Announcements

- Next section will be about:
  - Properties of stars and how we determine them
  - Energy source for stars
  - Stellar evolution
  - Stellar endpoints

Quiz 2: May 4

Stars

Stellar Properties

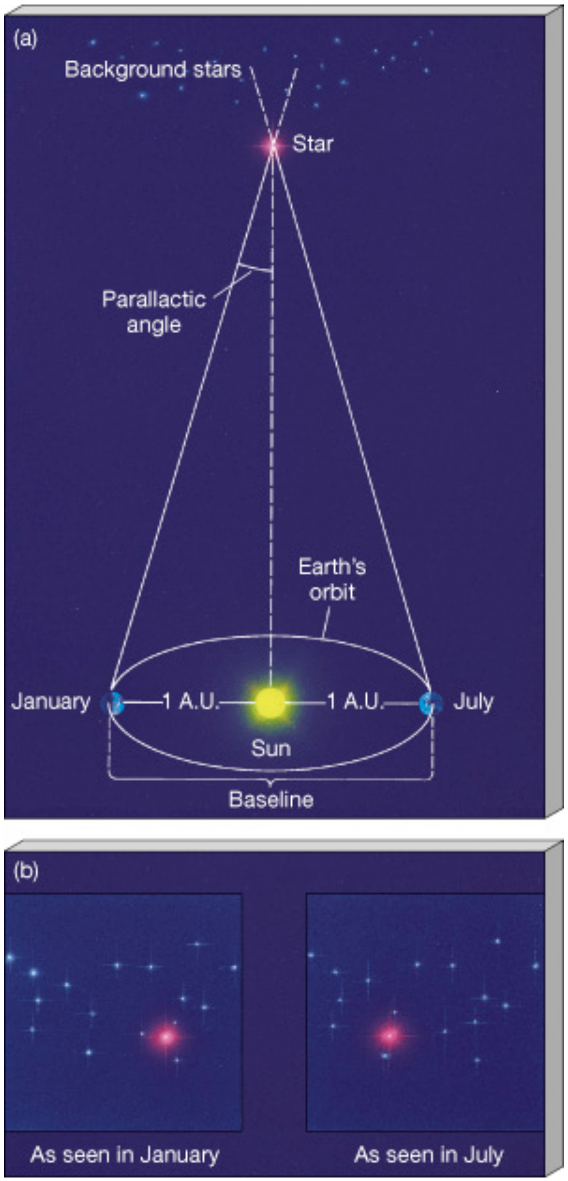
- *Luminosity* - an important intrinsic property that is equal to the amount of energy produced in the core of a star
- *Radius – physical size*
- *Mass – another physical property*
- *Surface Temperature*
- *Chemical Composition*
- *Brightness* - combination of distance and intrinsic luminosity
- *Distance* - this is not strictly a property of a star but is a crucial measurement to determine energy production

First problem: how far away are the stars?

Stellar confusion

- All stars are so far away that they are "point sources" even in very large telescopes*
- Suppose Star A is brighter in the sky than Star B:
  - Star A may have a higher luminosity (be producing more E-M radiation per unit time)
  - Star A may be closer than Star B
  - Some combination of the above
- So, understanding the *intrinsic* properties of stars depended historically on estimating distances to stars

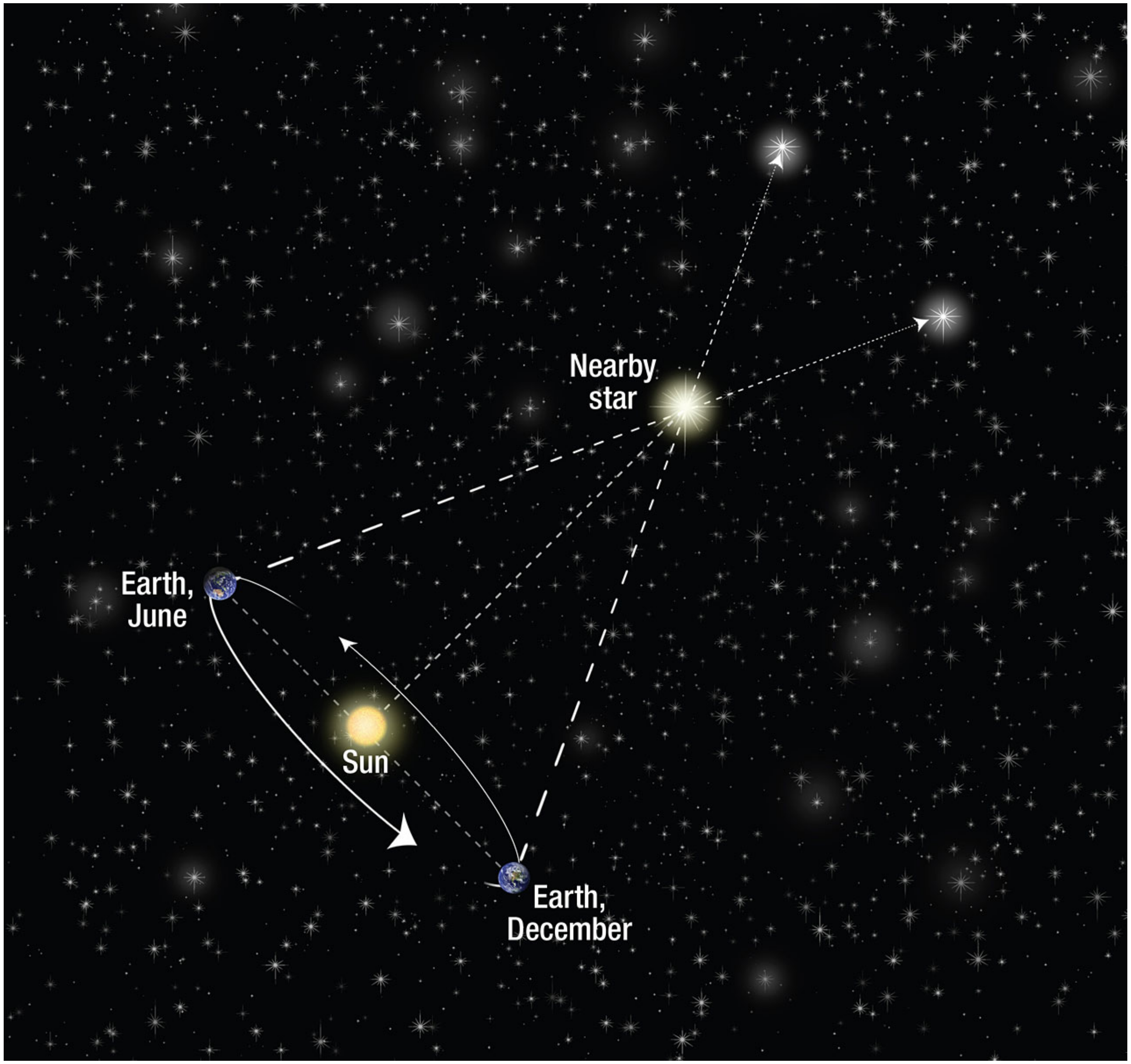
Stellar Distances

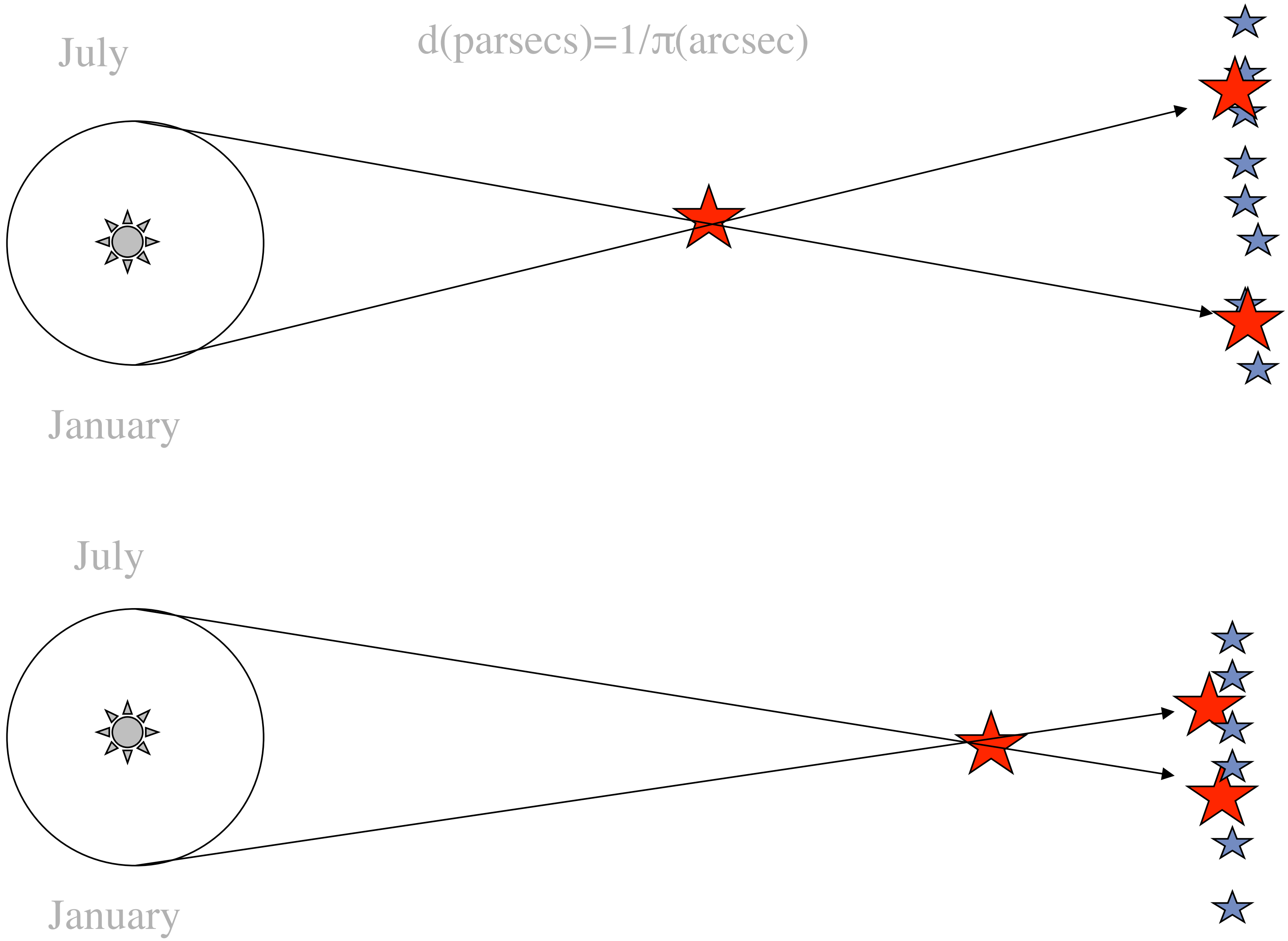


- The most reliable method for deriving distances to stars is based on the principle of Trigonometric Parallax
- The parallax effect is the *apparent* motion of a nearby object compared to distant background objects because of a change in viewing angle.

Stellar Distances

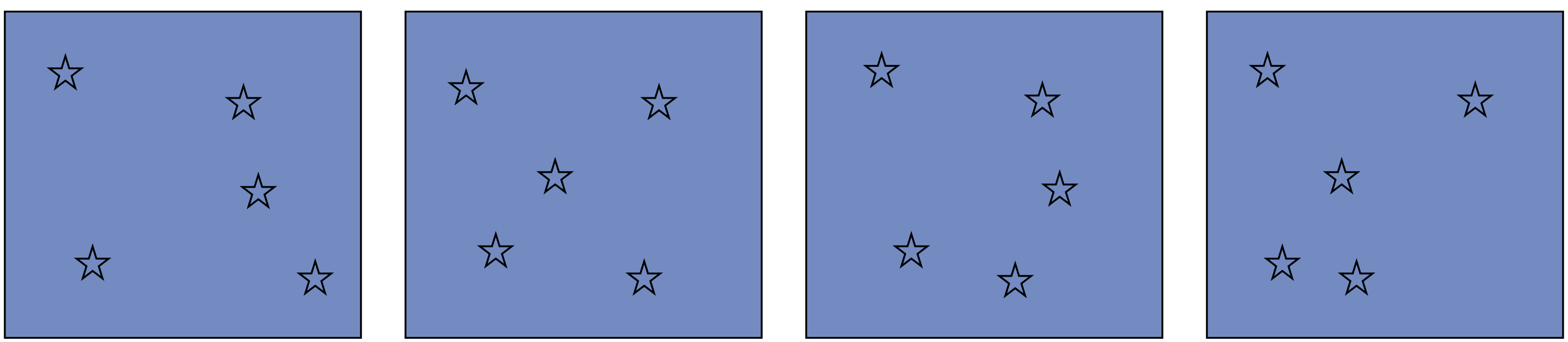
- Hold a finger in front of your face and view it with one eye, then the other. The apparent motion of the finger against the background is due to parallax. The baseline for the parallax effect is the distance between your eyes.
- For measuring the parallax distance to stars, we use a baseline which is the *diameter of the Earth's orbit*.
- There is an apparent annual motion of the nearby stars in the sky that is really just a reflection of the Earth's motion around the Sun.


