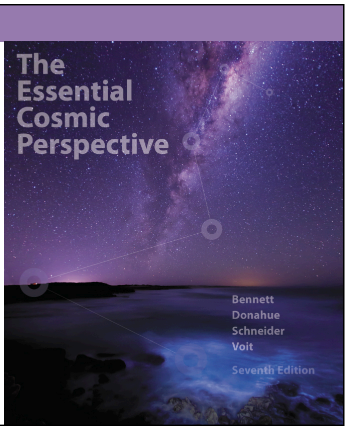
Lecture Outline

Chapter 12: Surveying the Stars

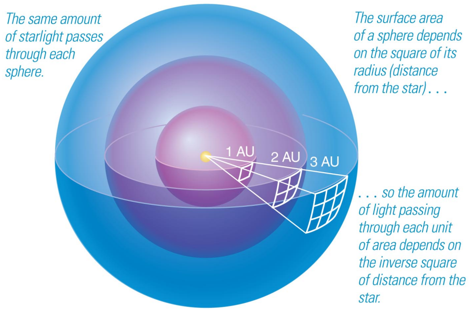


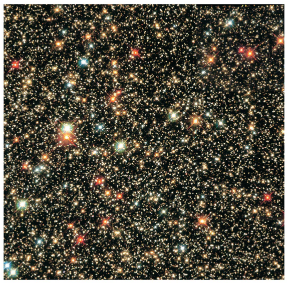
12.1 Properties of Stars

Our goals for learning:

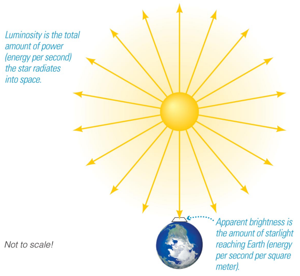
- How do we measure stellar luminosities?
- How do we measure stellar temperatures?
- How do we measure stellar masses?

How do we measure stellar luminosities?





Brightness of a star depends on both distance and luminosity.

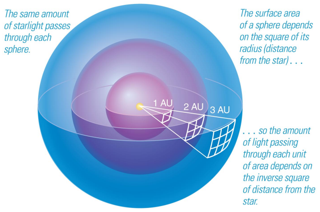


Luminosity:

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

Apparent brightness:

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



Luminosity passing through each sphere is the same.

Area of sphere:
4π (radius)^2

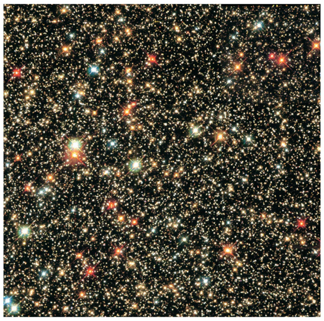
Divide luminosity by area to get brightness.

The relationship between apparent brightness and luminosity depends on distance:

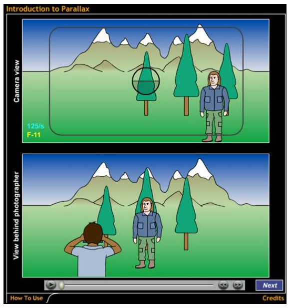
$$\text{Brightness} = \frac{\text{Luminosity}}{4\pi\,(\text{distance})^2}$$

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

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

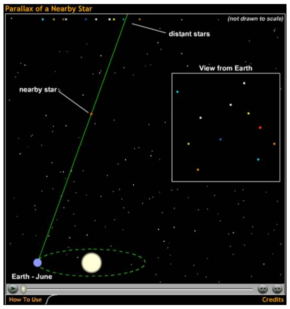


So how far away are these stars?



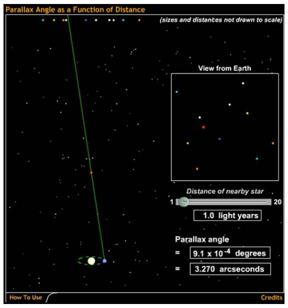
Parallax is the apparent shift in position of a nearby object against a background of more distant objects.

