Lecture 14 -
Understanding the Properties of Stars

Properties of Stars

Stars have much in common with our Sun:

They formed from great clouds of gas and dust.

Roughly the same chemical composition.

Nevertheless, stars differ in size, age, brightness, and temperature. These differences come down to essentially three fundamental properties:

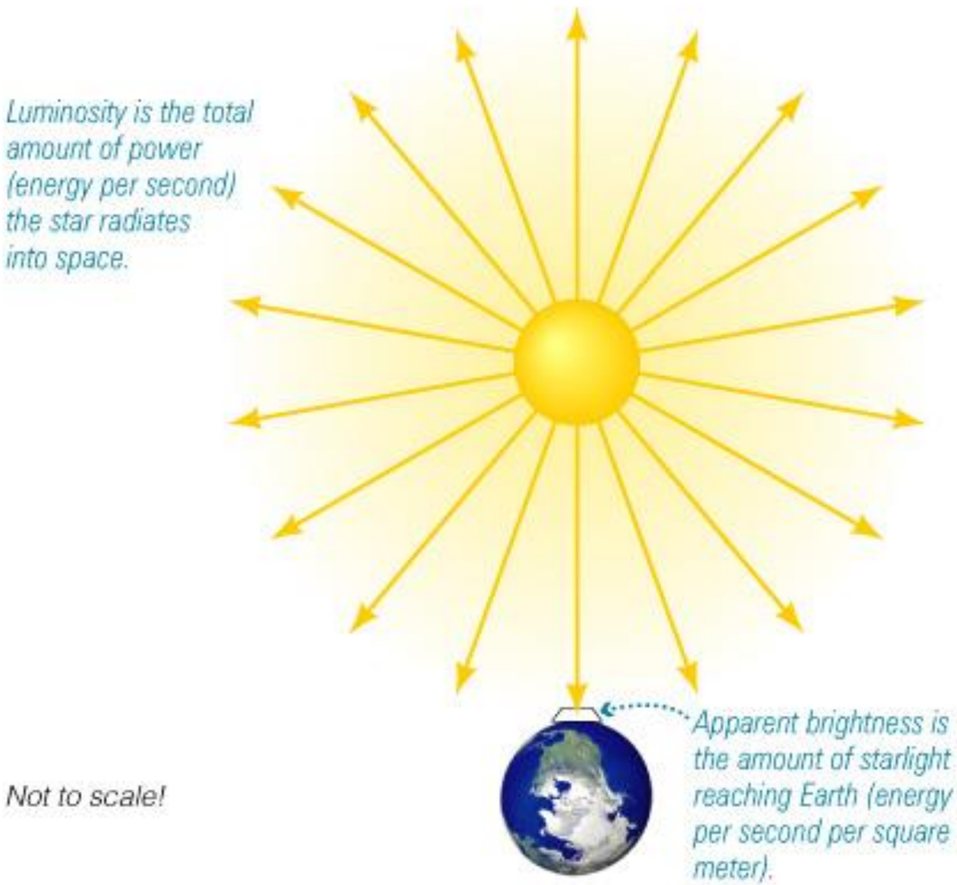
Luminosity

Surface Temperature

Mass

How do we measure stellar **luminosities**?

Luminosity vs apparent brightness

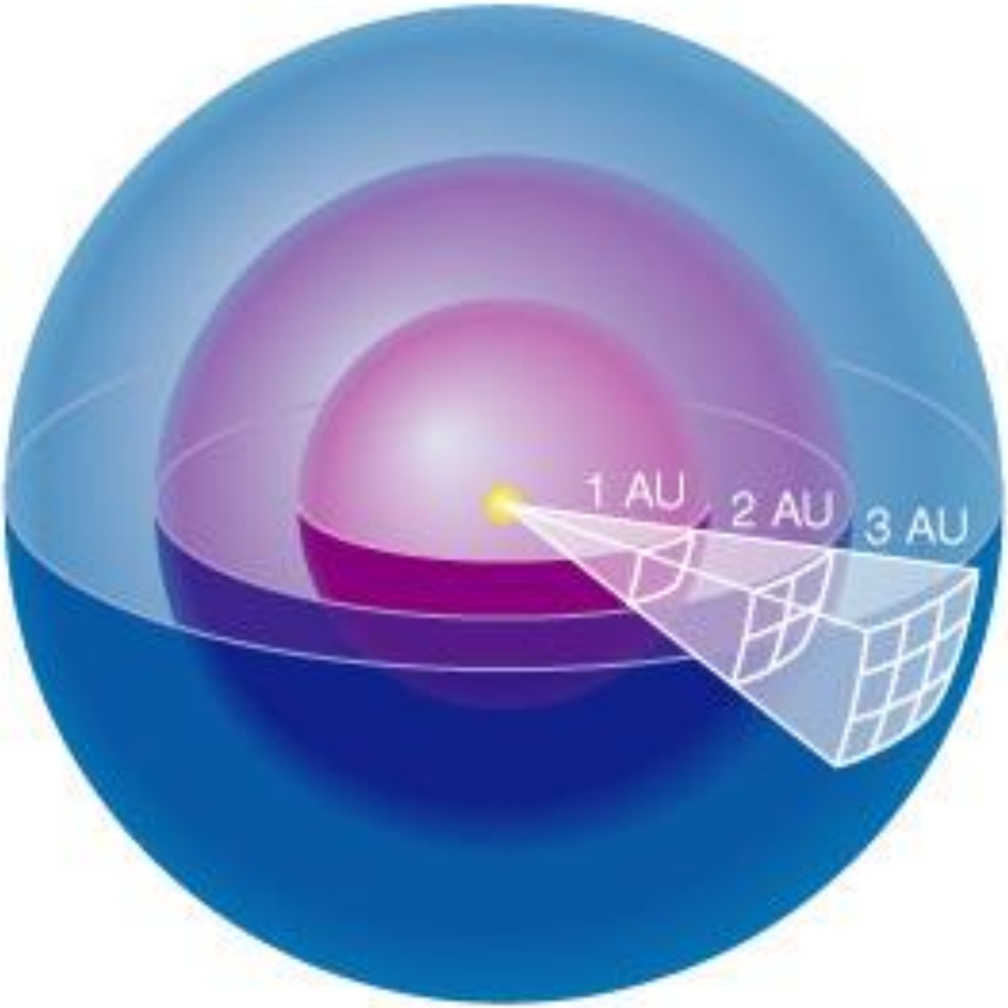


Luminosity:
Total amount of radiative power a star emits.

Brightness:
Amount of radiative power that reaches Earth

Brightness of a star depends on both *distance* and *luminosity*.

The Inverse Square Law of Light



Area of sphere = 4π (radius)^2

- Luminosity passing through each sphere is same.
- Divide luminosity by area to get brightness.
- *Brightness decreases as inverse square of distance.*

Luminosity / brightness / distance

• *The relationship between apparent brightness and luminosity depends on distance*:

$$\textbf{Brightness} = \frac{\textbf{luminosity}}{4\pi\,(\textbf{distance})^2}$$

(Inverse square law)

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

$$\textbf{Luminosity} = 4\pi\,(\textbf{distance})^2 \times (\textbf{brightness})$$

• We can determine distance if we know luminosity and brightness:

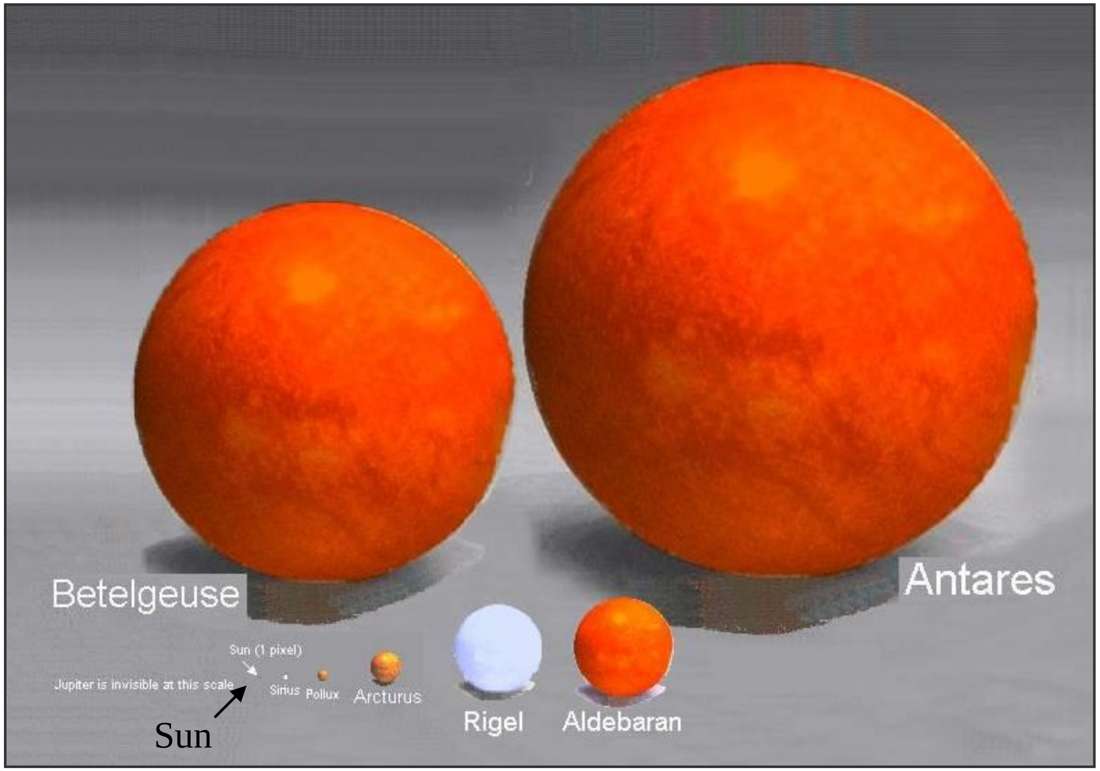
$$\textbf{Distance} = \sqrt{\textbf{luminosity} / (4\pi)\ \textbf{brightness}}$$

Stellar luminosity

Most luminous stars: 10^6 L_{Sun}

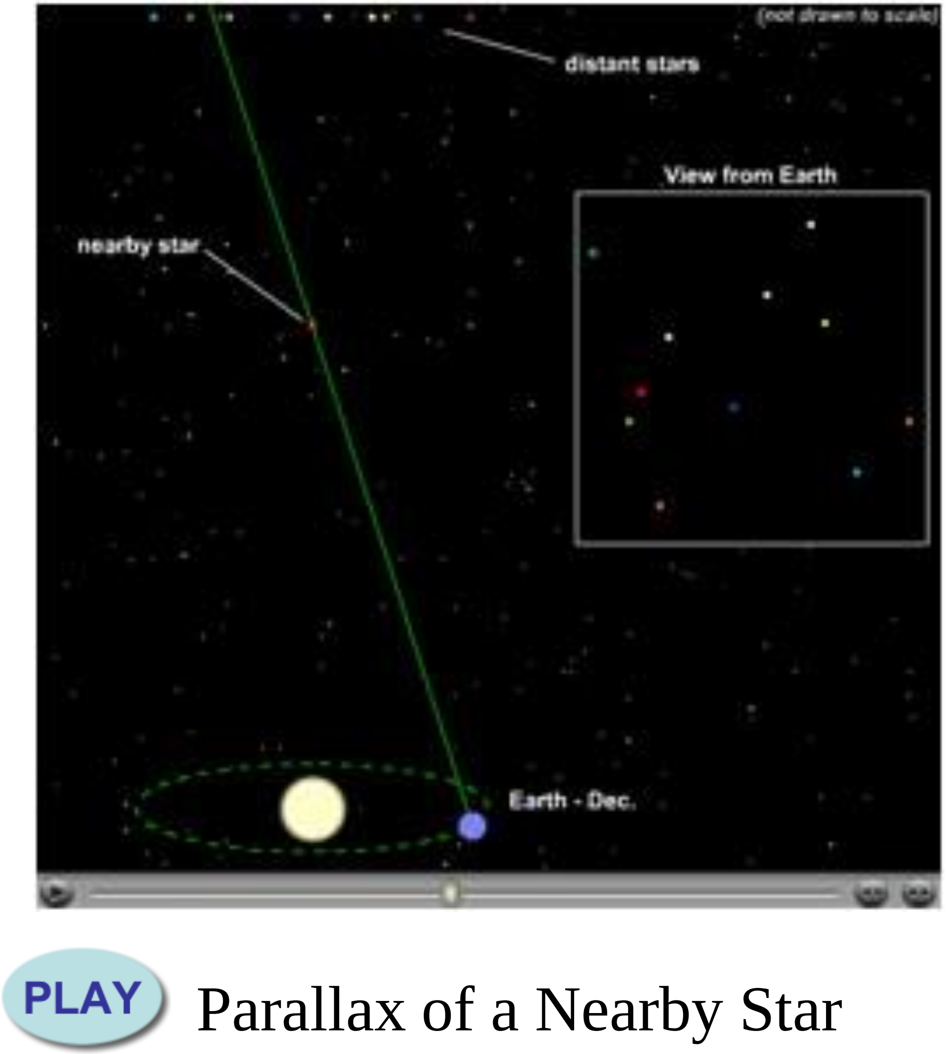
Least luminous stars: 10^{-4} L_{Sun}

(L_{Sun} is luminosity of Sun)



How do we measure stellar **distances**?

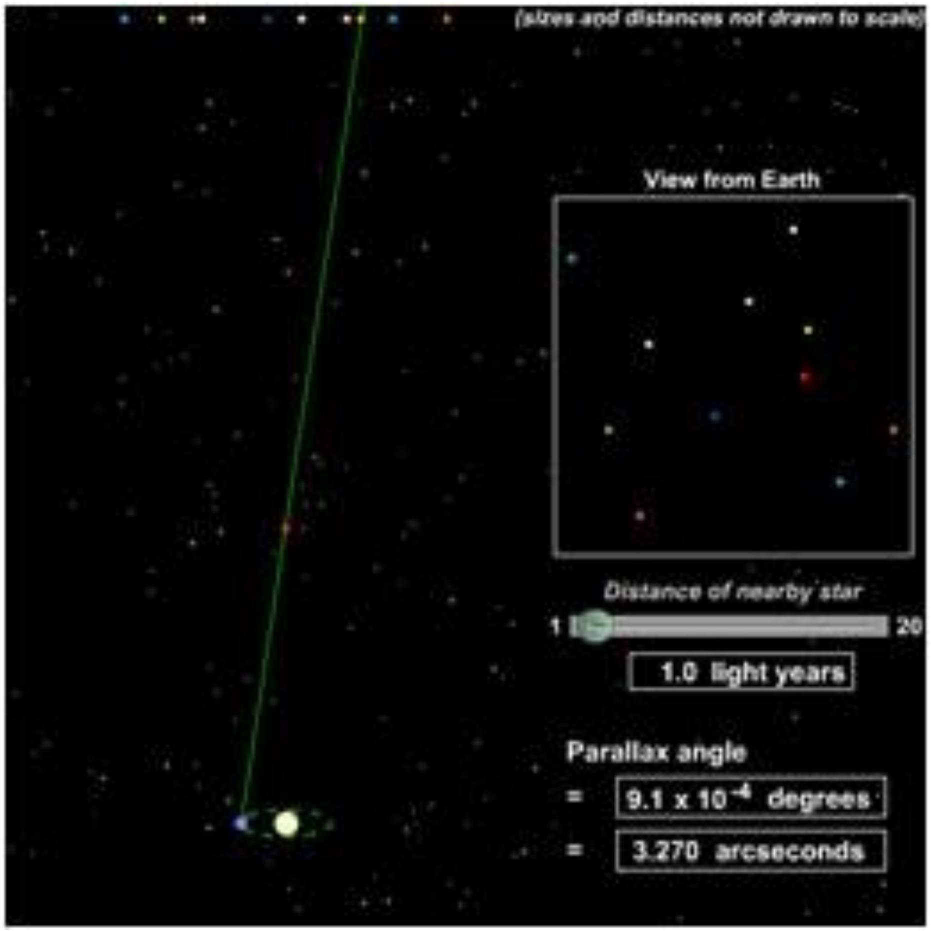
Finding the distance to the stars



Parallax of a Nearby Star

Parallax -
The apparent positions of the nearest stars shift by less than an arcsecond as Earth orbits the Sun.