Nearby
star
Earth,
June
Sun
Earth,
December

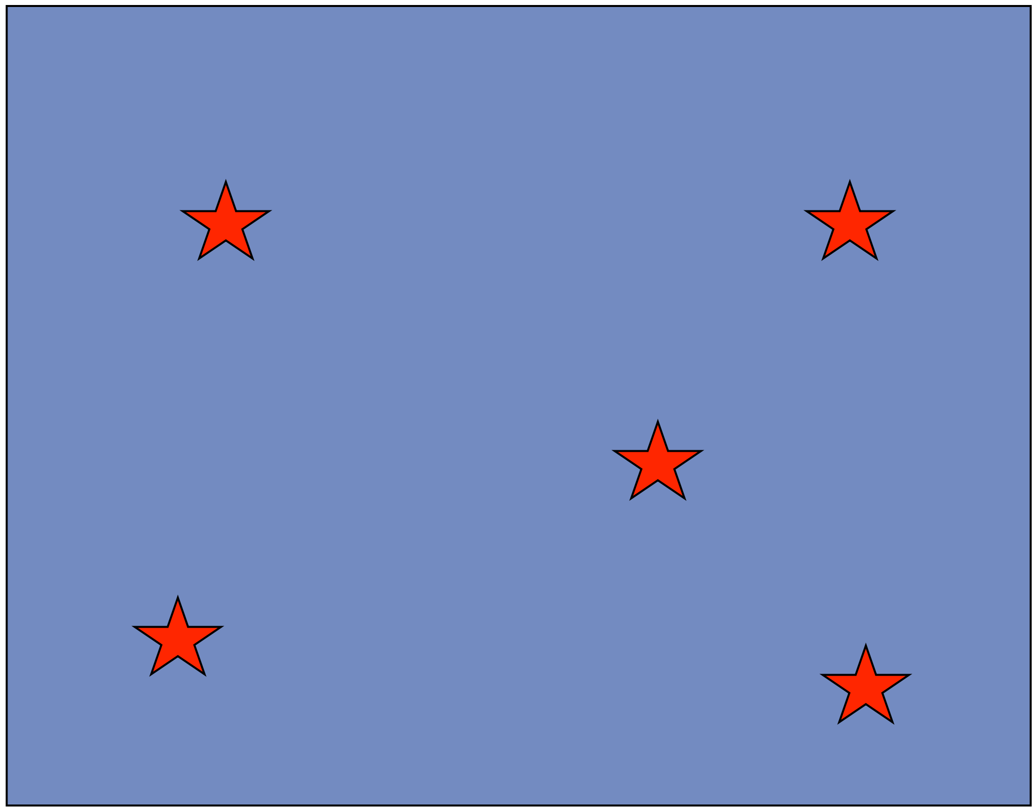

July
d(parsecs)=1/π(arcsec)
January
July
January

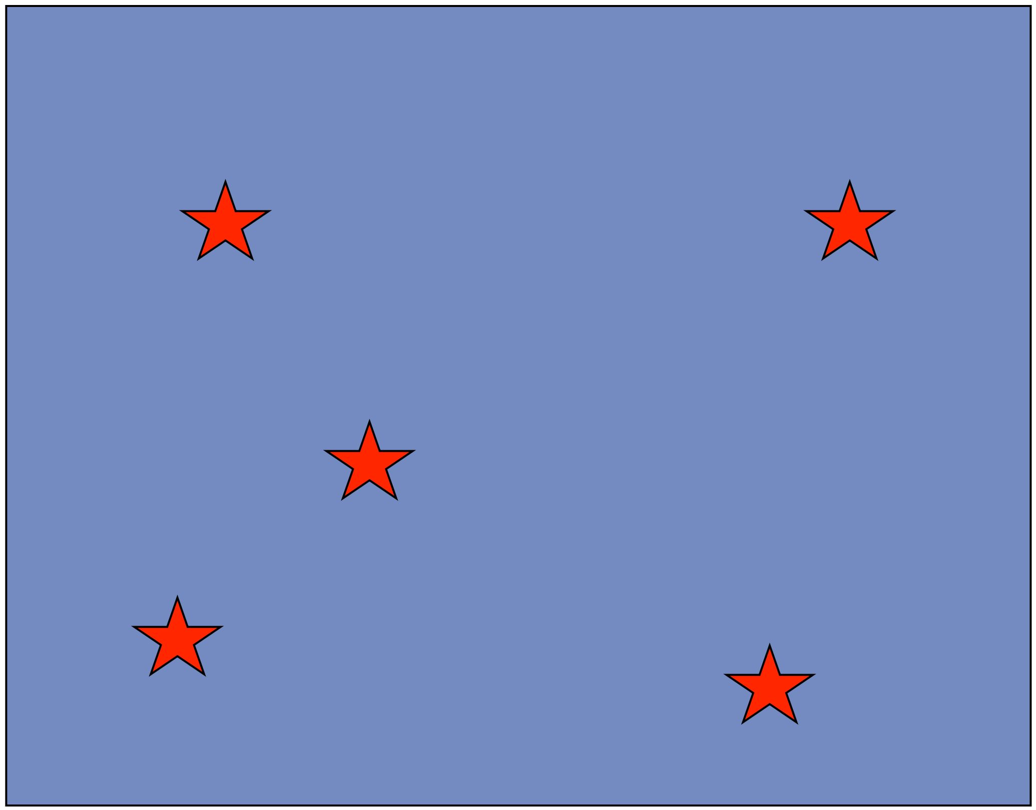
Stellar Parallax

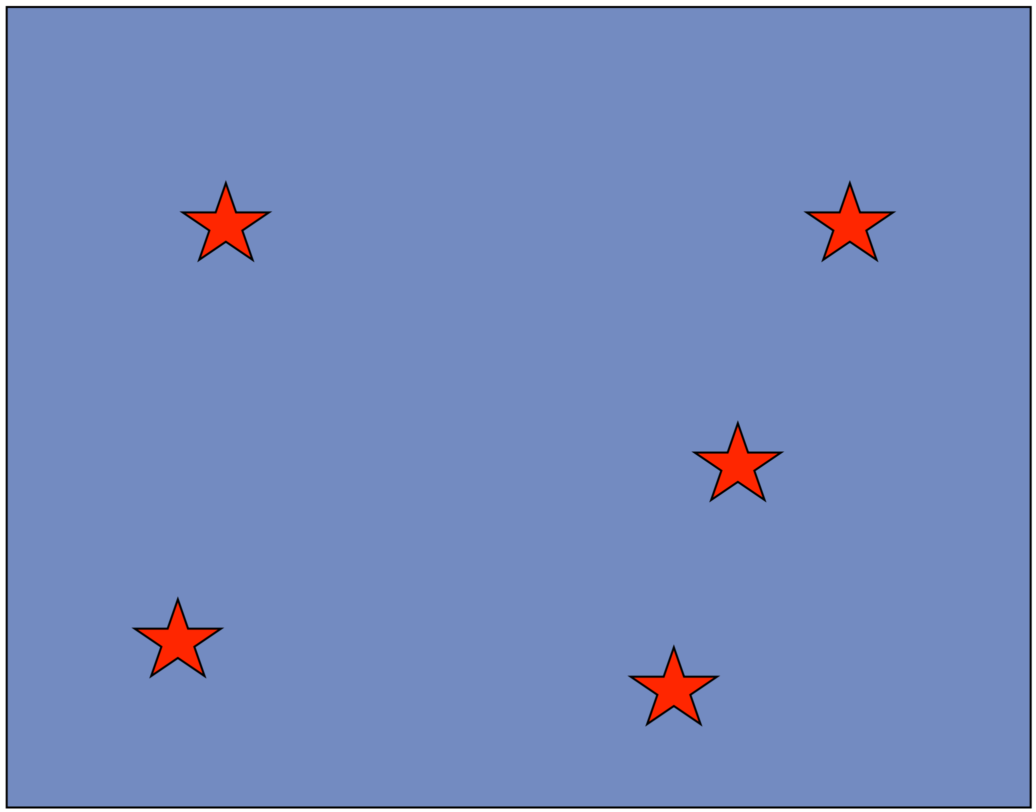
- Need to sort out parallax motion from proper motion -- in practice it requires years of observations.