PLAY Introduction to Parallax



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

PLAY Parallax of a Nearby Star



1.0 light years

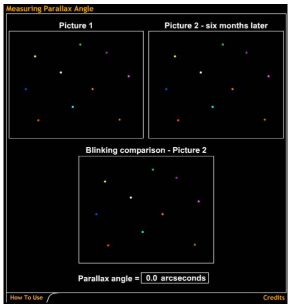
Parallax angle

= 9.1×10^{-4} degrees

= 3.270 arcseconds

The parallax angle depends on distance.

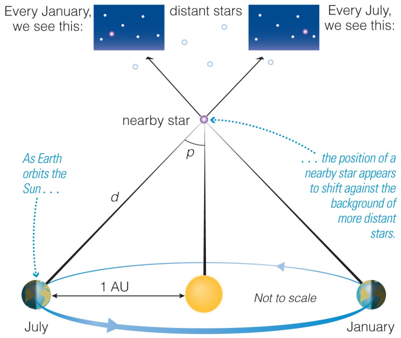
PLAY Parallax Angle as a Function of Distance



Parallax angle = 0.0 arcseconds

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

PLAY Measuring Parallax Angle

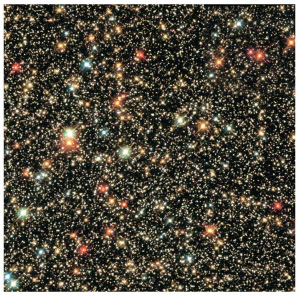


Parallax and Distance

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:

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

Least luminous stars:

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

(L_{Sun} is luminosity of the 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?

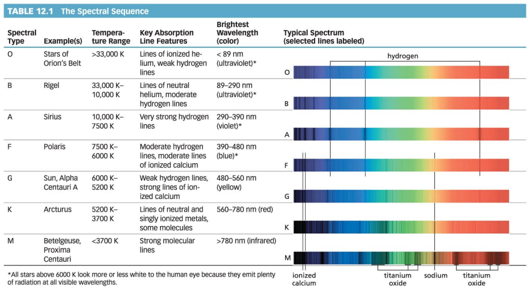
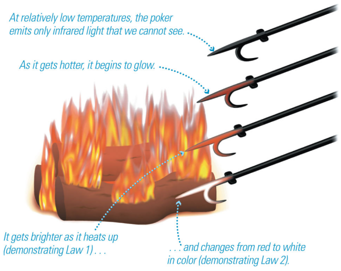


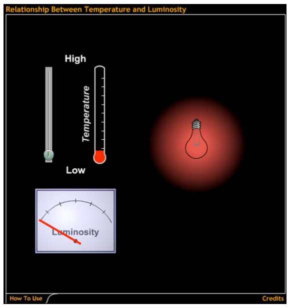
TABLE 12.1 The Spectral Sequence

Spectral Type	Example(s)	Temperature Range	Key Absorption Line Features	Brightest Wavelength (color)	Typical Spectrum (selected lines labeled)
O	Stars of Orion's Belt	>33,000 K	Lines of ionized helium, weak hydrogen lines	< 89 nm (ultraviolet)*	O
B	Rigel	33,000 K–10,000 K	Lines of neutral helium, moderate hydrogen lines	89–290 nm (ultraviolet)*	B
A	Sirius	10,000 K–7500 K	Very strong hydrogen lines	290–390 nm (violet)*	A
F	Polaris	7500 K–6000 K	Moderate hydrogen lines, moderate lines of ionized calcium	390–480 nm (blue)*	F
G	Sun, Alpha Centauri A	6000 K–5200 K	Weak hydrogen lines, strong lines of ionized calcium	480–560 nm (yellow)	G
K	Arcturus	5200 K–3700 K	Lines of neutral and singly ionized metals, some molecules	560–780 nm (red)	K
M	Betelgeuse, Proxima Centauri	<3700 K	Strong molecular lines	>780 nm (infrared)	M

*All stars above 6000 K look more or less white to the human eye because they emit plenty of radiation at all visible wavelengths.