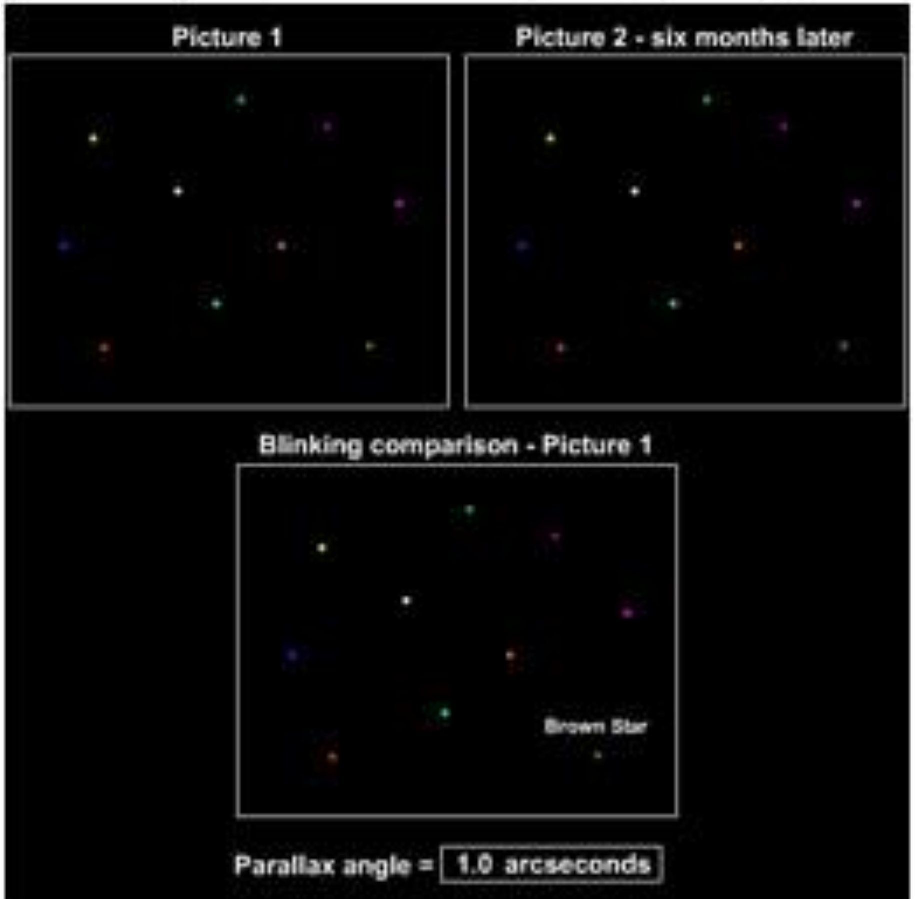
Finding the distance to the stars



The parallax angle depends on distance.

PLAY Parallax Angle as a Function of Distance

Finding the distance to the stars



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

PLAY Measuring Parallax Angle

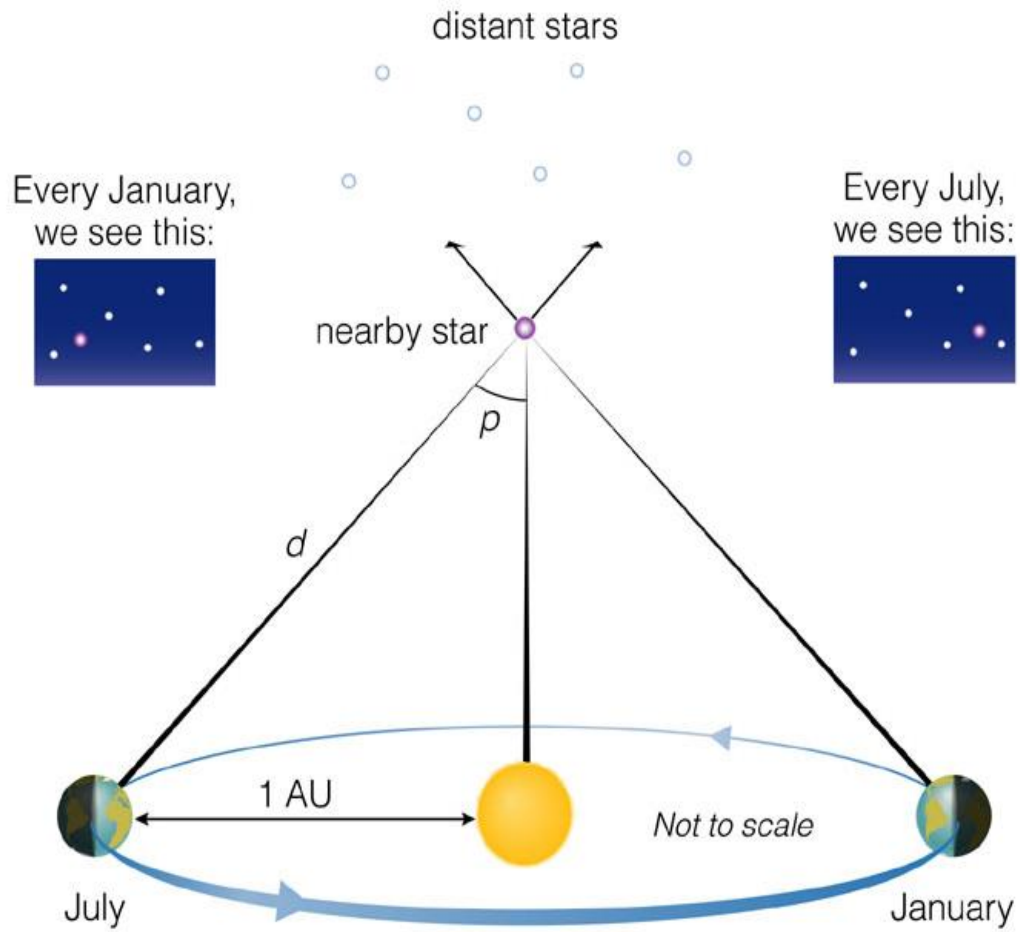
Parallax

Determining distance from parallax angle:

p = parallax angle

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

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



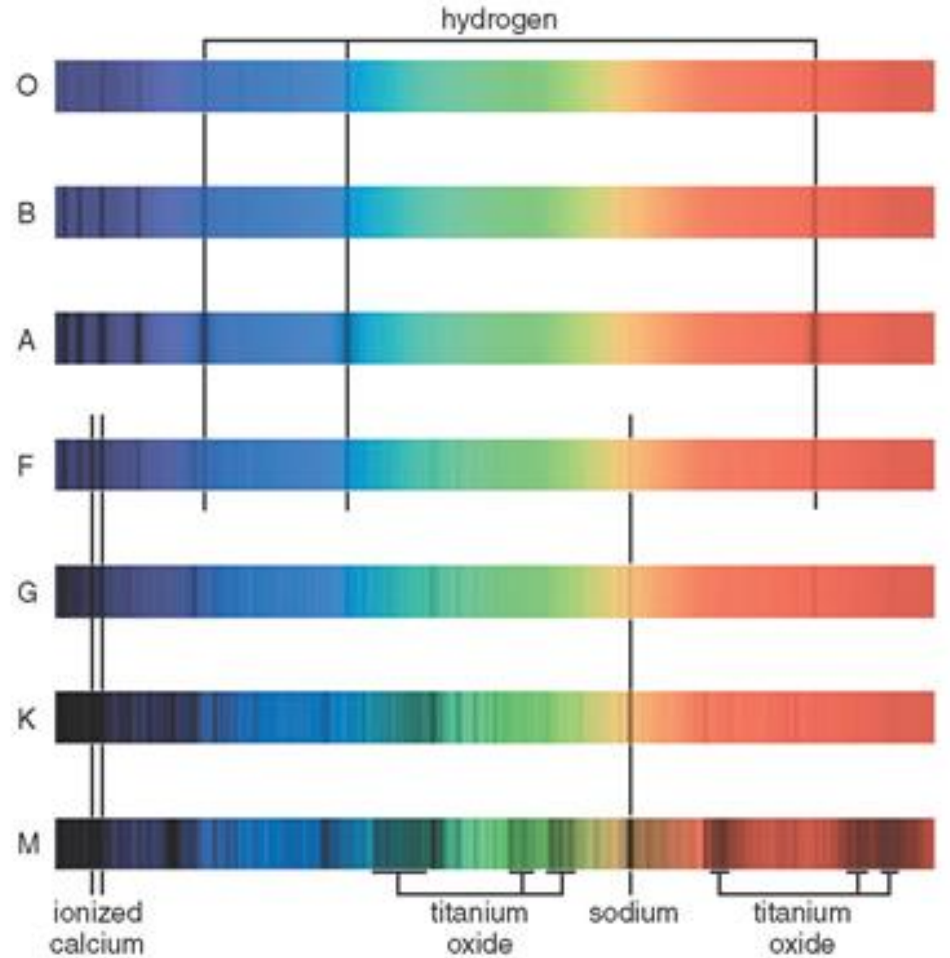
If we know distance from parallax, we can determine luminosity from brightness!

How do we measure stellar temperatures?

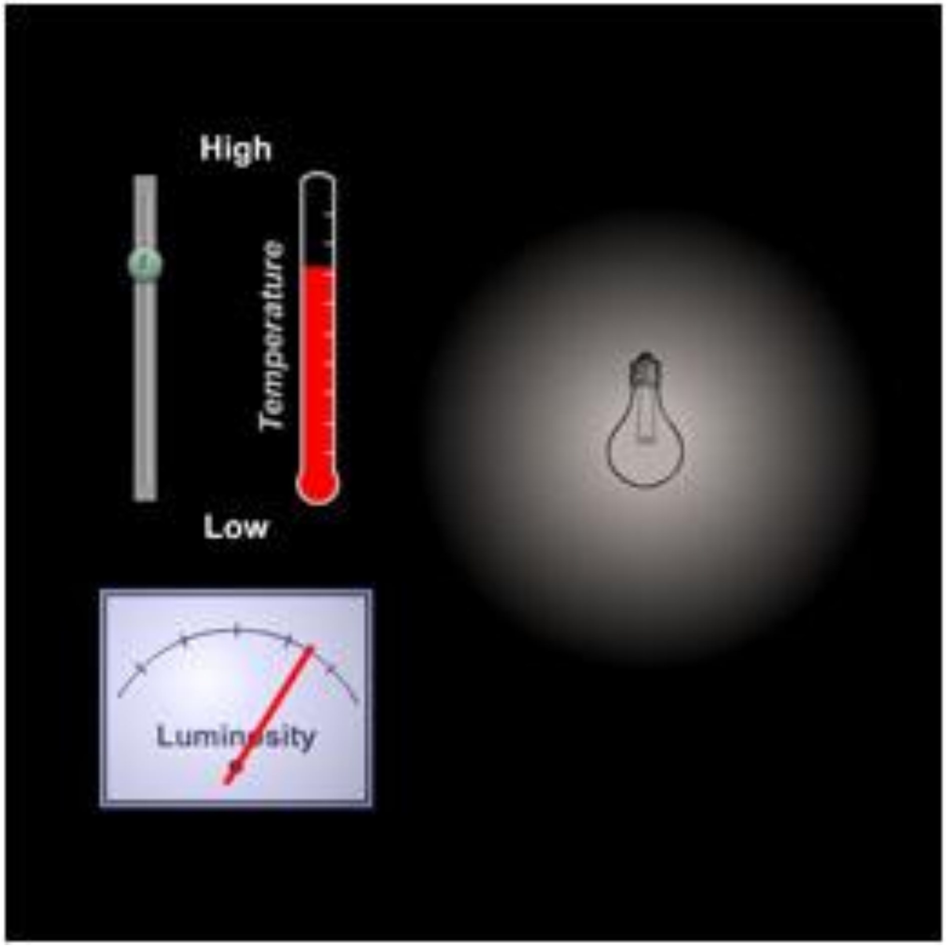
Spectroscopy

•Every star emits light with a (1) **color**, (2) **spectrum**, and (3) **peak wavelength** that *depends on its temperature*.

•We can measure temperature in any of these ways.



Temperature and Luminosity

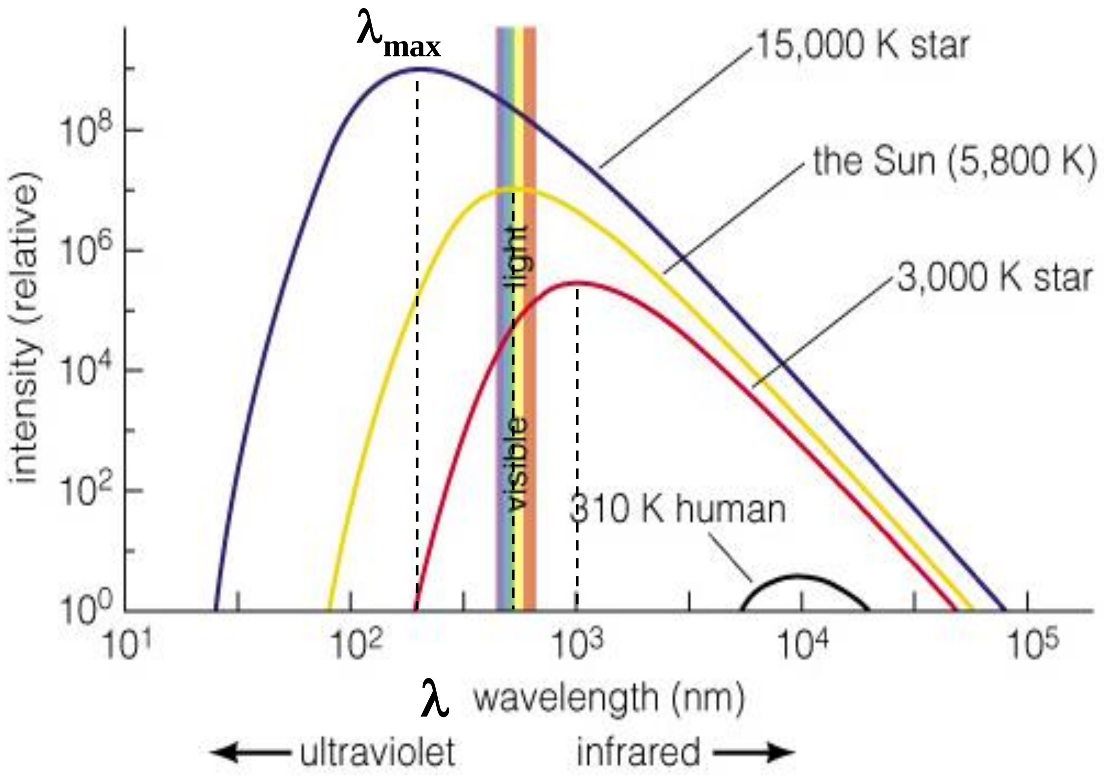


An object of fixed size grows more luminous as its temperature rises.

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.



<u>Wien's Law:</u>

λ_{max} **= 2.9 x 10^6 / T** or

T = 2.9 x 10^6 / λ_{max}

Hottest stars: 50,000 K

Sun's temp: 5,800 K

Coolest stars: 3,000 K

Stellar temperature from color

“B-V“ color index: difference between blue and yellow magnitudes.