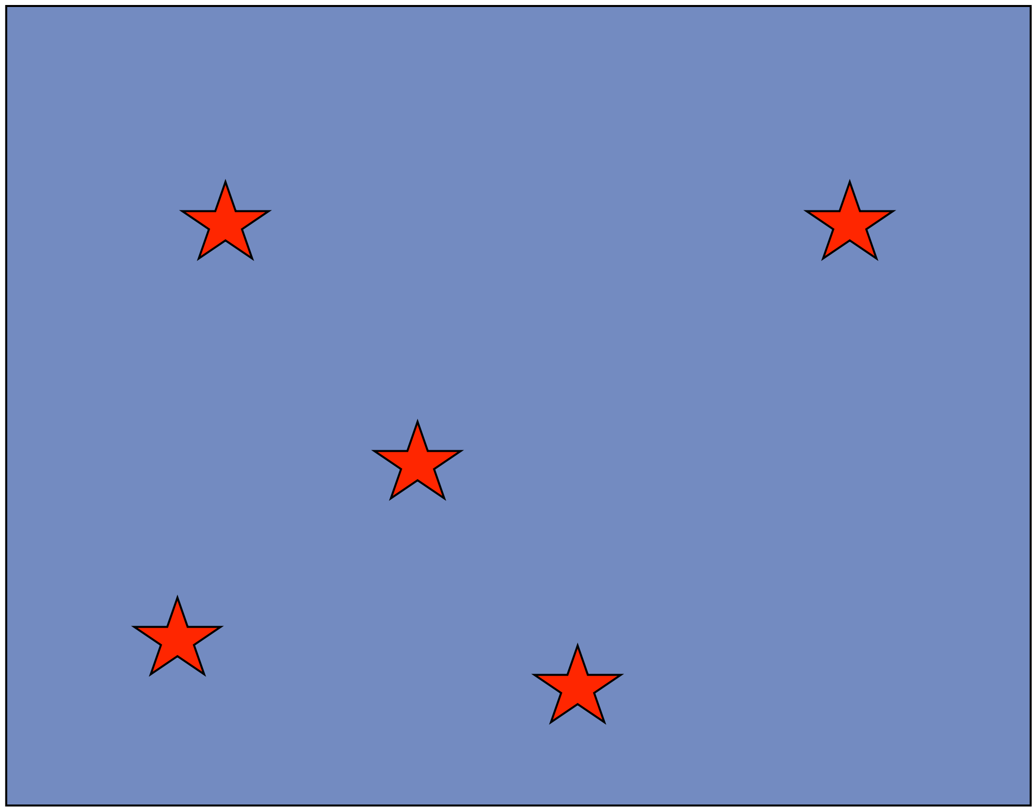


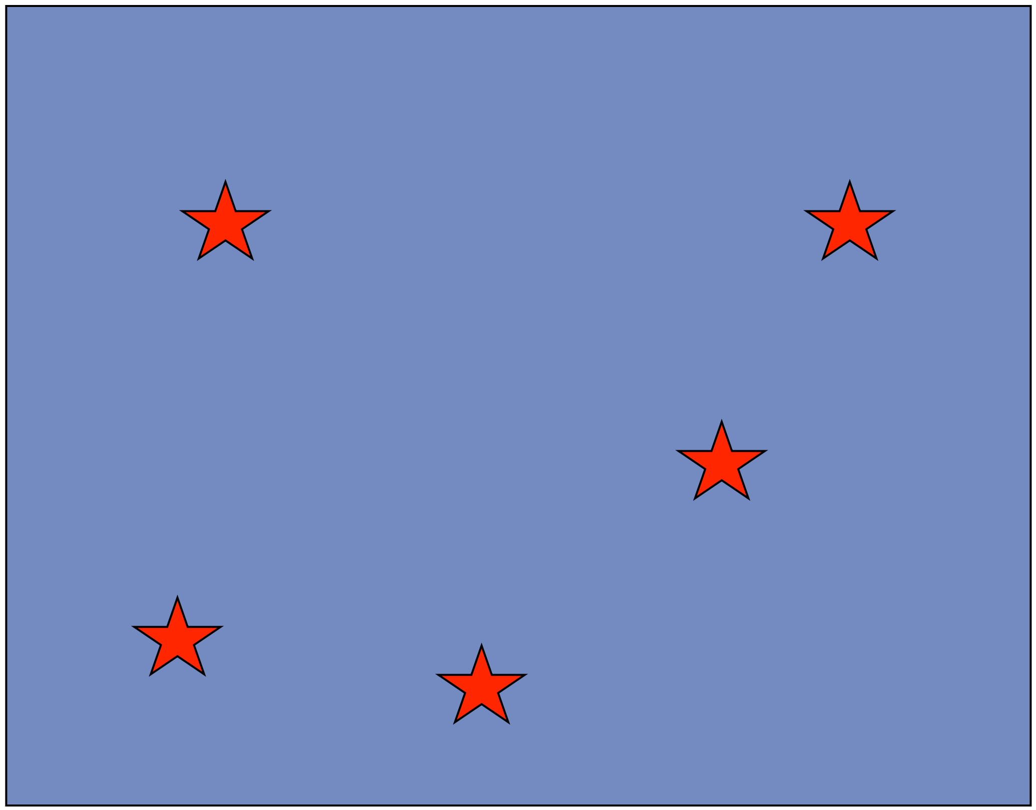
Jan 01 July 01 Jan 02 July 02

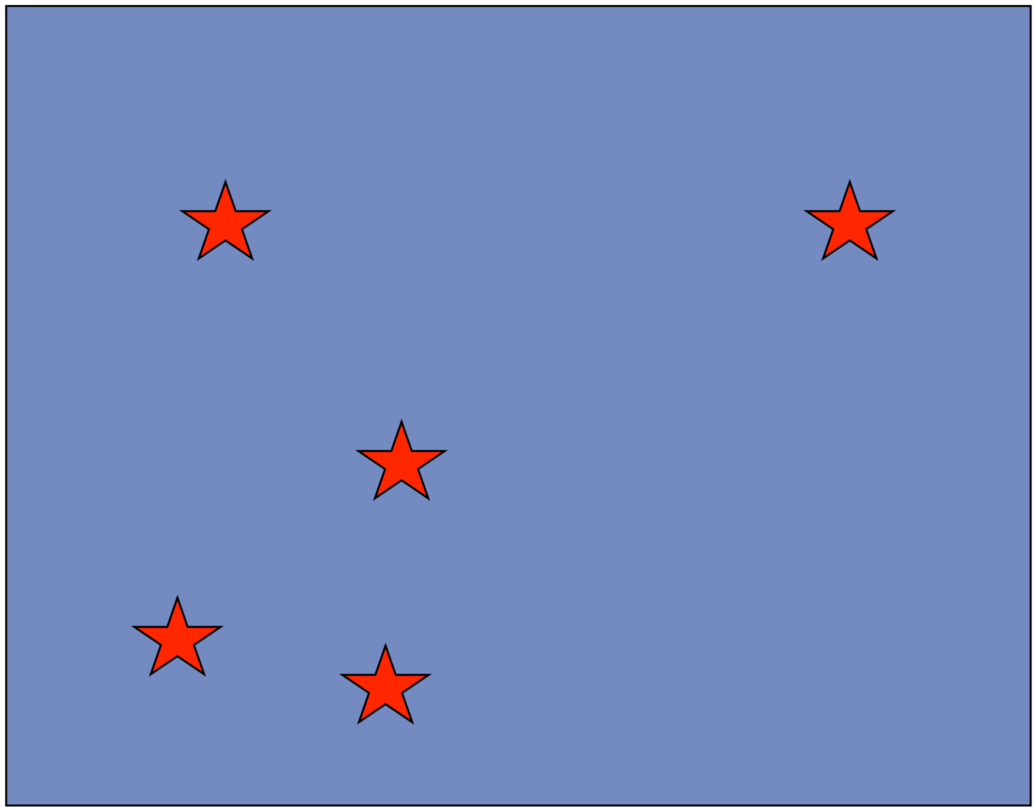


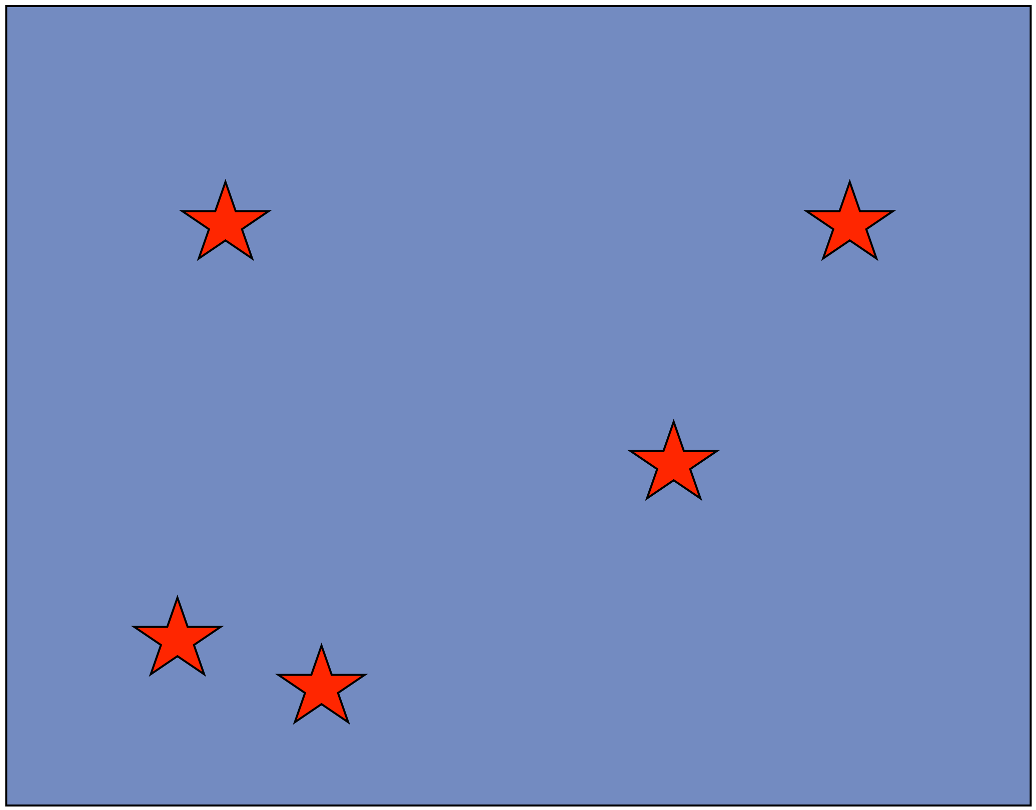


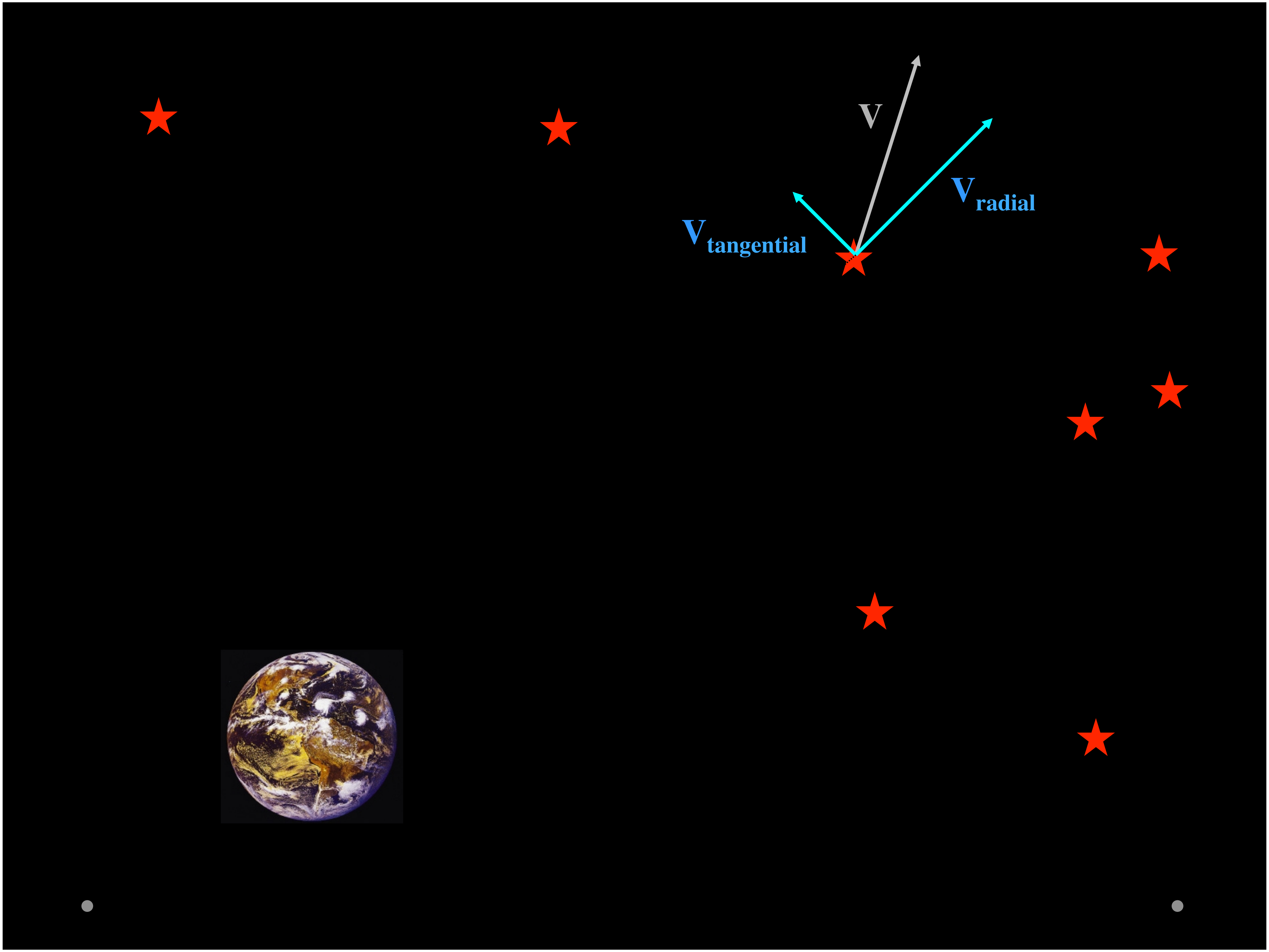






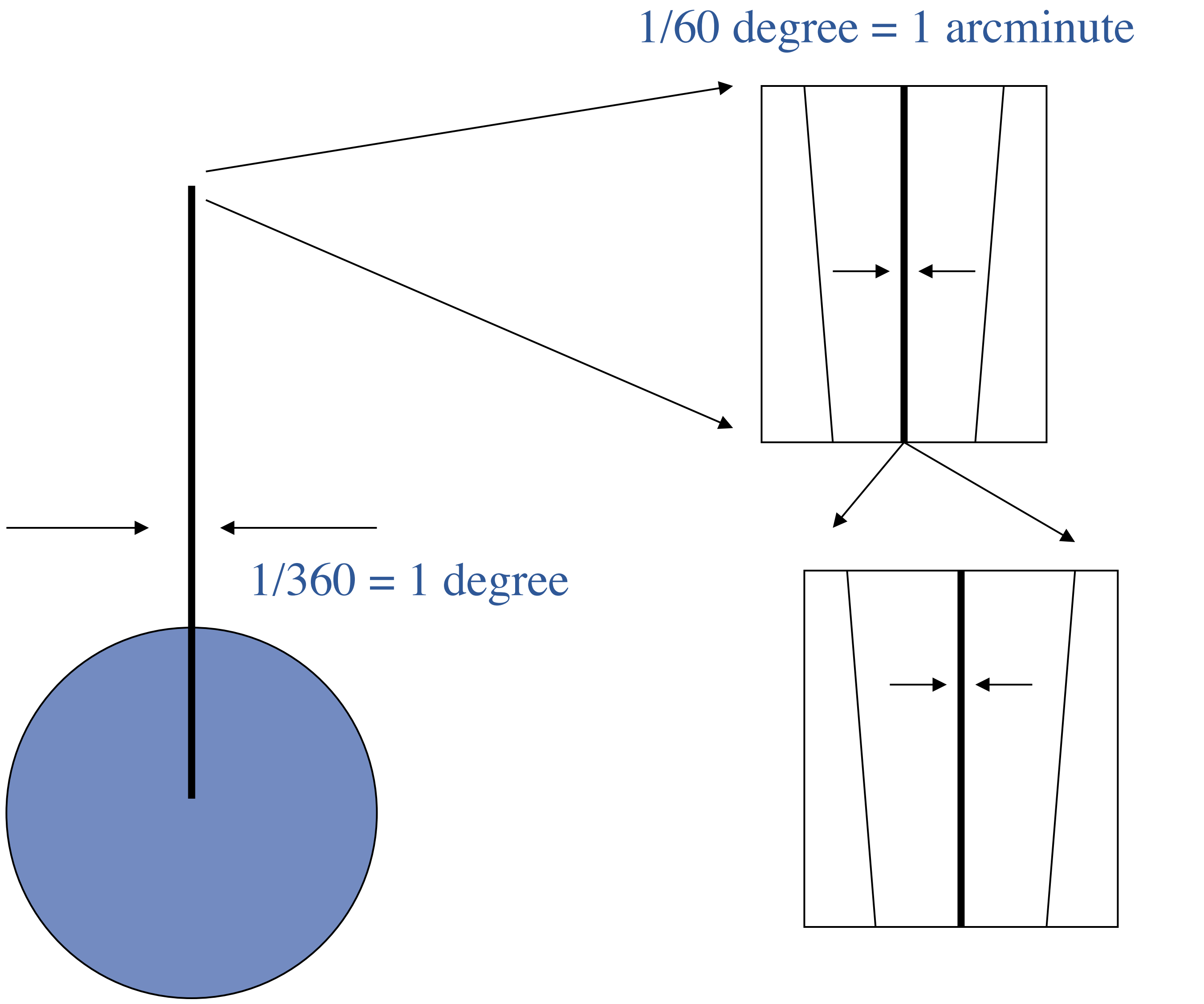





V
V radial
V tangential

Stellar Parallax

- *The Distance to a star is inversely proportional to the parallax angle*.
- There is a special unit of distance called a *parsec*.
- *This is the distance of a star with a parallax angle of 1 arcsec.*


1/60 degree = 1 arcminute
1/360 = 1 degree
1/60 arcminute = 1 arcsecond

Stellar Parallax

One arcsecond = 1´´ is therefore

$$1'' = \frac{1'}{60''} \times \frac{1^\circ}{60'} \times \frac{1\text{circle}}{360^\circ} = \frac{1}{1,296,000}\frac{\text{circle}}{''}$$

This is the angular size of a dime seen from 2 miles or a hair width from 60 feet.