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

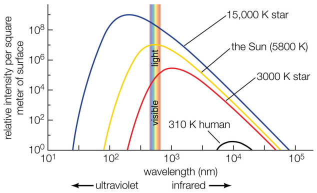


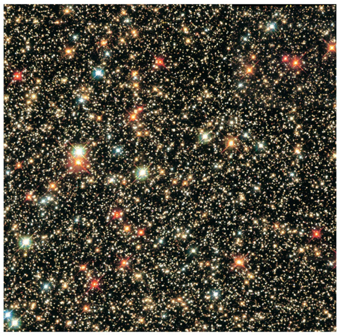
An object of fixed size grows more luminous as its temperature rises.

PLAY Relationship Between Temperature and Luminosity

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.





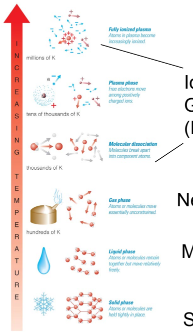
Hottest stars:

50,000 K

Coolest stars:

3000 K

(Sun's surface is 5800 K)



10^6 K

10^5 K

10^4 K

10^3 K

10^2 K

10 K

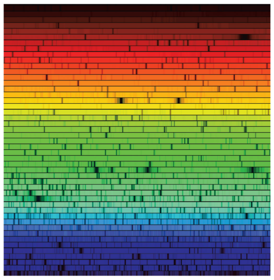
Ionized Gas (Plasma)

Neutral Gas

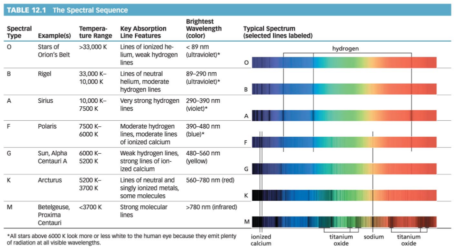
Molecules

Solid

Level of ionization also reveals a star's temperature.



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



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*All stars above 6000 K look more or less white to the human eye because they emit plenty of radiation at all visible wavelengths.

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

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

Remembering Spectral Types

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

- Oh, Be A Fine Girl/Guy, Kiss Me

Thought Question

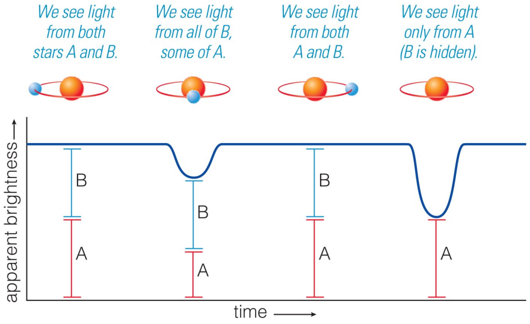
Which of the stars below is hottest?

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

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?



Binary Star Orbits

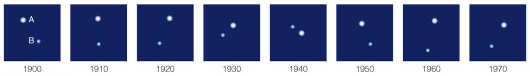
Orbit of a binary star system depends on the strength of gravity.

Types of Binary Star Systems

- Visual binary
- Eclipsing binary
- Spectroscopic binary

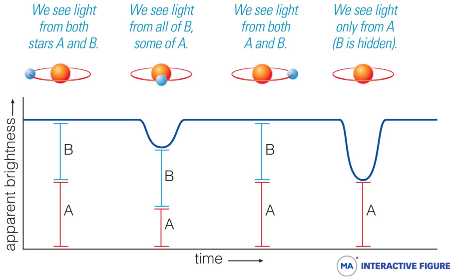
About half of all stars are in binary systems.

Visual Binary



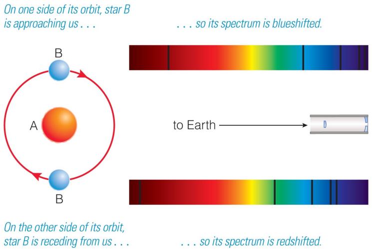
We can directly observe the orbital motions of these stars.

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.