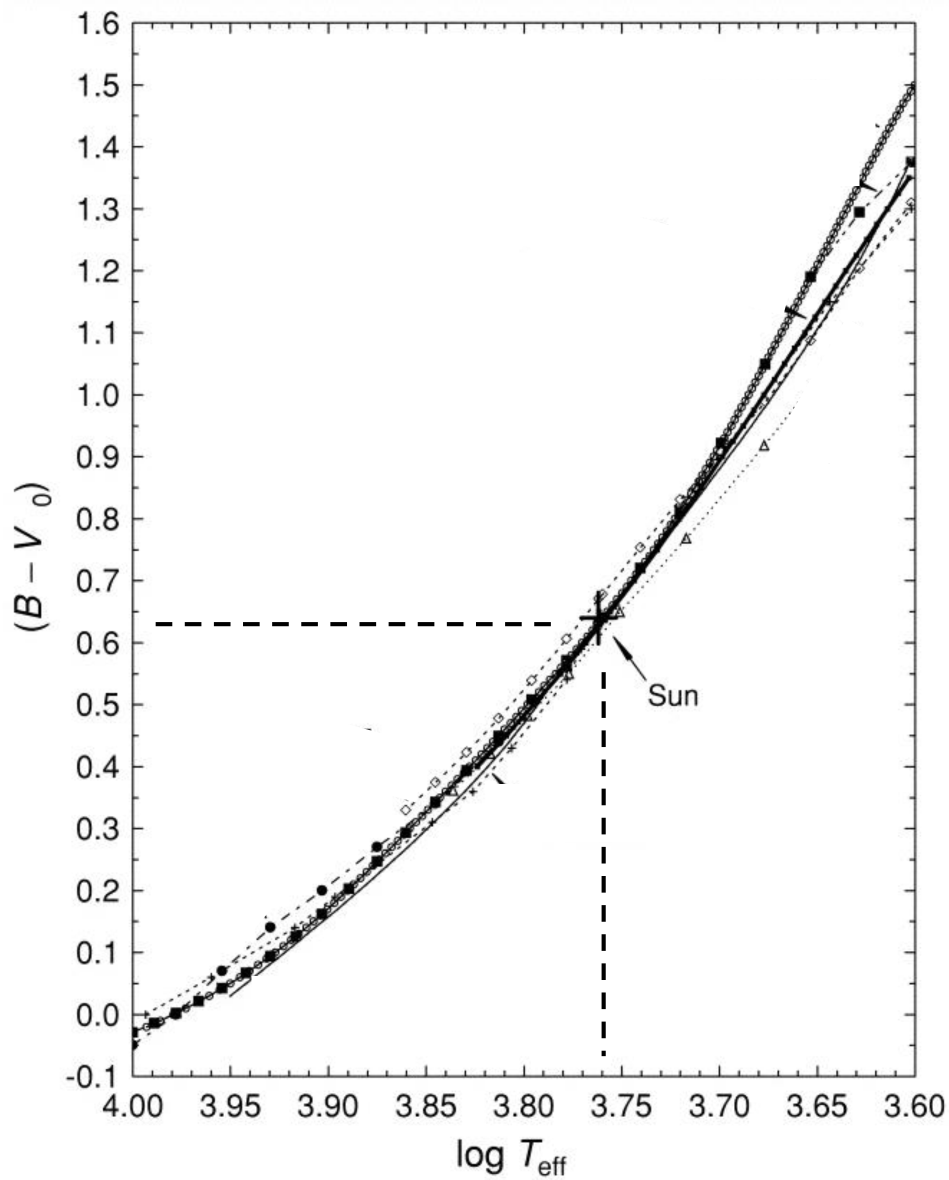
There is a simple relationship between the “B-V“ color index and temperature shown at right.

To determine temperature of a star: measure the brightness in **blue** and **visual** light, apply formula to turn difference (B-V *color index*) into temperature.

This is much faster (though less accurate) than taking the spectrum of each star individually.

In this example, the Sun has a B-V = 0.64 which indicates a temperature of about 5770 K.

Graph from Sekiguchi and Fukugita,
Astronomical Journal, Vol 120, p1072, (2000)

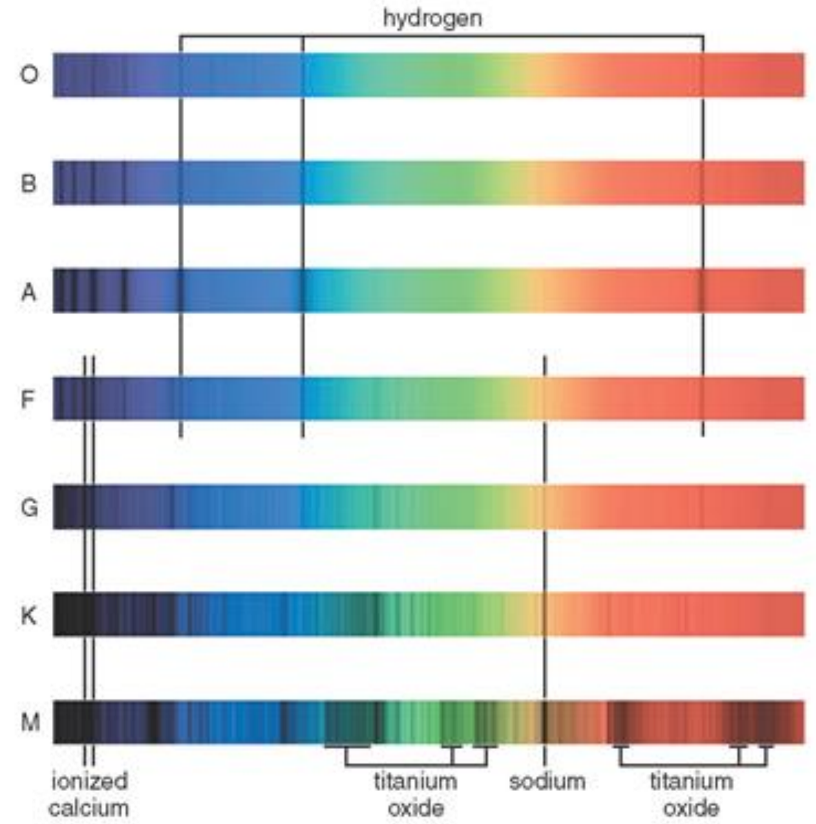


Spectral type

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

• Lines of ionized elements indicate high temperature, lines of molecules indicate cooler stars.

• **Stars are classified by spectral type (temperature).**



The Spectral Sequence
(Hottest) O B A F G K M (Coolest)

Think/Pair/Share

How can we best determine stellar temperatures?

A. By measuring the peak wavelength in a star's spectrum, we can use Wien's Law to calculate temperature.
B. Astronomers use sophisticated models of stellar interiors to calculate surface temperatures.
C. Surface temperature is directly related to radius for all stars; find the radius and you find the temperature.
D. All of the above work equally well.