Stellar Parallax

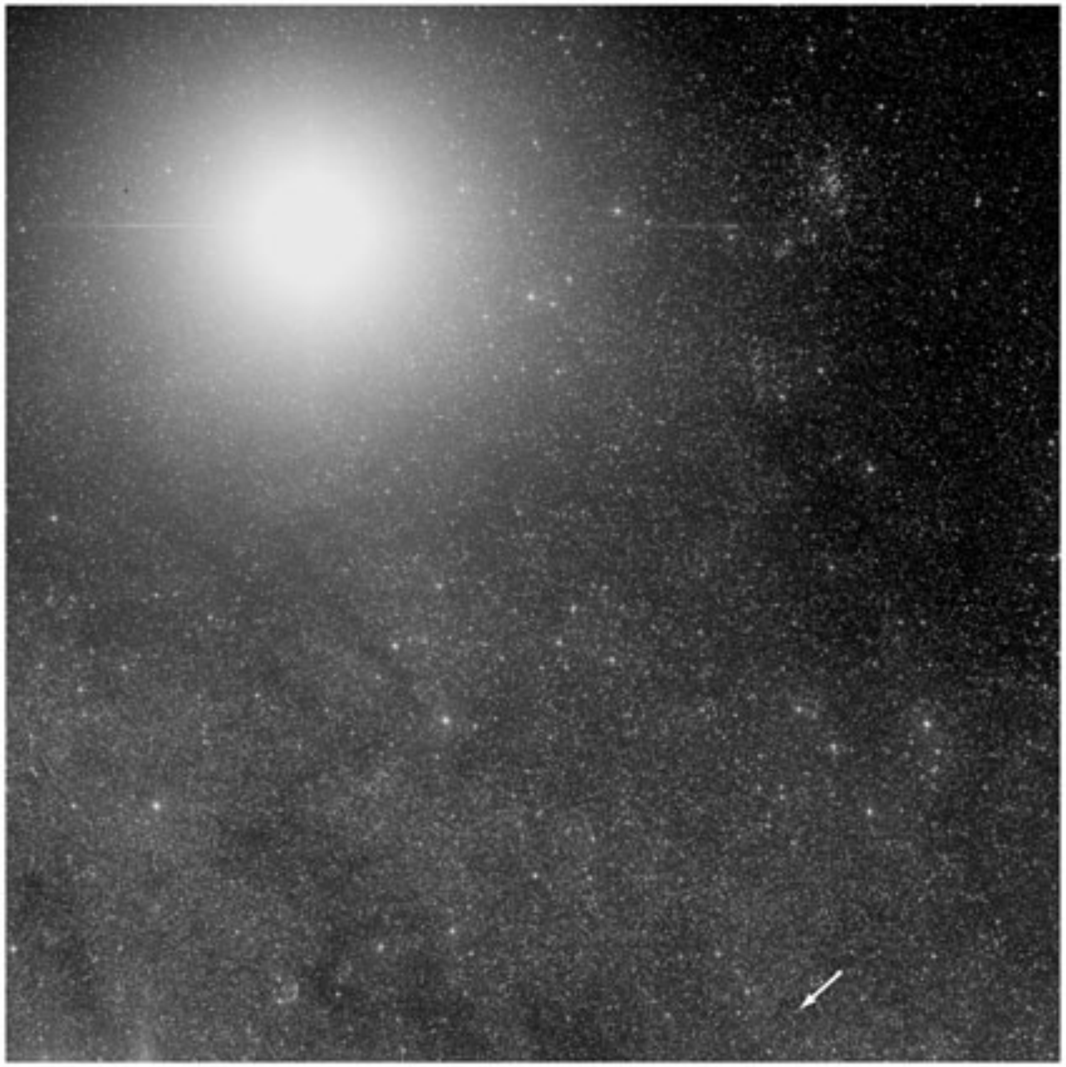
- Stellar parallax angle is usually called π
- The distance to a star in parsecs is:

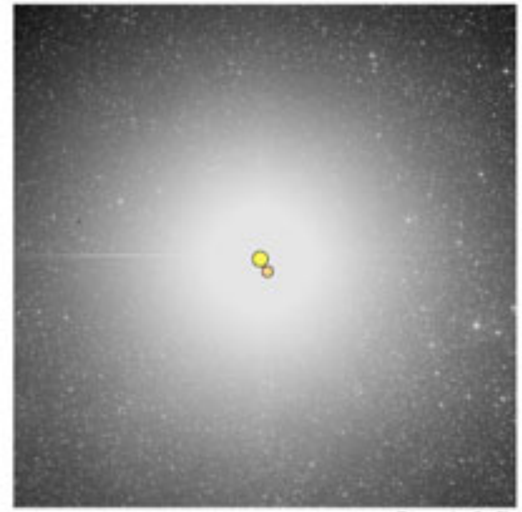
$$d = \frac{1}{\pi}$$

1 parsec = 3.26 light-years = 3.09×10^{13} km (recall that the Sun is 8.3 light-minutes from the Earth)

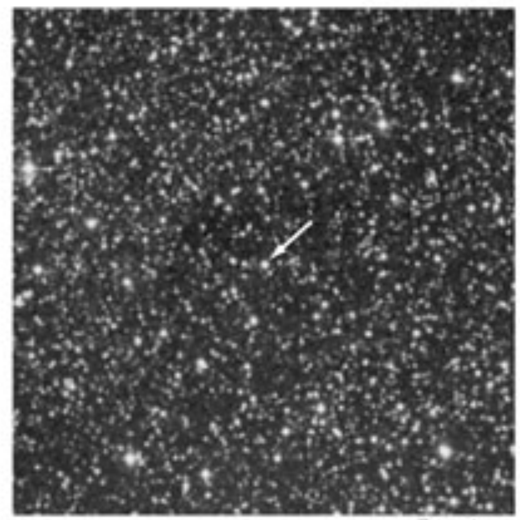
- How far away are the nearest stars?
- The nearest star, aside from the Sun, is called Proxima Centauri with a parallax of 0.77 arcsecond. Its distance is therefore:

$$d = \frac{1}{0.77} = 1.3pc$$





α Cen A & B



Proxima

Stellar parallax

Even the largest parallax (that for the nearest star) is small. The atmosphere blurs stellar images to about 1 arcsecond so "astrometrists" are trying to measure a tiny motion of the centroid as it moves back and forth every six months.

The *lack* of parallax apparent to the unaided eye was used as a proof that the Earth did not revolve around the Sun.

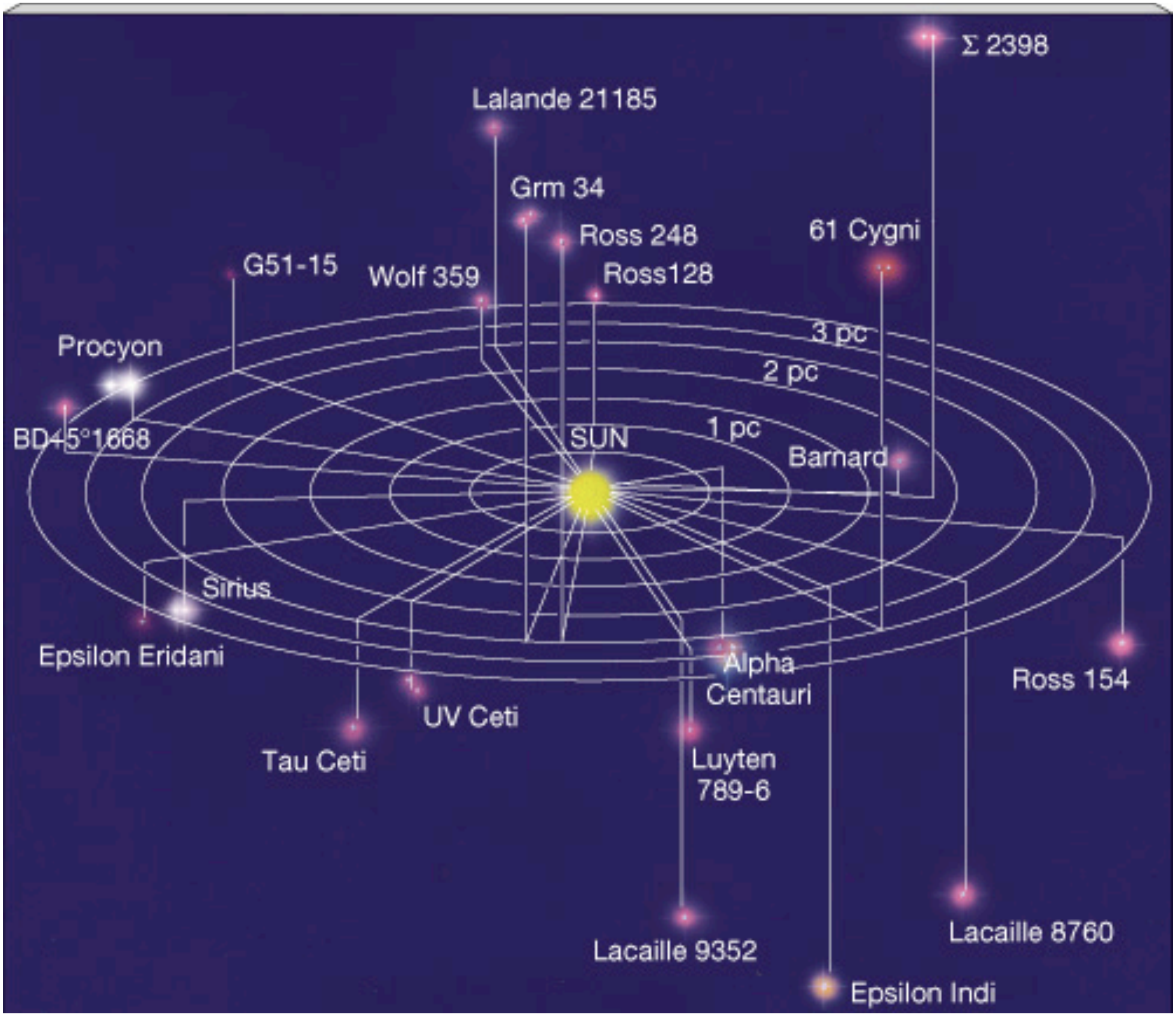
- In 189 B.C. the difference in the Moon shadow position from two different locations during an eclipse was used to get the parallax distance to the Moon
- Ground-based parallax distances are good to about 100 parsecs --- this is a parallax angle of only 0.01 arcseconds!
- Space-based missions have taken over parallax measurements. GAIA is a satellite that is in orbit right now measuring proper motions for 300 million stars and parallaxes for 20 million stars. Precision of ~0.00001 arcseconds
- GAIA Movie

Stellar Luminosity when distance is known

- It is crucial to be able to figure out the distances to stars so we can separate out the *Inverse Square Law dimming* and intrinsic brightness or Luminosity.

$$I \propto \frac{1}{d^2}$$

-
-


Σ 2398
Lalande 21185
Grm 34
Ross 248
61 Cygni
G51-15
Wolf 359
Ross128
3 pc
Procyon
2 pc
1 pc
BD+5°1668
SUN
Barnard
Sirius
Epsilon Eridani
Alpha Centauri
Ross 154
UV Ceti
Tau Ceti
Luyten 789-6
Lacaille 8760
Lacaille 9352
Epsilon Indi

The Nearest Stars

Name	Distance (light-years)	Apparent Brightness[1]	Luminosity[2]
Sun	---	(120 billion)	1.00
Alpha Centauri A	4.3	0.26	1.56
Alpha Centauri B	4.3	0.077	0.45
Alpha Centauri C	4.2	0.00001	0.00006
Barnard's Star	6.0	0.00004	0.0005
Wolf 359	7.7	0.000001	0.00002
BD +36 degrees 2147	8.2	0.0003	0.006
Luyten 726-8 A	8.4	0.000003	0.00006
Luyten 726-8 B	8.4	0.000002	0.00004
Sirius A	8.6	1.00	23.6
Sirius B	8.6	0.001	0.003
Ross 154	9.4	0.00002	0.0005

[1] apparent brightness compared to Sirius A
[2] intrinsic luminosity compared to Sun

Stellar Luminosities

Luminosity is the total amount of energy produced in a star and radiated into space in the form of E-M radiation.

How do we determine the luminosity of the Sun?

1) Measure the Sun's apparent brightness
2) Measure the Sun's distance
3) Use the inverse square law to correct for distance

Luminosity of the Sun

- Another way to look at this is to measure the amount of energy in sunlight falling on a unit surface area, then multiply by the number of unit areas on the surface of a sphere with a radius of 1 `AU' .
- One measure of the Sun's apparent brightness is the `Solar Constant' :

$$1.4 \times 10^6 \text{ ergs/cm}^2\text{/second}$$

Interesting energy facts

- `erg' is not a joke, it is a unit of energy
- A black horse outside on a sunny day absorbs about 8×10^9 ergs/sec = 1hp
- A normal-sized human emits about 10^9 ergs/sec = 100 watts in the Infrared.

How big is the solar constant?

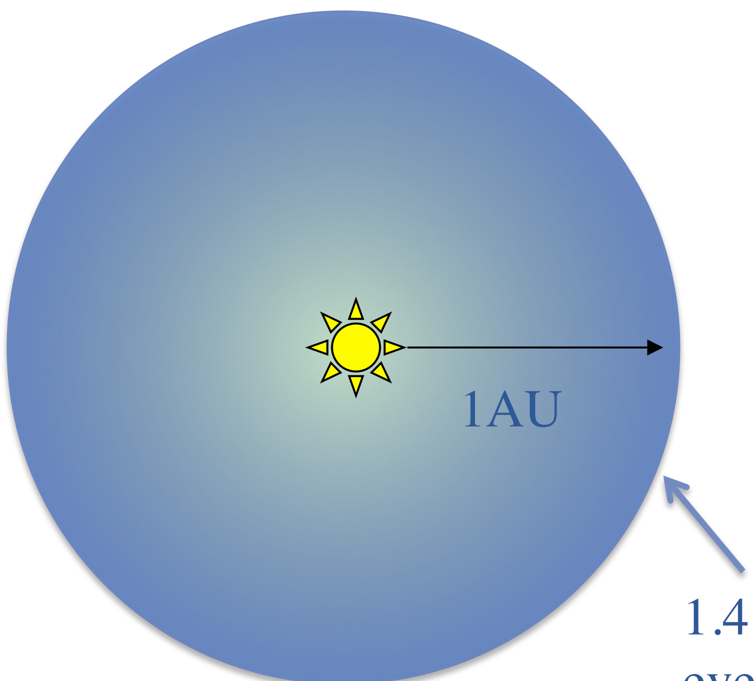
- On a sunny day, the amount of solar energy crashing into the roof of this building is the solar constant times the surface area of the roof.

$$1.4 \times 10^{6} \frac{\text{erg}}{\text{cm}^{2} \bullet \text{sec}} \times 10^{8}\,\text{cm}^{2} = 1.4 \times 10^{14} \frac{\text{ergs}}{\text{sec}}$$

- This is 14 MW (mega-watts). The total campus usage is 3.5 MW.

Solar Luminosity

- Given the solar constant, how do we find the total radiant energy of the Sun?



Surface area of sphere with radius of 1 AU is given by $4\pi R^2$

1.4×10^8 ergs/sec for every cm^2 on the surface of the sphere

Solar luminosity

- The surface area of a sphere centered on the Sun with a radius equal to the radius of the Earth's orbit is:

$$4\pi R^2 = 4\pi(1.5\times10^{10}cm^2) = 2.8\times10^{27}cm^2$$

- The total energy flowing through this surface is the total energy of the Sun

$$1.4\times10^{6}\frac{ergs}{cm^2\bullet\sec}\times2.8\times10^{27}cm^2 = 3.9\times10^{33}\frac{ergs}{\sec}$$

Solar Luminosity

- L_o=3.9 x 10^{33}ergs/sec
- At PGE rates, the Sun would cost 10^{20} \$/second

Q. What is the Solar Luminosity at the distance of Mars (1.5 AU)? (i>clicker quiz)

A. 3.9 x 10^{33} ergs/sec
B. 3.9 x 10^{33} x $(1/1.5)^2$ ergs/sec
C. 3.9 x 10^{33} x 1.5^2 ergs/sec
D. 3.9 x 10^{33} x 1.5 ergs/sec

- What is the Solar Luminosity at the surface of the Sun?