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

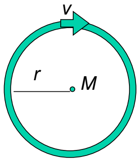
p = period

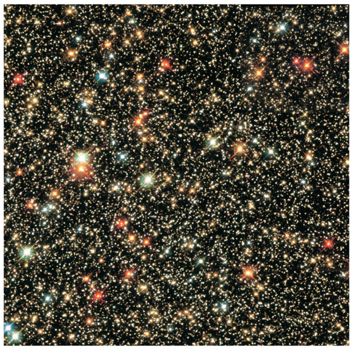
a = average separation

Need two out of three observables to measure mass:

1. Orbital period (p)
2. Orbital separation (a or r = radius)
3. Orbital velocity (v)

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





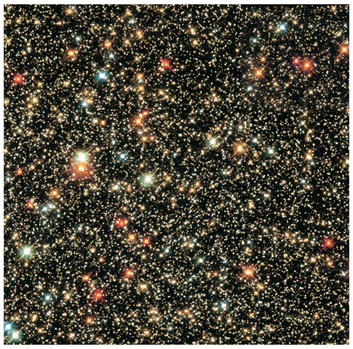
Most massive stars:

$100M_{Sun}$

Least massive stars:

$0.08M_{Sun}$

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



Most massive stars:

$100M_{\text{Sun}}$

(some very rare stars may have $> 100\ M_{\text{Sun}}$)

Least massive stars:

$0.08M_{\text{Sun}}$

(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?

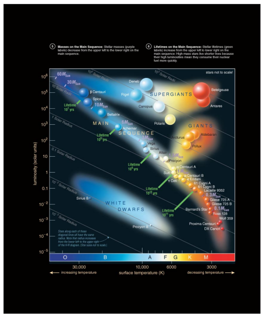
- How do we measure stellar masses?
  - Newton's version of Kepler's third law tells us the total mass of a binary system, if we can measure the orbital period (*p*) and average orbital separation of the system (*a*).

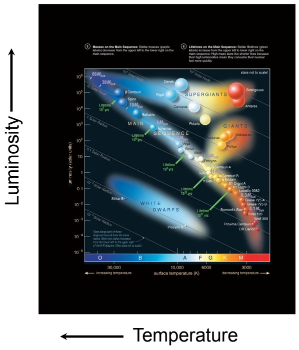
12.2 Patterns Among Stars

Our goals for learning:

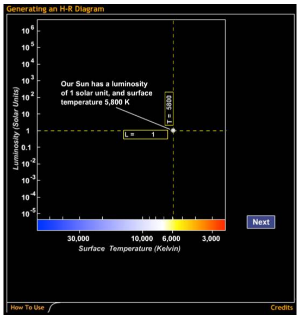
- What is a Hertzsprung–Russell diagram?
- What is the significance of the main sequence?
- What are giants, supergiants, and white dwarfs?

What is a Hertzsprung–Russell diagram?

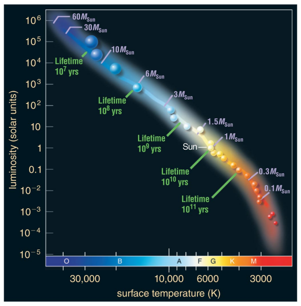




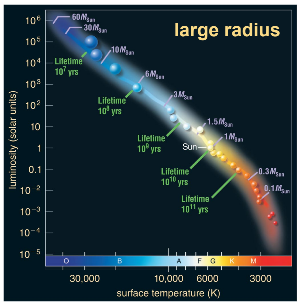
An H-R diagram plots the luminosities and temperatures of stars.



PLAY Generating an H-R Diagram

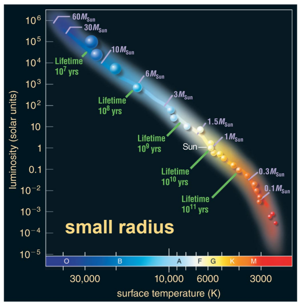


Most stars fall somewhere on the ***main sequence*** of the H-R diagram.