Think/Pair/Share

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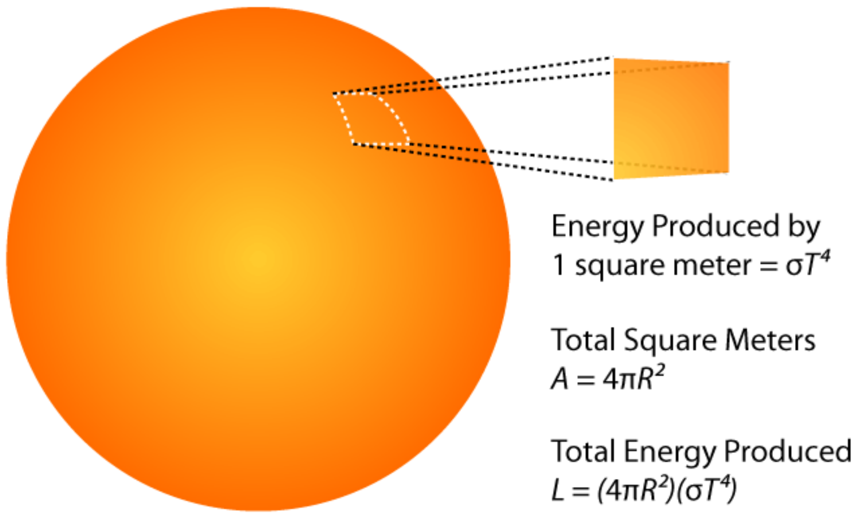
Determining stellar **radius**

1. Stellar size depends on **luminosity** (total power) and **surface temperature** (power / square meter):

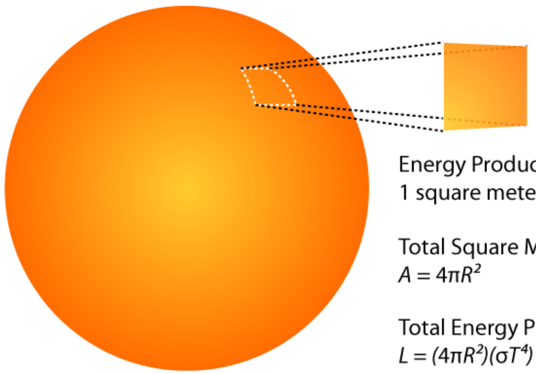
$$\text{Surface area of star} = \frac{\text{Total } \cancel{\text{power}}}{\cancel{\text{Power}}\text{/sq. meter}}$$

2. Surface area gives **radius** of sphere:

$$\text{Radius} = \frac{\text{Surface area}}{4\pi}$$



Determining stellar **radius**



The luminosity of a star is its energy per unit area multiplied by its total surface area:

$L = (4\pi r^2)(\sigma T^4)$ or solving this equation for radius:

$$R = \sqrt{\frac{L}{4\pi\sigma T^4}}$$

$r = (L / 4\pi\sigma T^4)^{1/2}$

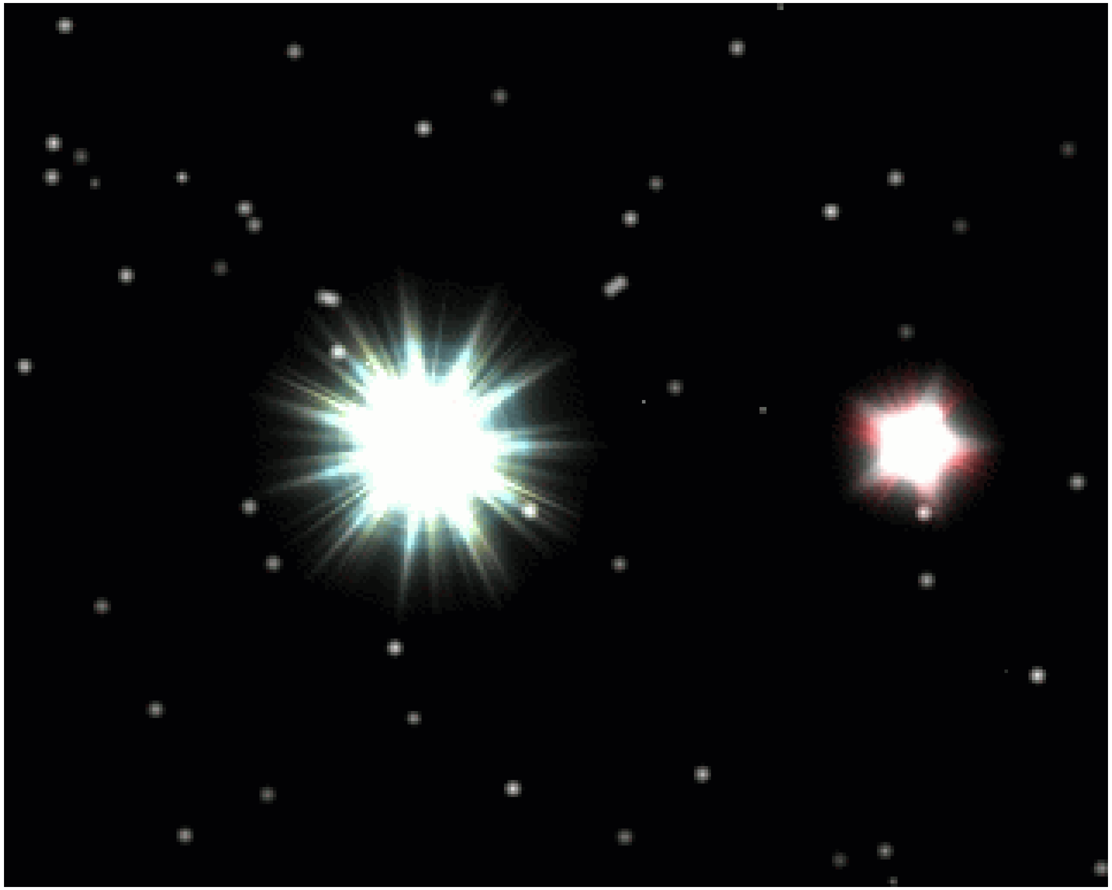
Example: (NOTE: solar luminosities must be multiplied by 3.8×10^{26} watts)

If a star has a luminosity of 1500 L_{Sun} and a surface temperature of 8400 K, what is it's radius?

$$r = (L / 4\pi\sigma T^4)^{1/2} = \sqrt{\frac{(1500)(3.8 \times 10^{26})}{4\pi (5.7 \times 10^{-8})\, 8400^4}} = \mathbf{1.26 \times 10^{10}} \textbf{ meters}$$

How do we measure stellar masses?

How do we measure stellar **masses**?



Orbit of a **binary star system** depends on strength of gravity

How do we measure stellar masses?

Isaac Newton

- *Using Newton's version of Kepler's third law,* ***we measure mass using gravity.***
- Direct mass measurements are possible only for stars in binary star systems.