Still 3.9×10^{33} ergs/sec!

- Luminosity is an intrinsic property of the Sun (and any star).

- A *REALLY GOOD* question: How does the Sun manage to produce all that energy for at least 4.5 billion years?

Stellar luminosities

- What about the luminosity of all those other stars?
- Apparent brightness is easy to measure, starting with nearby stars with parallax measurements and calibrating other distance measurement techniques we get the distances to stars:
- Brightness + distance + inverse square law for dimming allow us to calculate intrinsic luminosity.

- For stars we discover a huge range in L.

$10^6 L_{sun} > L_* > 0.00001 L_{sun}$

1,000,000 times the Luminosity of the Sun

1/100,000 the luminosity of The Sun

Q. Two stars have the same Luminosity.
Star A has a parallax angle of 1/3 arcsec;
Star B has a parallax angle of 1/6 arcsec.

a) Which star is more distant?

Star B has the SMALLER parallax and therefore the LARGER distance

Q. Two stars have the same Luminosity.
Star A has a parallax angle of 1/3 arcsec,
Star B has a parallax angle of 1/6 arcsec.

b) What are the two distances?

$$d = \frac{1}{\pi}$$

$$d_A = \frac{1}{\left(\frac{1}{3}\right)} = 3\text{parsecs}$$

$$d_B = \frac{1}{\left(\frac{1}{6}\right)} = 6\text{parsecs}$$

Q. Two stars have the same Luminosity.

Star A has a parallax angle of 1/3 arcsec,

Star B has a parallax angle of 1/6 arcsec.

c. Compare the apparent brightness of the two stars.

Star B is twice as far away, same L, If there is no dust along the the line of sight to either star, B will be ¼ = $1/2^2$ as bright.

Stellar Radius

- With another physics principle first recognized in the 19th century we can determine the sizes of stars.
- Stephan's Law:

$$\frac{Energy}{area} = \sigma T^4$$

- This says that the energy radiated in the form of E-M waves changes proportional to the temperature of an object to the 4th power. σ is another of the constants of nature: the Stephan-Boltzmann constant.

Stellar Radius

- For example, if you double the temperature of an object, the amount of energy it radiates increases by $2^4 = 2 \times 2 \times 2 \times 2 = 16$ (!)
- Think about the Sun and Betelguese:

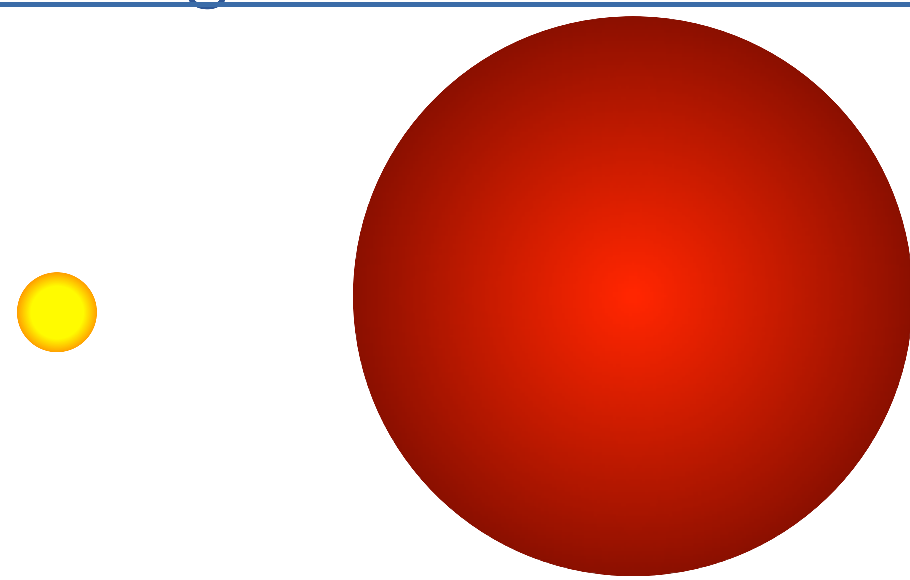
Sun: $1 L_{\odot}$; T=5500k

Symbol for solar value

Betelguese: $27{,}500 L_{\odot}$; T=3400k

Stellar Radius

- Something is fishy with this. The Sun has a higher surface temperature so must put out more energy per unit surface area. For Betelguese to have a higher total luminosity, it must have a larger total surface area!



Stellar Radius

- How much larger is Betelguese?

From Stephan's Law, each square cm of the Sun emits more energy than a square cm of Betelguese by a factor of:

$$\left(\frac{5500}{3400}\right)^4 = 6.8$$

If the Sun and Betelguese were the same radius and surface area, the Sun would be more luminous by this same factor. If Betelguese had 6.8x the surface area of the Sun, the two stars would have the same surface area, need another factor of 27,500 for the Betelguese surface area to give the Luminosity Ratio measured for the two stars.

- Stated another way:

$$\mathrm{Lum}_{\mathrm{Betel}} = \left(\frac{Energy}{Area}\right)_{Betel} \times \left(Area\right)_{Betel} = 27,500 \times \left(\frac{Energy}{Area}\right)_{Sun} \times \left(Area\right)_{Sun}$$

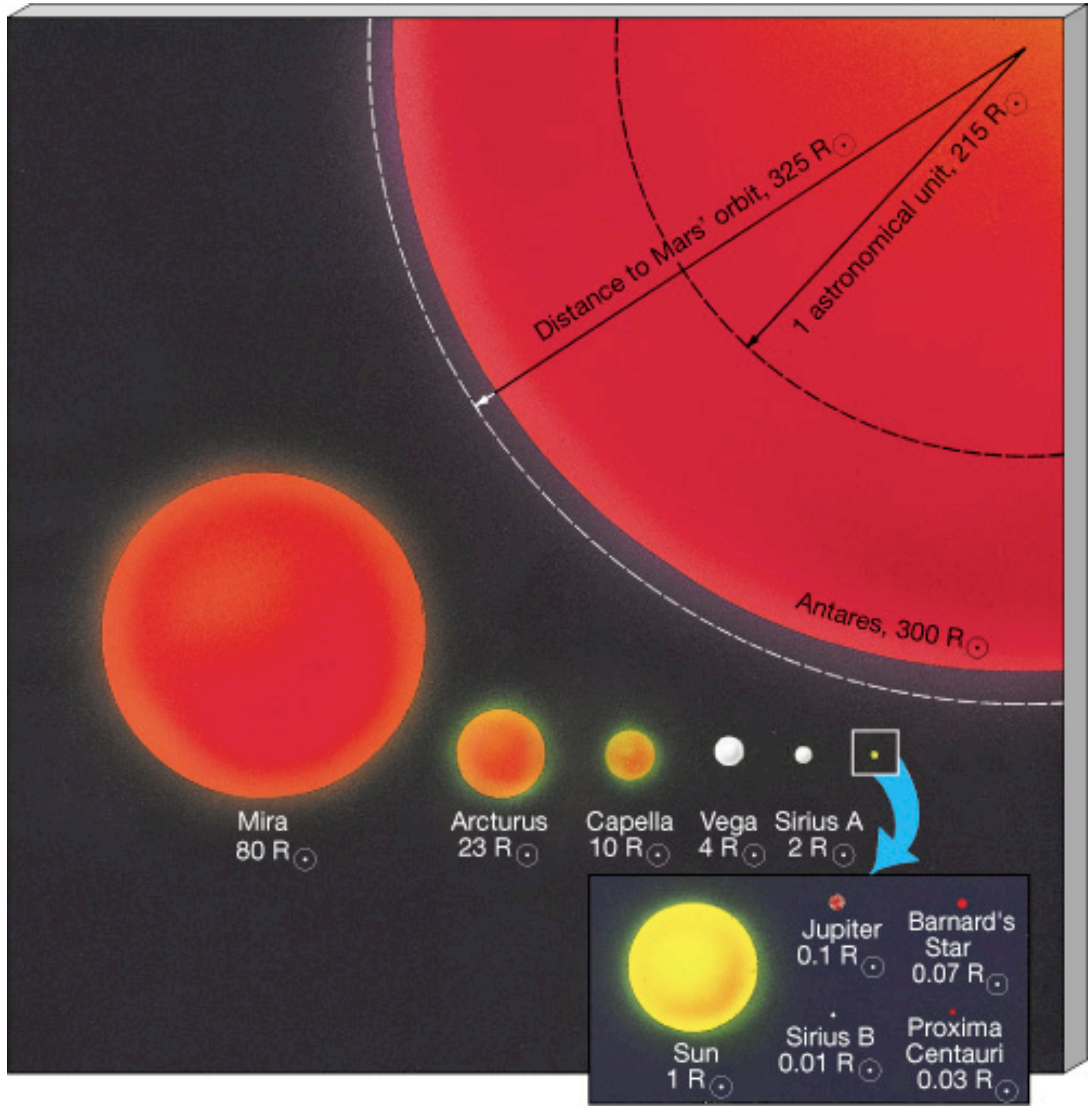
$$\left(Area\right)_{Betel} = 27,500 \times \frac{(E/A)_{Sun}}{(E/A)_{Betel}} \times \left(Area\right)_{Sun}$$

- Surface area goes like R^2, so Betelguese has a radius that is >400 times that of the Sun!

$$\left(Area\right)_{Betel} = 27,500 \times 6.8 \times \left(Area\right)_{Sun} = 187,000\left(Area\right)_{Sun}$$

Stellar Radius

- The range in stellar radius seen is from 0.01 to about 1000 times the radius of the Sun.

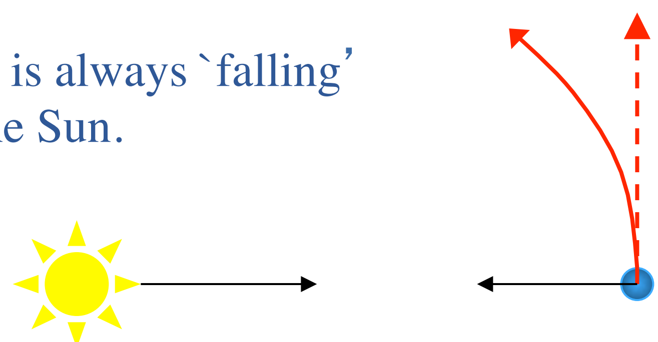


Distance to Mars' orbit, 325 R☉
1 astronomical unit, 215 R☉
Antares, 300 R☉
Mira
80 R☉
Arcturus
23 R☉
Capella
10 R☉
Vega
4 R☉
Sirius A
2 R☉
Sun
1 R☉
Jupiter
0.1 R☉
Barnard's Star
0.07 R☉
Sirius B
0.01 R☉
Proxima Centauri
0.03 R☉

One More Stellar Property: Mass

- To understand how we determine stellar masses we need to learn a little about the Laws of Motion and Gravity.

The Earth is always `falling' Toward the Sun.



Without the gravitational force of the Sun, the Earth would continue in a straight line

Stellar Mass

- The Earth and the Sun feel an equal and opposite gravitational force and each orbits the `center of mass' of the system. The center of mass is within the Sun: the Earth moves A LOT, the Sun moves only a tiny bit because the mass of the Sun is much greater than the mass of the Earth.
- Measure the size and speed of the Earth's orbit, use the laws of gravity and motion and determine:

$$\text{Mass}_{\text{Sun}} = 2 \times 10^{33} \text{ grams} = 300{,}000\ M_{\text{Earth}}$$

Stellar Mass

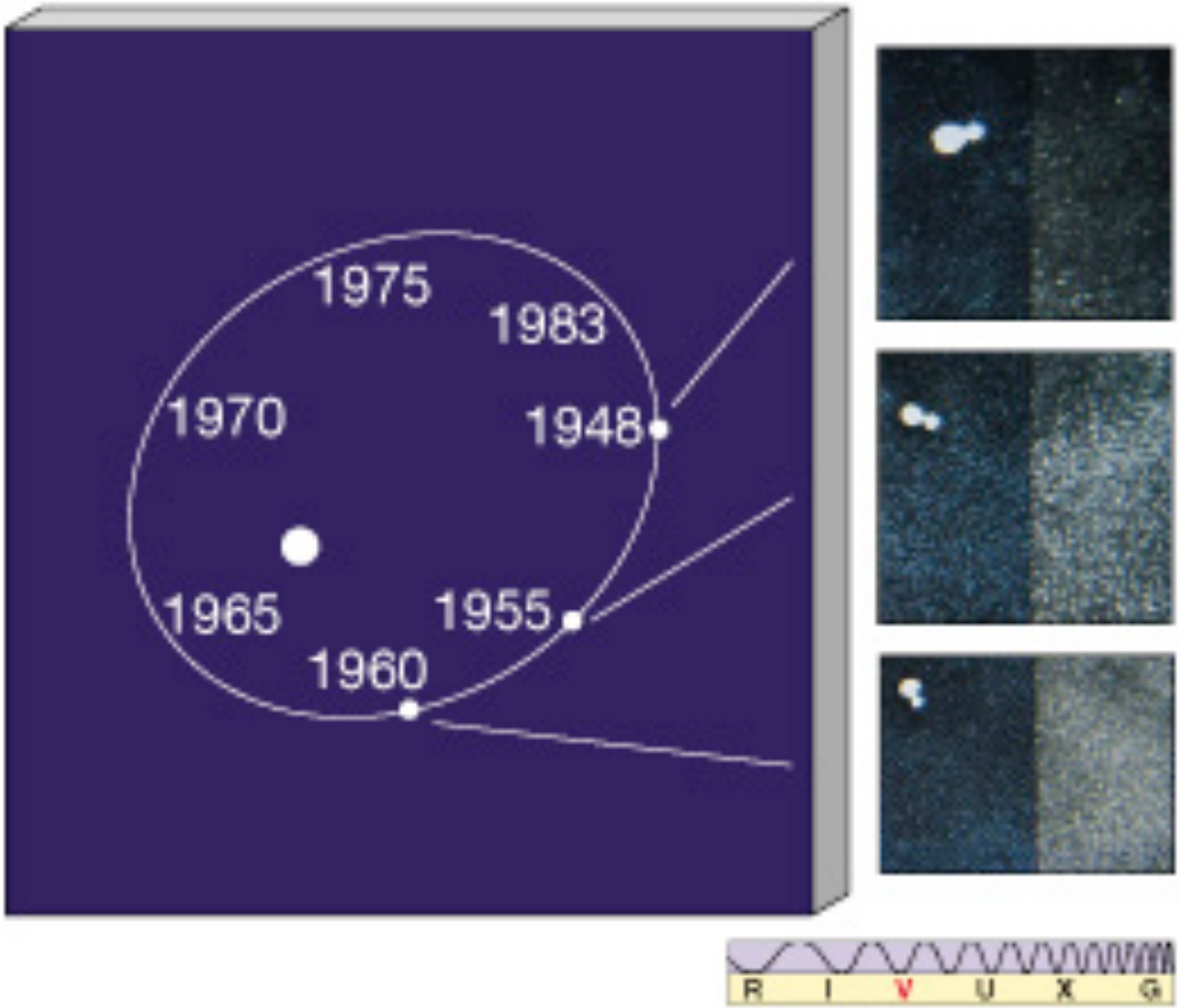
- Interesting note. The mean Density of the Sun is only 1.4 grams/cm^3
- To measure the masses of other stars, we need to find some binary star systems.
- Multiple star systems are common in the Galaxy and make up at least 1/3 of the stars in the Galaxy.