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

giants and ***supergiants***



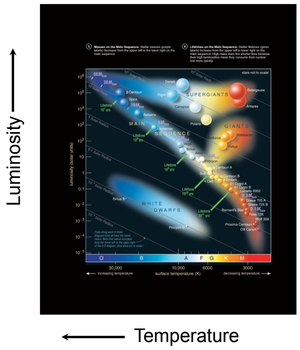
Stars with higher *T* and lower *L* than main-sequence stars must have smaller radii:

white dwarfs

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

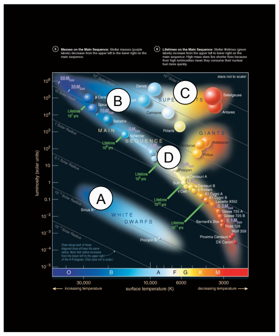
I — supergiant
II — bright giant
III — giant
IV — subgiant
V — main sequence

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

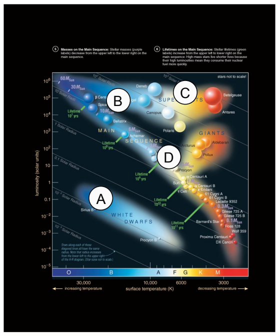


H-R diagram depicts:

Temperature
Color
Spectral type
Luminosity
Radius

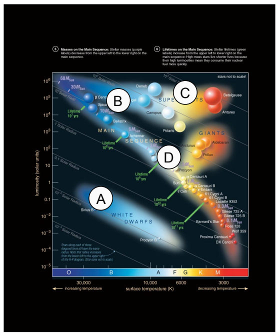


Which star is the hottest?

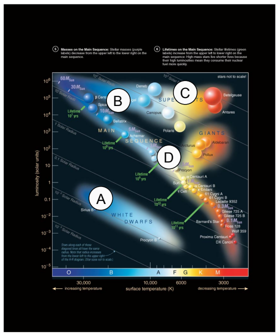


Which star is the hottest?

Ⓐ

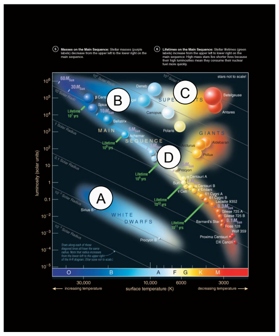


Which star is the most luminous?

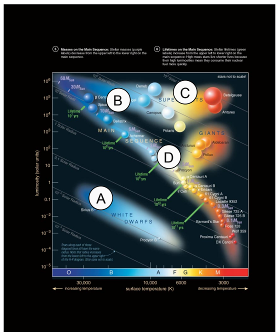


Which star is the most luminous?

Ⓒ

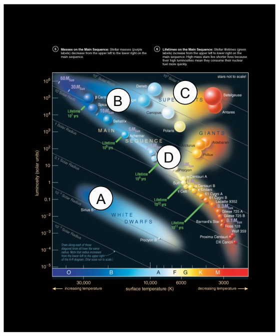


Which star is a main-sequence star?

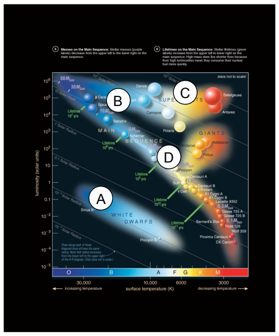


Which star is a main-sequence star?

Ⓓ



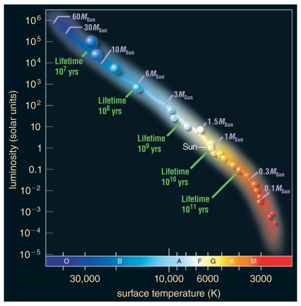
Which star has the largest radius?

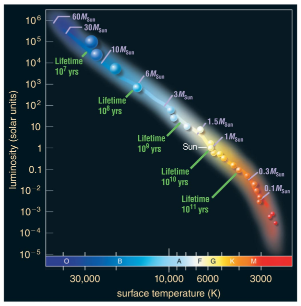


Which star has the largest radius?

Ⓒ

What is the significance of the main sequence?