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

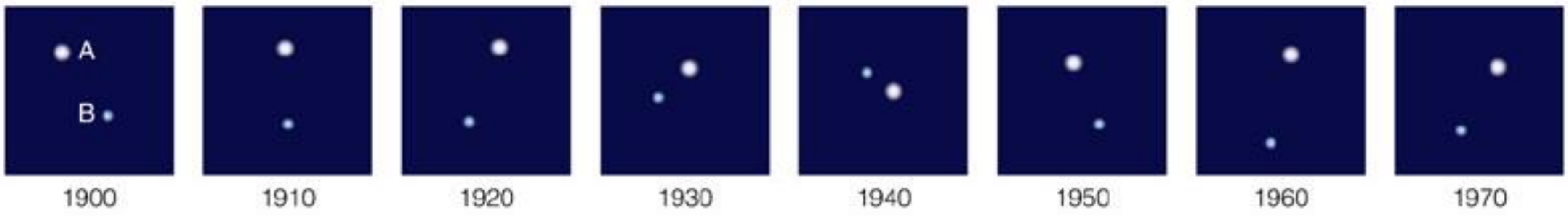
p = period

a = average separation

Types of Binary Star Systems

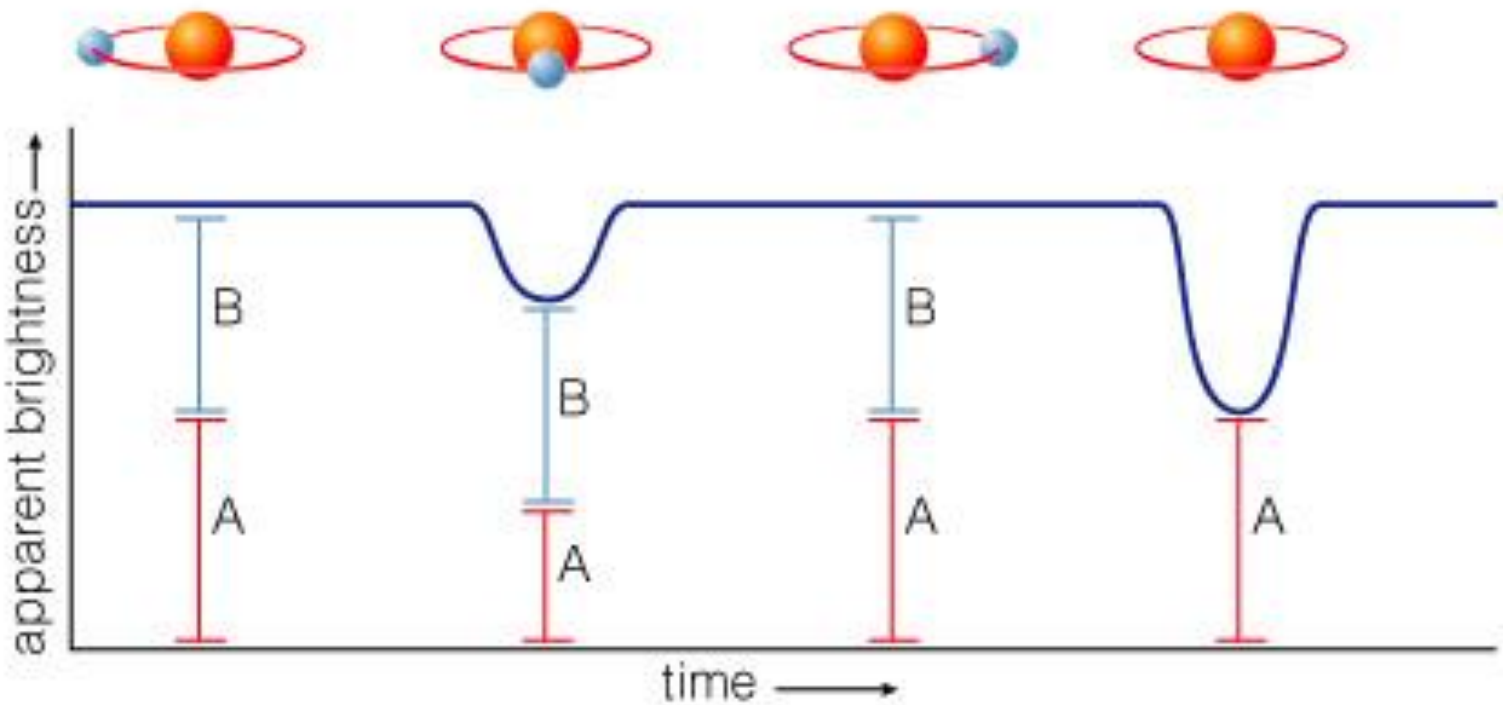
- Visual binary
- Eclipsing binary
- Spectroscopic binary

Visual Binary



- We can directly observe the orbital motions of these stars.
- Careful measures over long periods allow us to find the **periods of their orbits** which can tell us the masses using Newton’s Version of Kepler’s Third law.

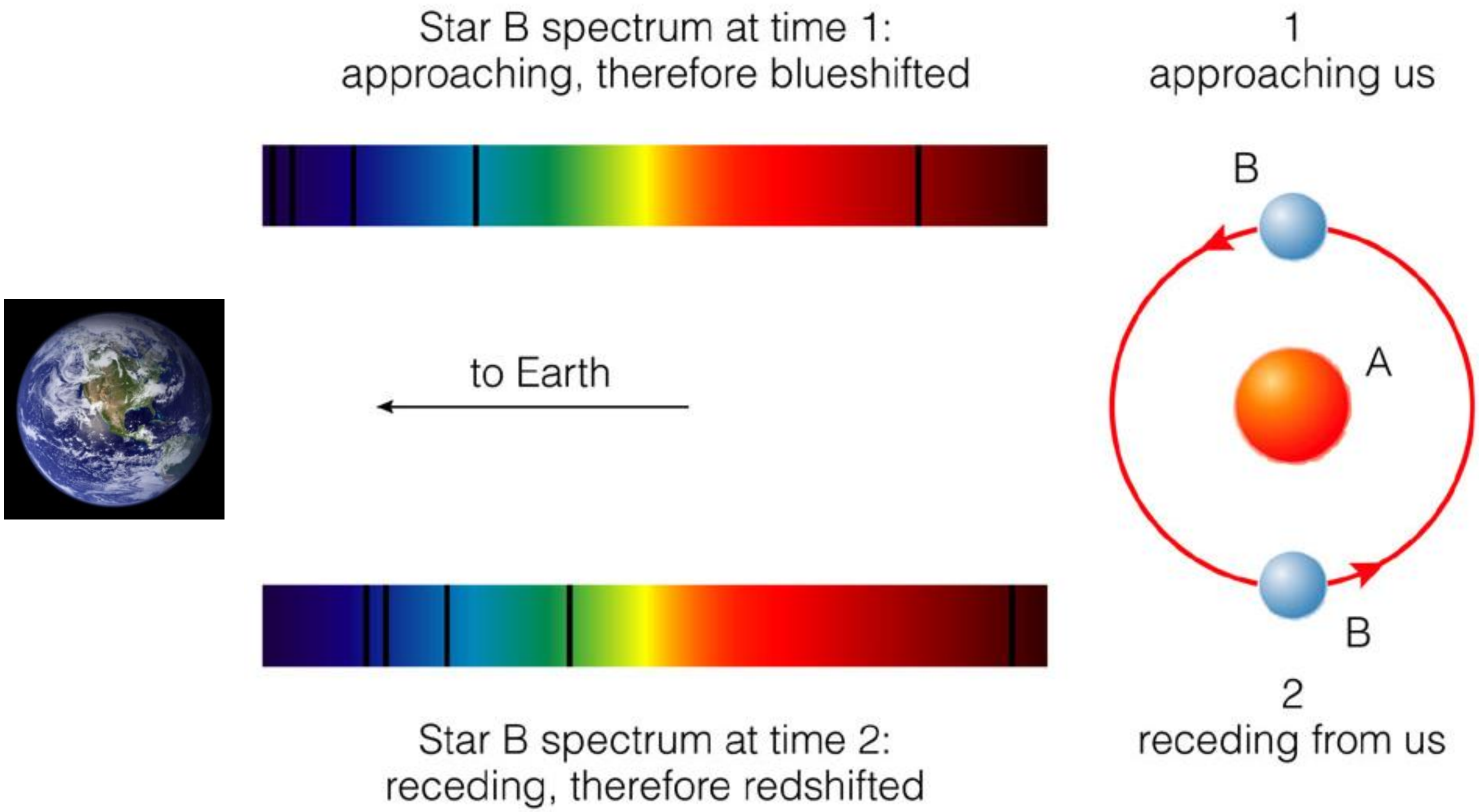
Eclipsing Binary



The Light Curve of an Eclipsing Binary Star System

- We can measure periodic eclipses of stars orbiting in same plane.
- The period of the eclipses tells us the *period* of the orbit.

Spectroscopic Binary



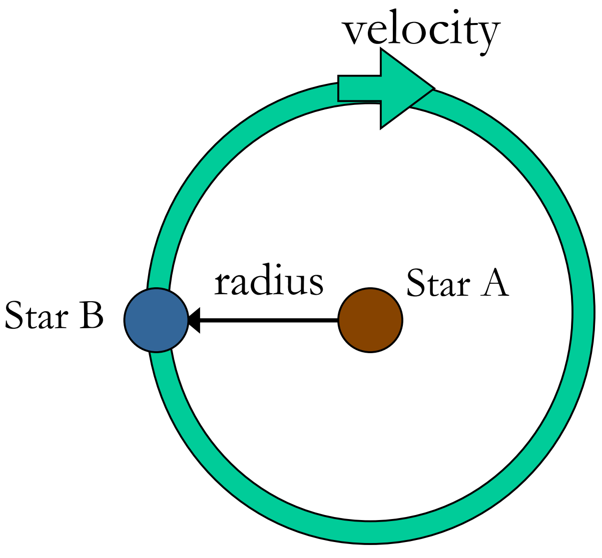
We determine the orbital period by measuring the **period** of the Doppler shifts.