Stellar Mass

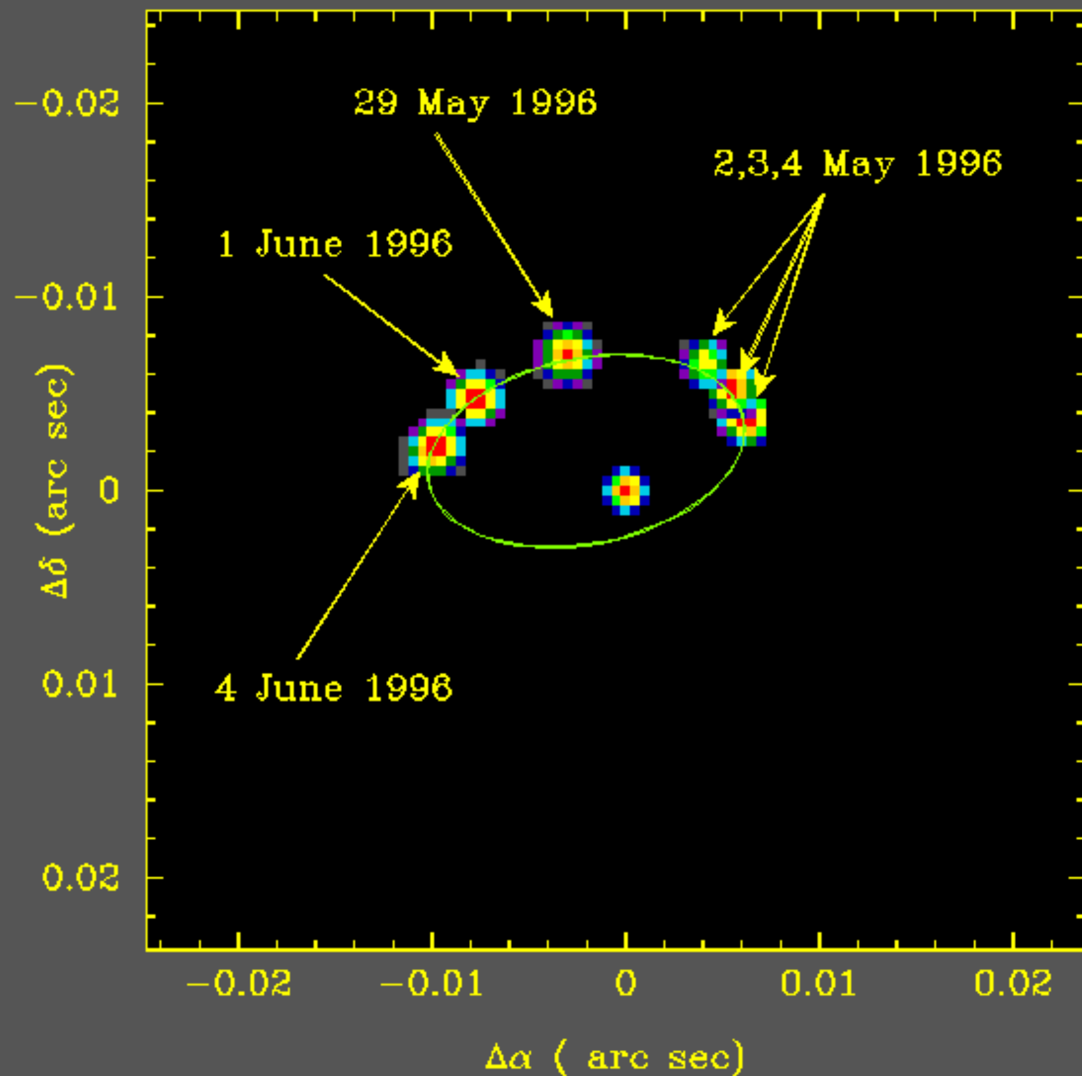
- There are several types of binary system

(1) Optical double -- chance projections of stars on the sky. Not interesting or useful.

(2) Visual double -- for these systems, we can resolve both members, and watch the positions change on the sky over looooong time scale. Timescales for the orbits are 10s of year to 100s of years.

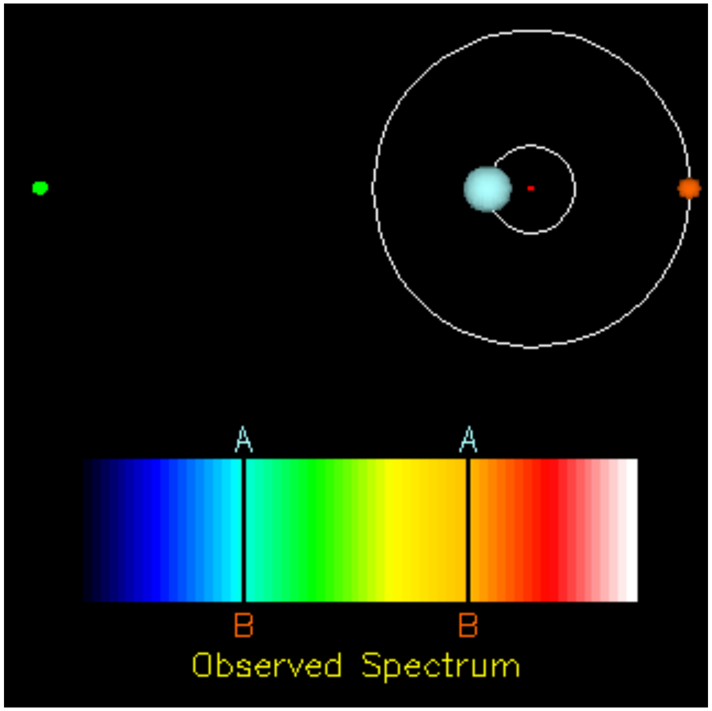

1975
1983
1970
1948
1965
1955
1960
R
I
V
U
X
G

ζ^1 Ursae Majoris



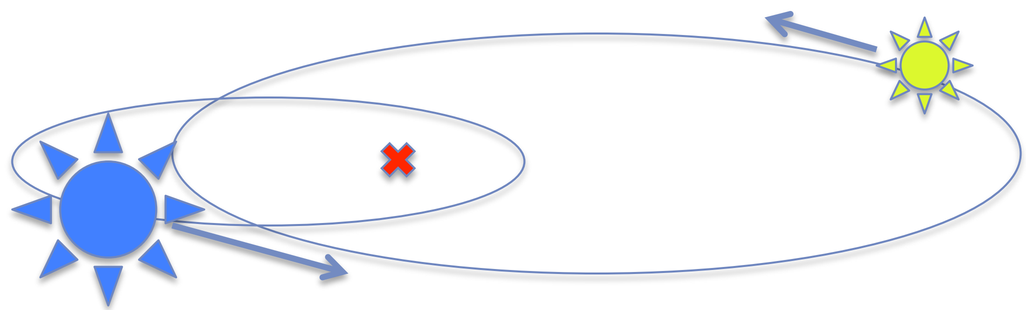
Stellar Mass

(3) Spectroscopic binary -- now it is getting interesting. There are three subclasses, but the basic effect is the same.

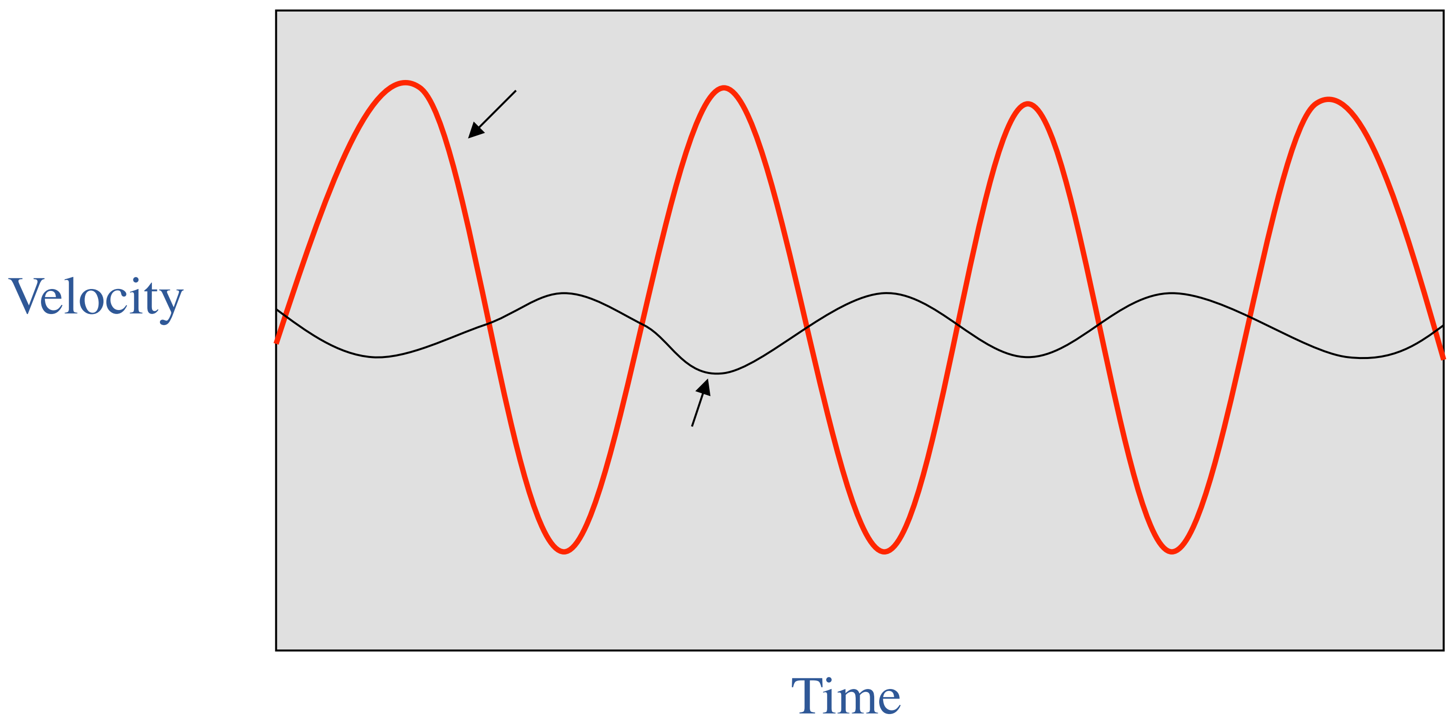


Stellar Masses

- The changing position of the absorption lines is due to the Doppler Effect.
- This is the effect that the apparent frequency of a wave changes when there is relative motion between the source and observer.

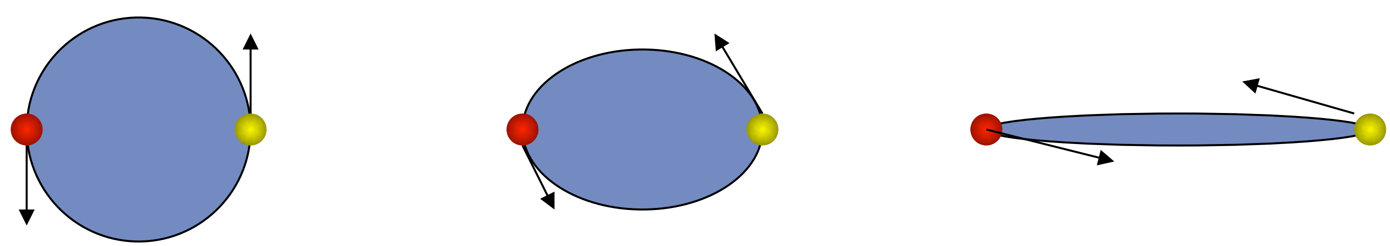


Double-lined Spectroscopic Binary



Stellar Masses

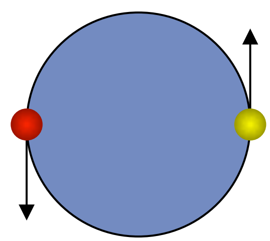
- With Double-lined Spectroscopic Binary stars you can determine the mass of each member of the binary to within a factor of the inclination of the orbit.

