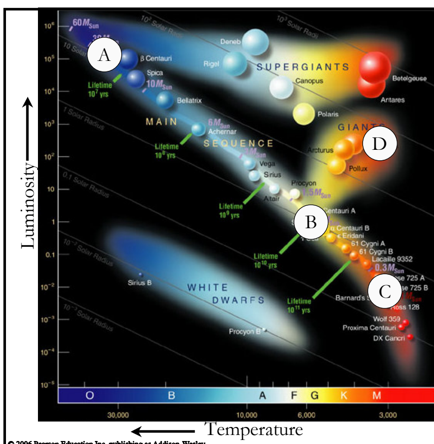

Which star is most like our Sun?

B

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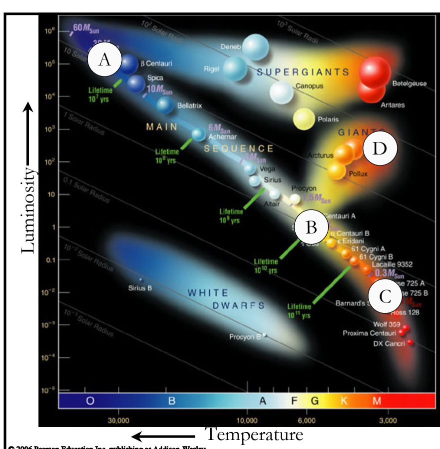

Which of these stars will have changed the least 10 billion years from now?

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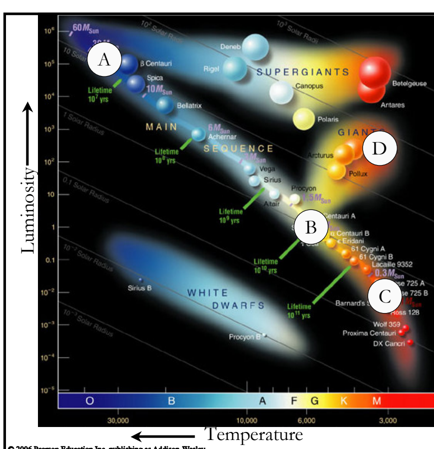

Which of these stars will have changed the least 10 billion years from now?

C

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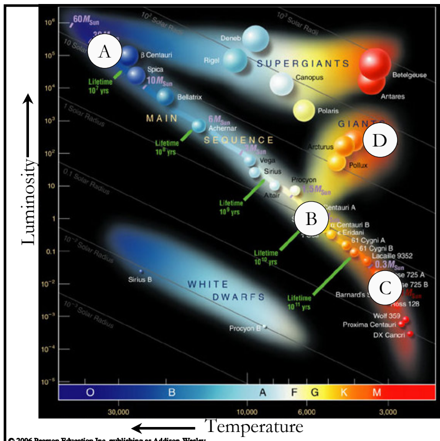
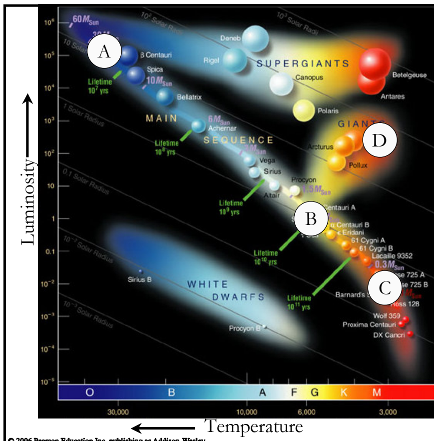


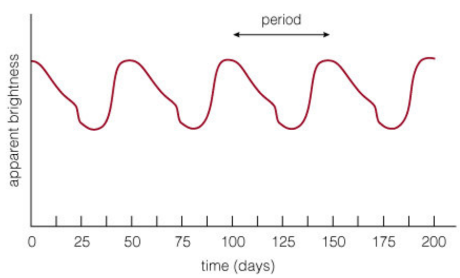
Which of these stars can be no more than 10 million years old?



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

(A)

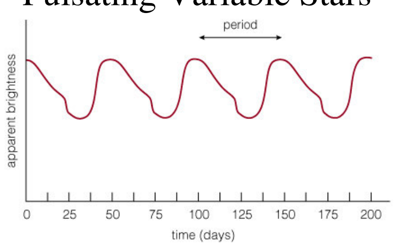
Why do the properties of some stars vary?