Finding orbital separation

1. Orbital **period** (*p*) (from eclipses, spectral line shifts)
2. Orbital **velocity** (*v*) (from Doppler shift)
3. Orbital **separation** (*a* or *r* = radius from velocity and period)

For circular orbits, $v = \dfrac{2\pi r}{p}$ *or* $r = \dfrac{vp}{2\pi}$

So, we can calculate radius (or semimajor axis, a) using velocity and period!

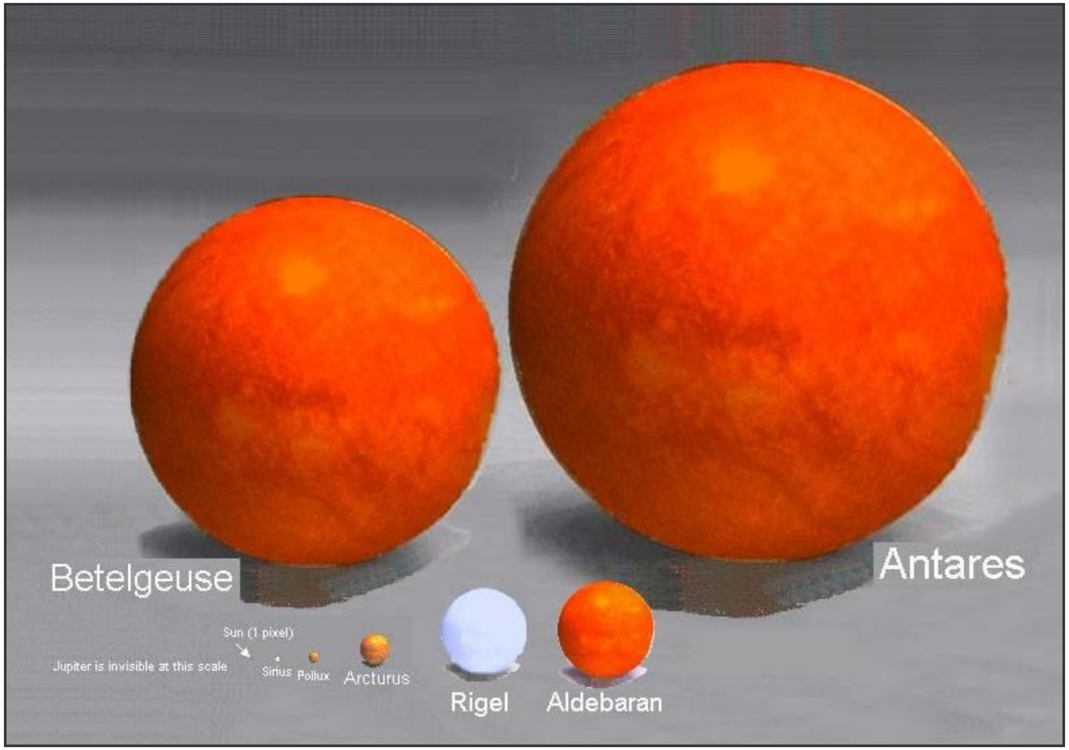


Stellar masses

Most massive stars: 150 M_{Sun}

Least massive stars: 0.08 M_{Sun}

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



What have we learned?

Begin 3 minute review

What have we learned?

How do we measure stellar **distances**

Parallax tells us distances to the nearest stars.

How do we measure stellar **luminosities**

If we measure a star's **apparent brightness and distance**, we can calculate its luminosity with the **inverse square law for light**.

How do we measure stellar **temperatures**

A star's **color** and **spectral type** both reflect its temperature.

Wien's Law tells us temperature from peak wavelength.

How do we measure stellar **radii**?

Comparing **luminosity** and **temperature** gives **radii**.

How do we measure stellar **masses**?

We measure the orbital period (*p*) and average orbital separation of the system (*a*).

Newton's version of Kepler's third law tells us the total mass of a binary system.

Spectral types

Class	Effective temperature[1][2][3]	Conventional color description[4][nb 1]	Actual apparent color[5][6][7]	Main-sequence mass[1][8] (solar masses)	Main-sequence radius[1][8] (solar radii)	Main-sequence luminosity[1][8] (bolometric)	Hydrogen lines	Fraction of all main-sequence stars[9]
O	≥ 30,000 K	blue	blue	≥ 16 $M_\odot$	≥ 6.6 $R_\odot$	≥ 30,000 $L_\odot$	Weak	~0.00003%
B	10,000 –30,000 K	blue white	deep blue white	2.1–16 $M_\odot$	1.8–6.6 $R_\odot$	25–30,000 $L_\odot$	Medium	0.13%
A	7,500 –10,000 K	white	blue white	1.4–2.1 $M_\odot$	1.4–1.8 $R_\odot$	5–25 $L_\odot$	Strong	0.6%
F	6,000–7,500 K	yellow white	white	1.04–1.4 $M_\odot$	1.15–1.4 $R_\odot$	1.5–5 $L_\odot$	Medium	3%
G	5,200–6,000 K	yellow	yellowish white	0.8–1.04 $M_\odot$	0.96 –1.15 $R_\odot$	0.6–1.5 $L_\odot$	Weak	7.6%
K	3,700–5,200 K	orange	pale yellow orange	0.45–0.8 $M_\odot$	0.7–0.96 $R_\odot$	0.08–0.6 $L_\odot$	Very weak	12.1%
M	2,400–3,700 K	red	light orange red	0.08 –0.45 $M_\odot$	≤ 0.7 $R_\odot$	≤ 0.08 $L_\odot$	Very weak	76.45%

Stellar Class	Radius	Mass	Luminosity	Temperature	Absolute	Habitable Zone	Lifetime	Abundance	Examples[25]
	$R/R_\odot$	$M/M_\odot$	$L/L_\odot$	K	V	AU	Myr	%	
O3	28	120	1,400,000	53,000	-6.0	1,200	2	0.00003%	Cygnus OB2–7
O5	22	60	790,000	45,000	-5.7	890	3	0.00003%	Zeta Puppis
O6	18	40	500,000	38,000	-5.5	670	4	0.00003%	Theta1 Orionis C
O8	8.5	23	170,000	35,000	-4.9	410	6	0.00003%	39 Ori
B0	7.4	17	50,000	30,000	-4.0	220	9	0.1%	Phi^1 Orionis
B3	4.8	7.6	1,900	19,000	-1.6	44	30	0.1%	Eta Ursae Majoris
B5	3.9	5.9	830	15,000	-1.2	29	50	0.1%	Pi Andromedae A
B8	3.0	3.8	180	12,000	-0.2	13	150	0.1%	18 Tau
A0	2.4	2.9	54	9,500	+0.6	7.3	300	0.7%	Alpha Coronae Borealis A
A5	1.7	2.1	14	8,200	+1.9	3.7	1,000	0.7%	Beta Pictoris
F0	1.5	1.6	6.5	7,200	+2.7	2.5	1,900	2%	Gamma Virginis
F5	1.3	1.3	3.2	6,400	+3.5	1.8	3,200	2%	Eta Arietis
G0	1.1	1.1	1.5	6,000	+4.4	1.2	8,000	3.5%	Beta Comae Berenices
G2	1.0	1.0	1.0	5,800	+4.8	1.0	10,000	3.5%	Sun
G5	0.93	0.93	0.79	5,700	+5.1	0.89	12,000	3.5%	Alpha Mensae
K0	0.85	0.79	0.42	5,200	+5.9	0.65	22,000	8%	70 Ophiuchi A
K5	0.72	0.67	0.15	4,300	+7.4	0.39	45,000	8%	61 Cygni A
M0	0.60	0.51	0.08	3,800	+8.8	0.28	68,000	80%	Gliese 185
M5	0.27	0.21	0.011	3,200	+12.3	0.10	200,000	80%	EZ Aquarii A
M8	0.15	0.06	0.001	2,600	+16.0	0.03	700,000	80%	Van Biesbroeck's star