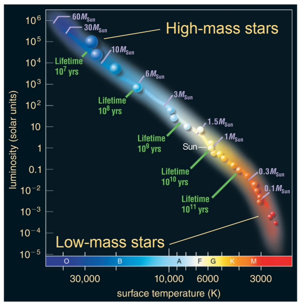




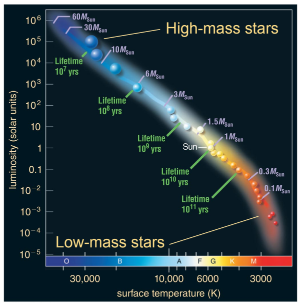
Main-sequence stars are fusing hydrogen into helium in their cores, like the Sun.

Luminous main-sequence stars are hot (blue).

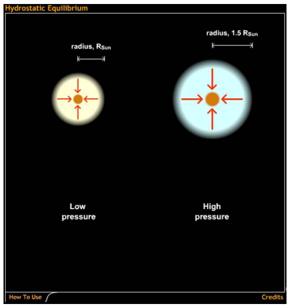
Less luminous ones are cooler (yellow or red).



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-fusing star determines its luminosity and spectral type.



The core temperature of a higher-mass star needs to be higher in order to balance gravity.

A higher core temperature boosts the fusion rate, leading to greater luminosity.

PLAY Hydrostatic Equilibrium

Stellar Properties Review

Luminosity: from 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

$0.08M_{Sun} – 100M_{Sun}$

Stellar Properties Review

Luminosity: from brightness and distance

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

Temperature: from color and spectral type

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

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

$0.08M_{Sun} – 100M_{Sun}$

Mass and Lifetime

Sun's life expectancy: 10 billion years

Mass and Lifetime

Sun's life expectancy: 10 billion years

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

Mass and Lifetime

Sun's life expectancy: 10 billion years

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

Life expectancy of a $10M_{Sun}$ star:

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

10 million years ~ 10 billion years × $10/10^4$

Mass and Lifetime

Sun's life expectancy: 10 billion years

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

Life expectancy of a 10M_{Sun} star:

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

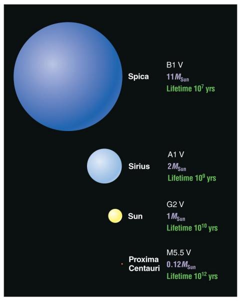
10 million years ~ 10 billion years × 10/10^4

Life expectancy of a 0.1M_{Sun} star:

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

100 billion years ~ 10 billion years × 0.1/0.01

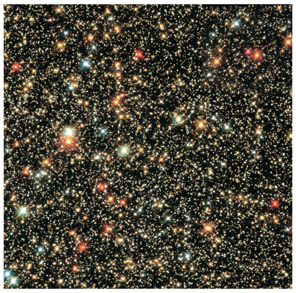
Main-Sequence Star Summary



High-mass:
High luminosity
Short-lived
Large radius
Blue

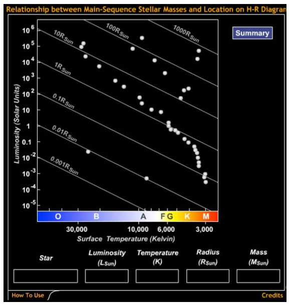
Low-mass:
Low luminosity
Long-lived
Small radius
Red

What are giants, supergiants, and white dwarfs?

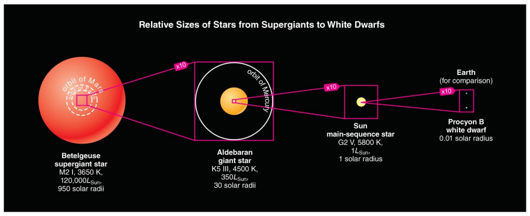


Off the Main Sequence

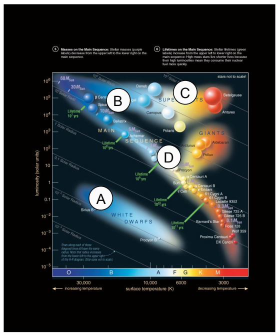
- Stellar properties depend on both mass and age: those that have finished fusing H to He in their cores are no longer on the main sequence.
- All stars become larger and redder after exhausting their core hydrogen: **giants** and **supergiants.**
- Most stars end up small and white after fusion has ceased: **white dwarfs.**



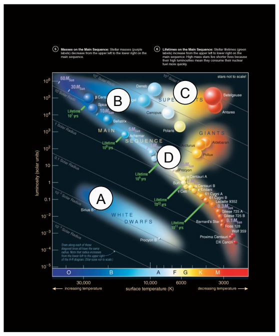
PLAY Relationship Between Main-Sequence Stellar Masses and Location on H-R Diagram



Giants and supergiants are far larger than main-sequence stars and white dwarfs.