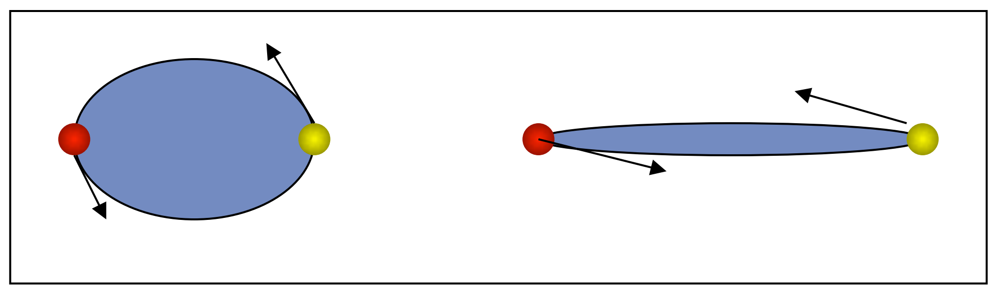


Which of these will show a doppler shift at some parts of the orbit?

Stellar Masses

- With Double-lined Spectroscopic Binary stars you can determine the mass of each member of the binary to within a factor of the inclination of the orbit.

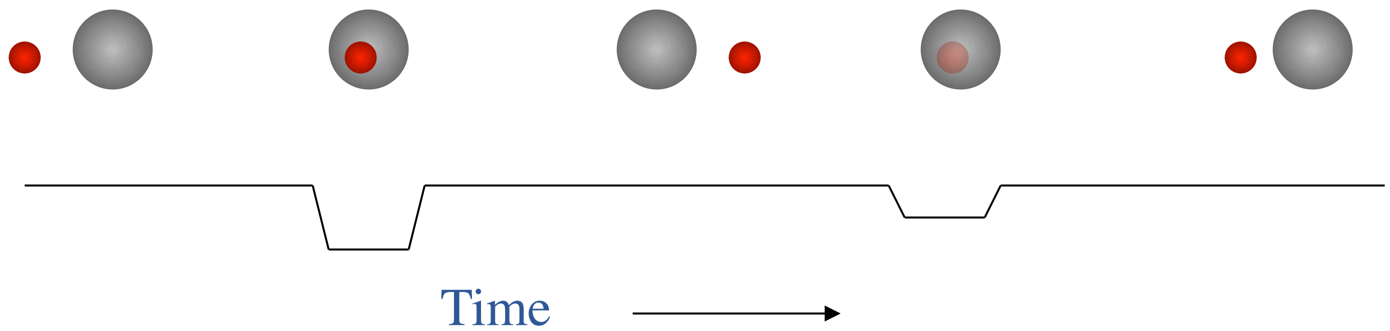




Which of these will show a doppler shift at some parts of the orbit?

Double-Lined Eclipsing Binary

- These are rare and precious! If a binary system has an orbit that is perpendicular to the plane of the sky. For this case the stars will eclipse one another and there will be no uncertainty as to the inclination of the orbit or the derived masses.

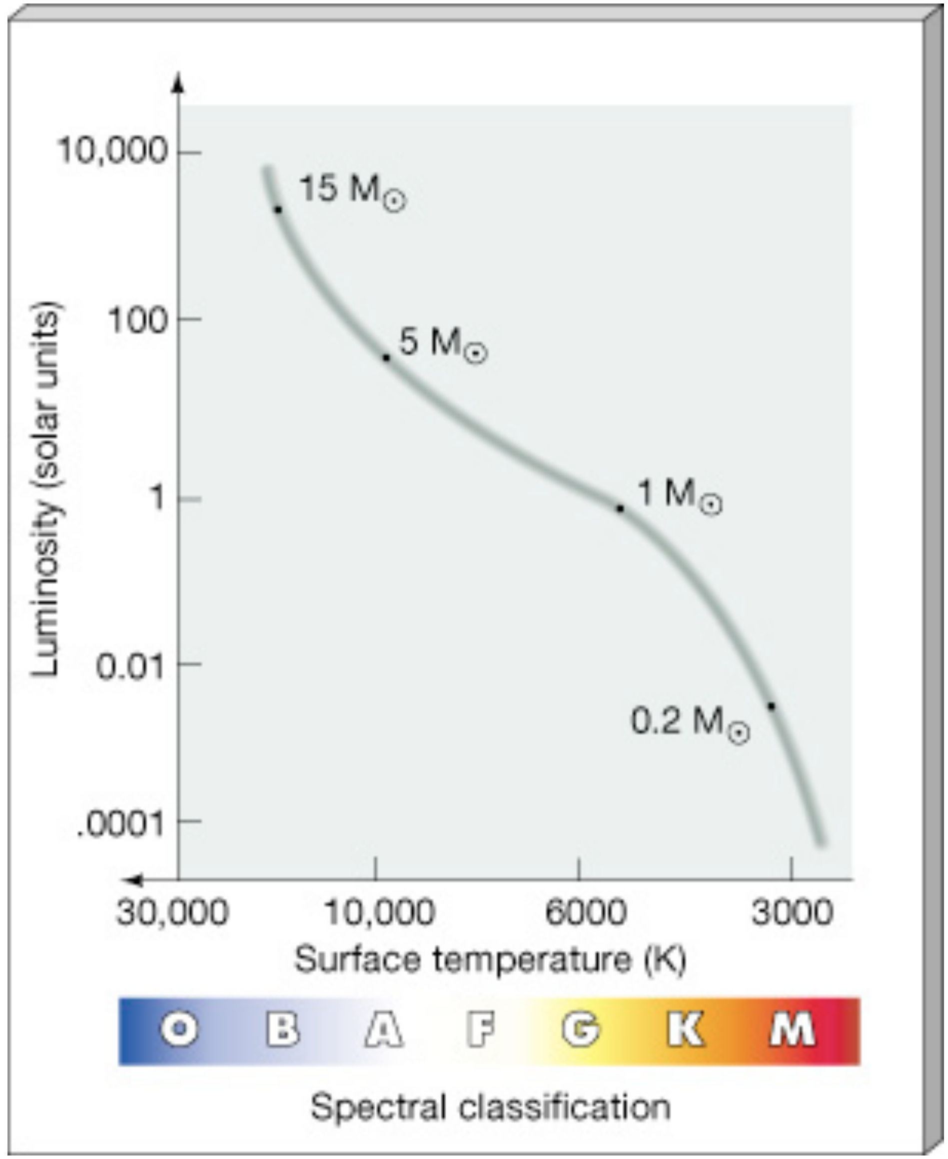


Mass-Luminosity Relation

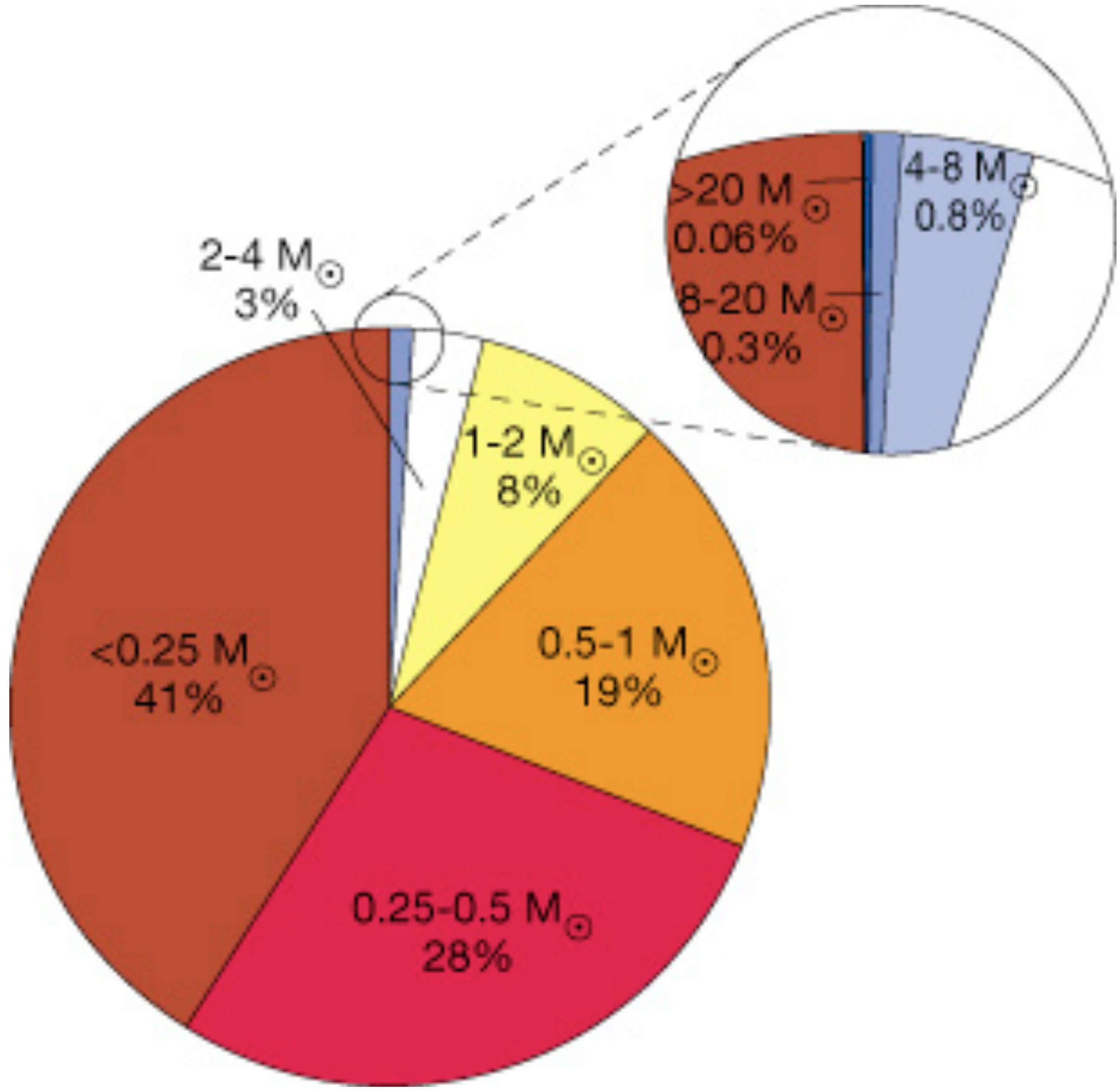
- Measure masses for as many stars as you can and discover that there is a very important Mass-Luminosity relation for main-sequence stars.

$$L \propto M^{3.5}$$

- *The main-sequence in the H-R Diagram is a mass sequence.*
- Temp, Luminosity and Mass all increase and decrease together.

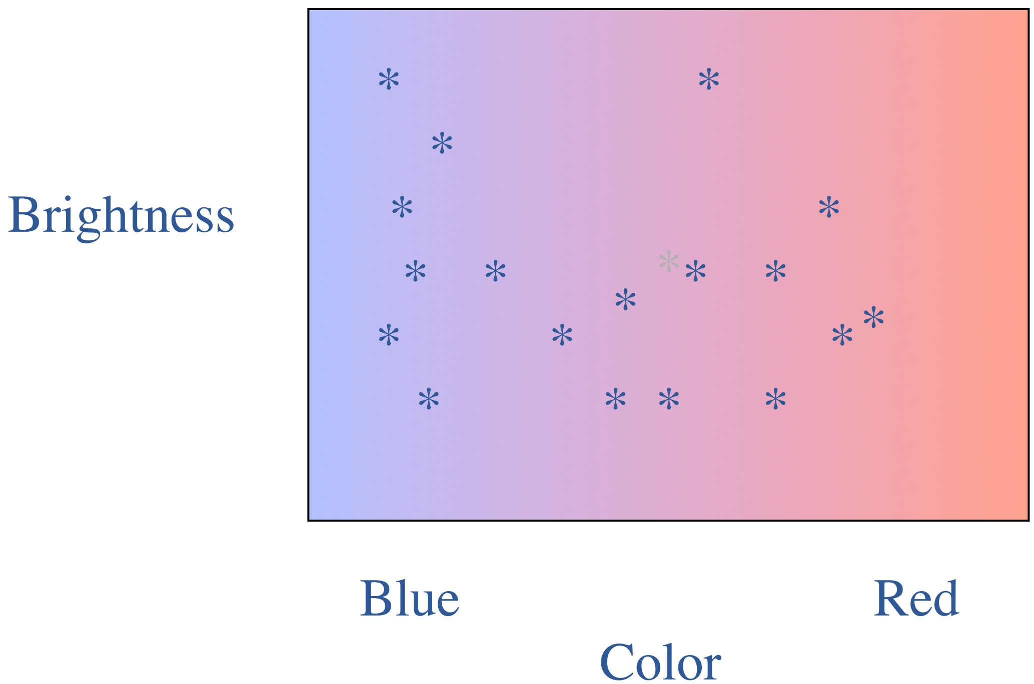


10,000
100
1
0.01
.0001
Luminosity (solar units)
15 $M_\odot$
5 $M_\odot$
1 $M_\odot$
0.2 $M_\odot$
30,000
10,000
6000
3000
Surface temperature (K)
O B A F G K M
Spectral classification