Variable Stars

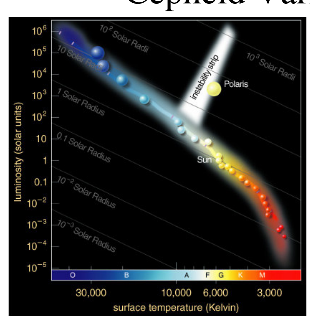
- Any star that varies significantly in brightness with time is called a *variable star*
- Some stars vary in brightness because they cannot achieve proper balance between power welling up from the core and power radiated from the surface
- Such a star alternately expands and contracts, varying in brightness as it tries to find a balance

Pulsating Variable Stars



- The light curve of this *pulsating variable star* shows that its brightness alternately rises and falls over a 50-day period

Cepheid Variable Stars



- Most pulsating variable stars inhabit an *instability strip* on the H-R diagram
- The most luminous ones are known as *Cepheid variables*

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)

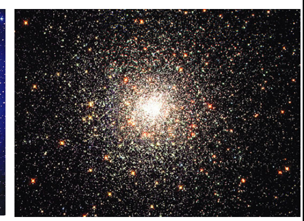
What have we learned?

- 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 do the properties 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?

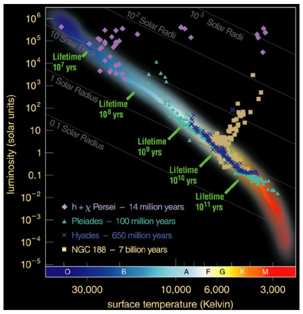
What are the two types of star clusters?

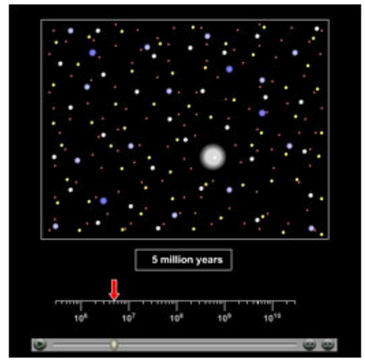



Open cluster: A few thousand loosely packed stars

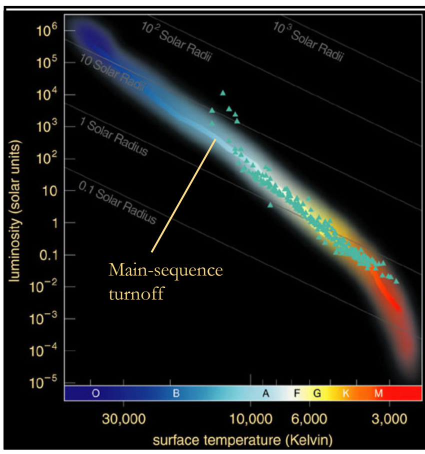
Globular cluster: Up to a million or more stars in a dense ball bound together by gravity

How do we measure the age of a star cluster?

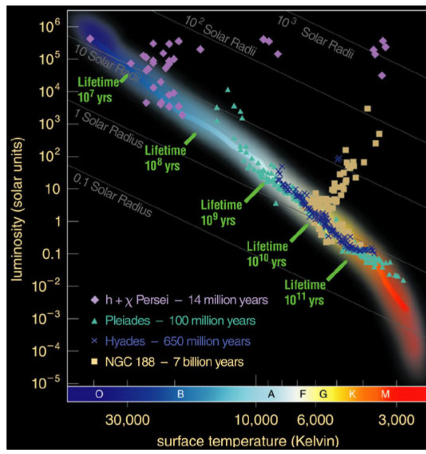




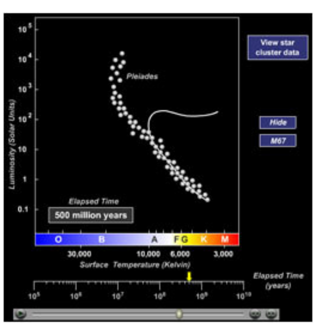
Massive blue stars die first, followed by white, yellow, orange, and red stars



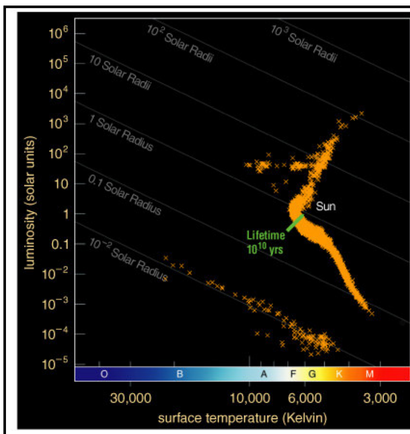
Pleiades now has no stars with life expectancy less than around 100 million years



Main-sequence turnoff point of a cluster tells us its age



To determine accurate ages, we compare models of stellar evolution to the cluster data



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

Lab

- Not just about taking data, and calculating
- Need to be able to **critically** analyze data!
- It's hard!

Three big issues to conquer

1. Uncertainty
   - Precision of a measurement
   - All measurements have uncertainty
2. Error
   - Inaccuracy of a measurement
3. Drawing conclusions