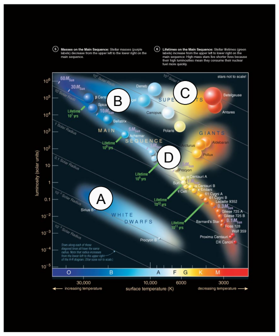


Which star is most like our Sun?

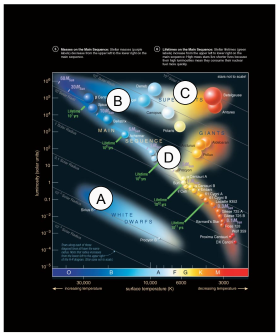


Which star is most like our Sun?

Ⓓ



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?

Ⓐ

What have we learned?

- What is a Hertzsprung–Russell diagram?
  - An H-R diagram plots the 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?

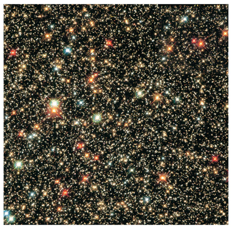
- What are giants, supergiants, and white dwarfs?
  - All stars become larger and redder after core hydrogen is exhausted: **giants** and **supergiants.**
  - Most stars end up as tiny **white dwarfs** after fusion has ceased.

12.3 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

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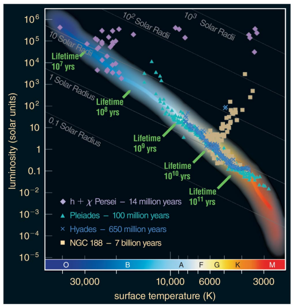
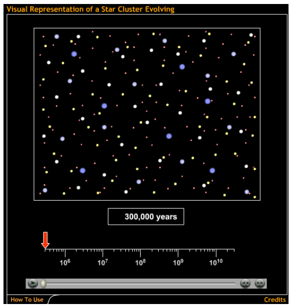
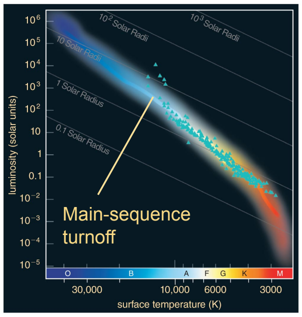
How do we measure the age of a star cluster?



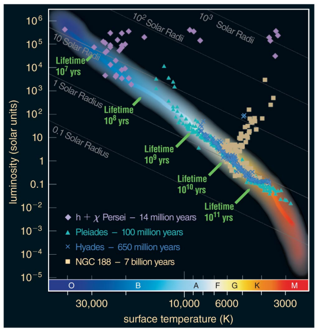


Massive blue stars die first, followed by white, yellow, orange, and red stars.

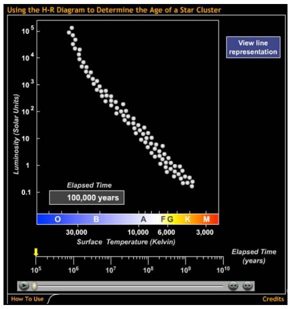
PLAY Visual Representation of a Star Cluster Evolving



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

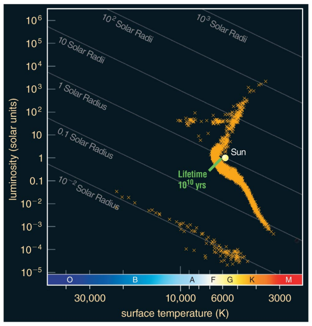


The main-sequence turnoff point of a cluster tells us its age.



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

PLAY Using the H-R Diagram to Determine the Age of a Star Cluster



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.