2-4 M☉
3%
>20 M☉
0.06%
8-20 M☉
0.3%
4-8 M☉
0.8%
1-2 M☉
8%
0.5-1 M☉
19%
<0.25 M☉
41%
0.25-0.5 M☉
28%

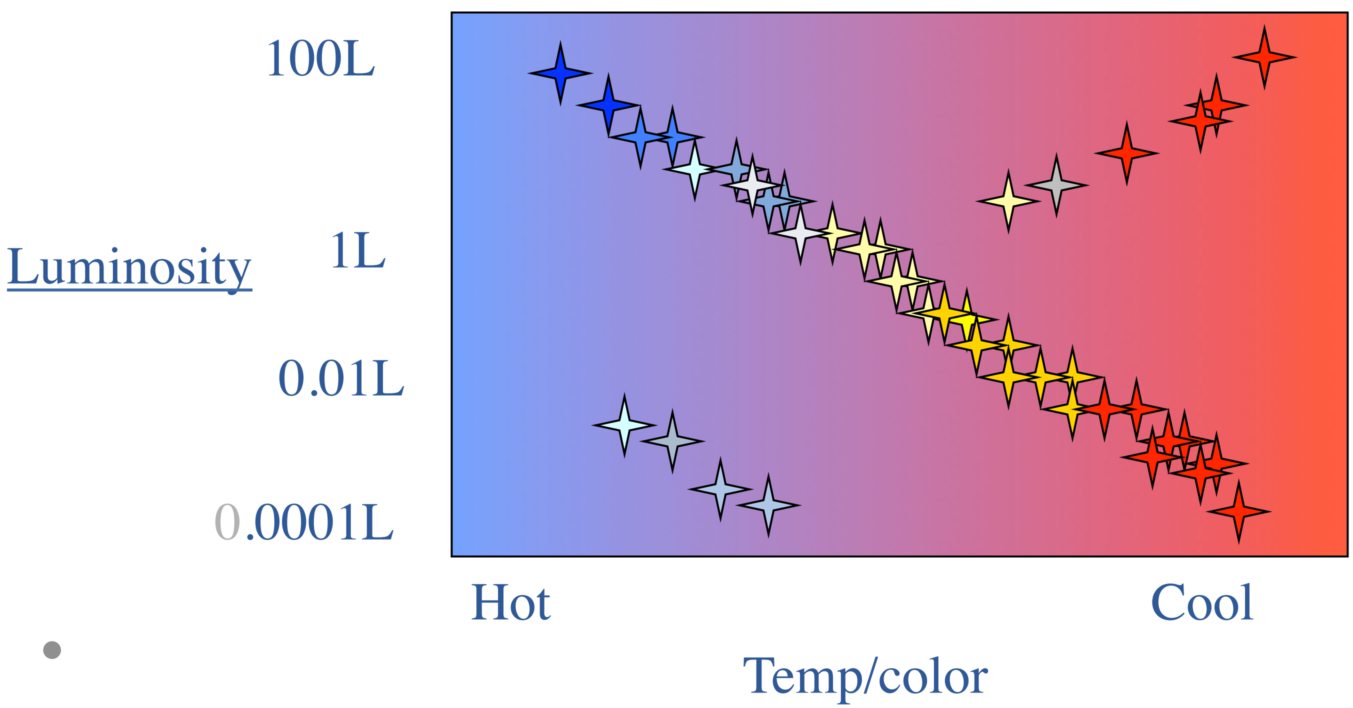
Properties of Stars: The H-R Diagram

- If you plot the brightness vs color (or temperature) for stars the result is a scatter plot.



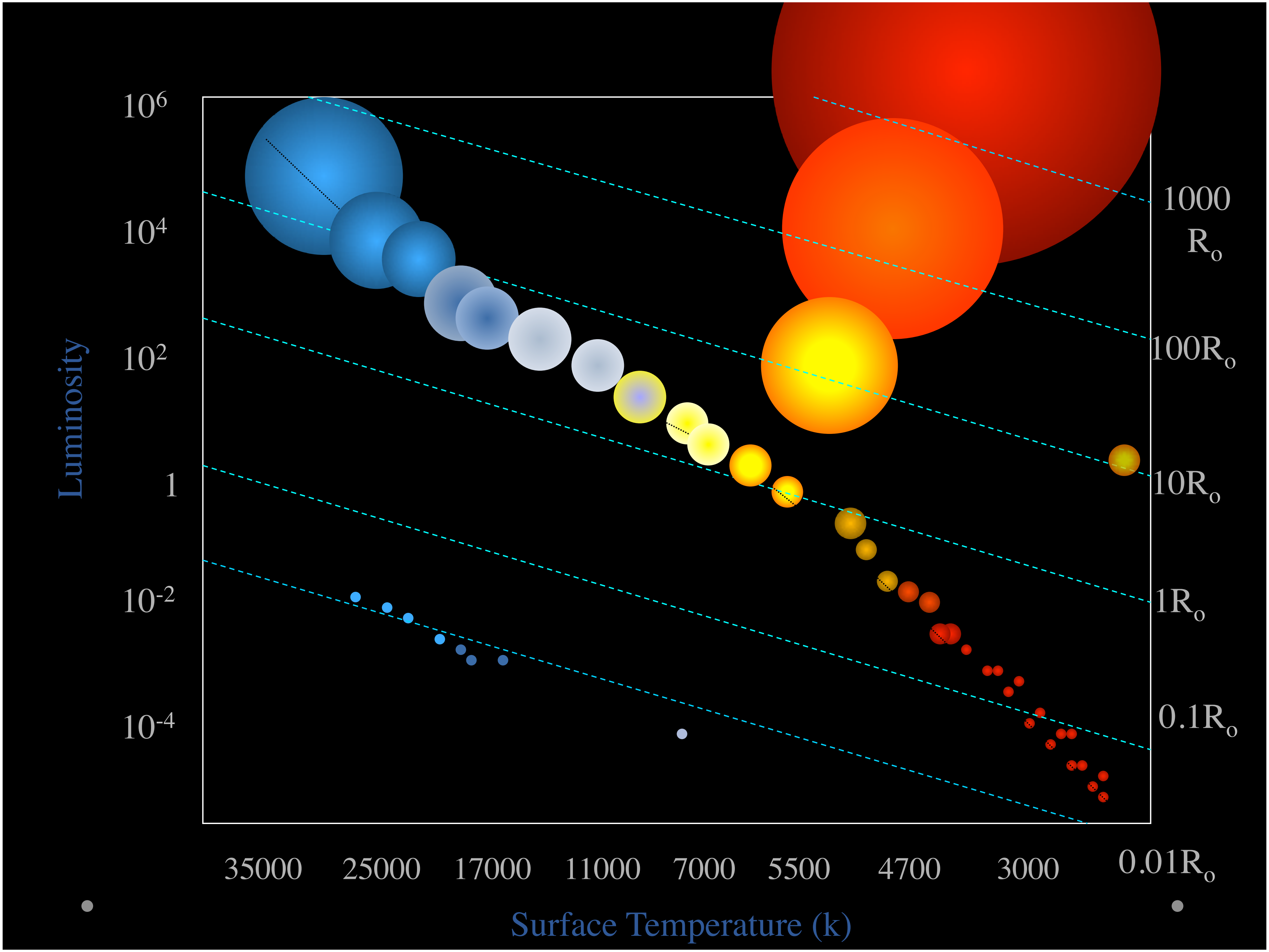
H-R Diagram

- But a plot of Luminosity vs color (or temperature) is called a Hertzsprung-Russell Diagram and shows some interesting sequences.



H-R Diagram

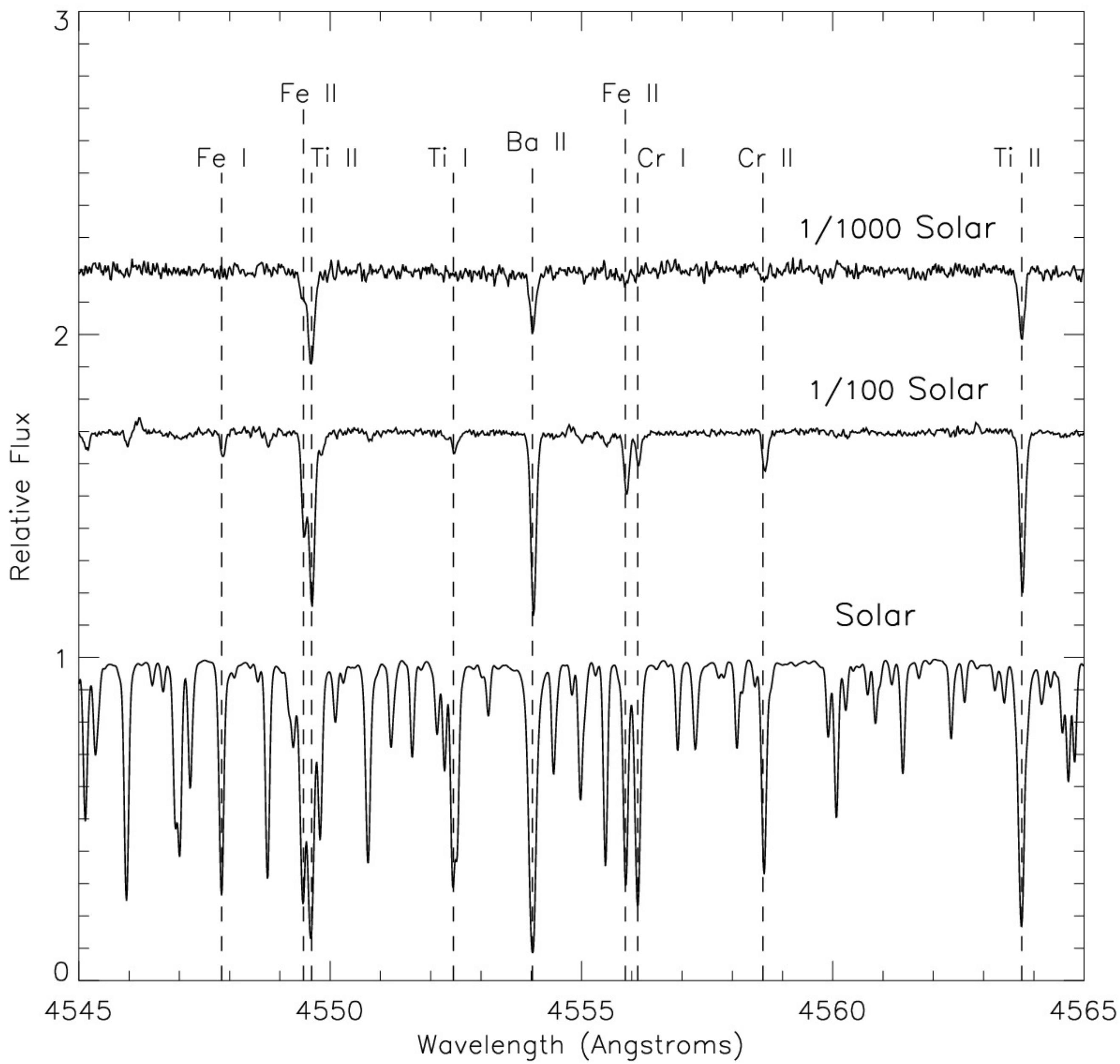
- The majority of stars fall along what is called the main sequence. For this sequence, there is a correlation in the sense that hotter stars are also more luminous.
- The H-R Diagram has played a crucial in developing our understanding of stellar structure and evolution. In about a week we will follow through that history.



Luminosity
10^6
10^4
10^2
1
10^-2
10^-4
1000 R_o
100R_o
10R_o
1R_o
0.1R_o
0.01R_o
35000
25000
17000
11000
7000
5500
4700
3000
Surface Temperature (k)

Chemical Composition

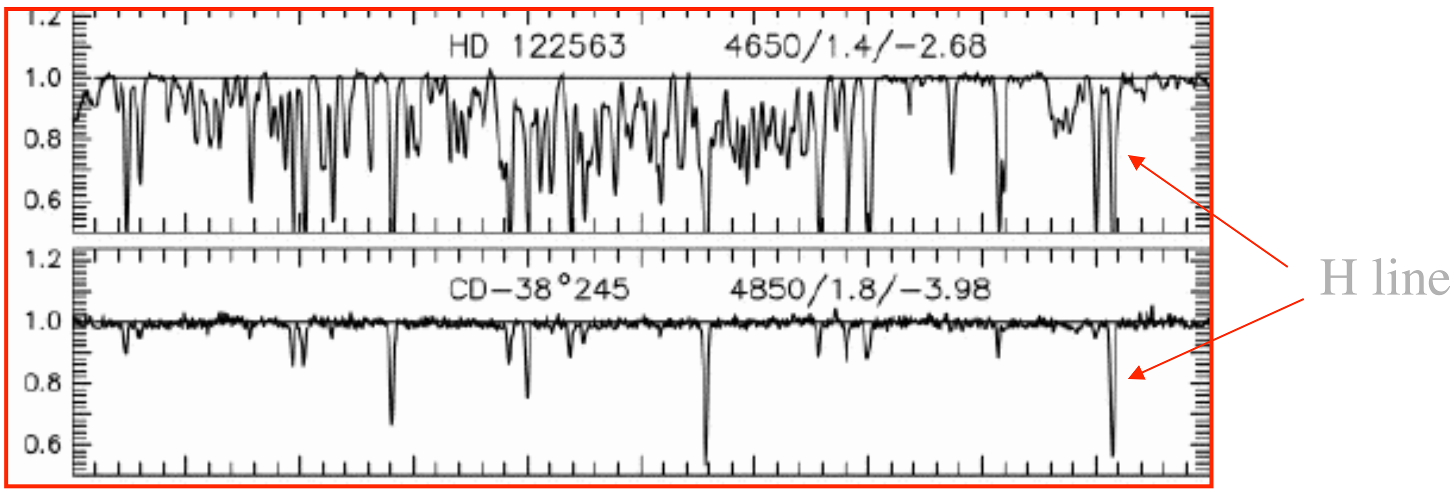
- We can also determine the abundances of many elements in stars by using the `atomic fingerprints' seen in spectral absorption lines.



Fe II
Fe II
Fe I
Ti II
Ti I
Ba II
Cr I
Cr II
Ti II
1/1000 Solar
1/100 Solar
Solar
Relative Flux
0
1
2
3
4545
4550
4555
4560
4565
Wavelength (Angstroms)

Chemical Composition

- We find that most stars in the galaxy have a composition very similar to that of the Sun which is 70% H, 28% He and 2% everything else.
- But, very interestingly, there are stars that are deficient in the abundances of all elements with Z>2 compared to the Sun.



Chemical Composition

- There is a very interesting story of the chemical enrichment history of the Galaxy and Universe that goes with these `metal-poor' stars that we will return to in a few weeks. For now will only note that the chemically deficient stars are the oldest stars in the Galaxy. So far the most chemically deficient star known has an abundance of iron about 1/100,000 that of the Sun.

Stellar Properties

Property	Technique	Range of Values
Distance	Trig parallax	1.3pc - 100pc
Surface Temp.	Colors/Spec Type	3000K-50000K
Luminosity	Distance +brightness	$10^{-5}L_o$ - $10^{6}L_o$
Radius	Stephan's Law	$0.01R_o$ - $800R_o$
Mass	Binary orbits	$0.08M_o$ - $80M_o$