

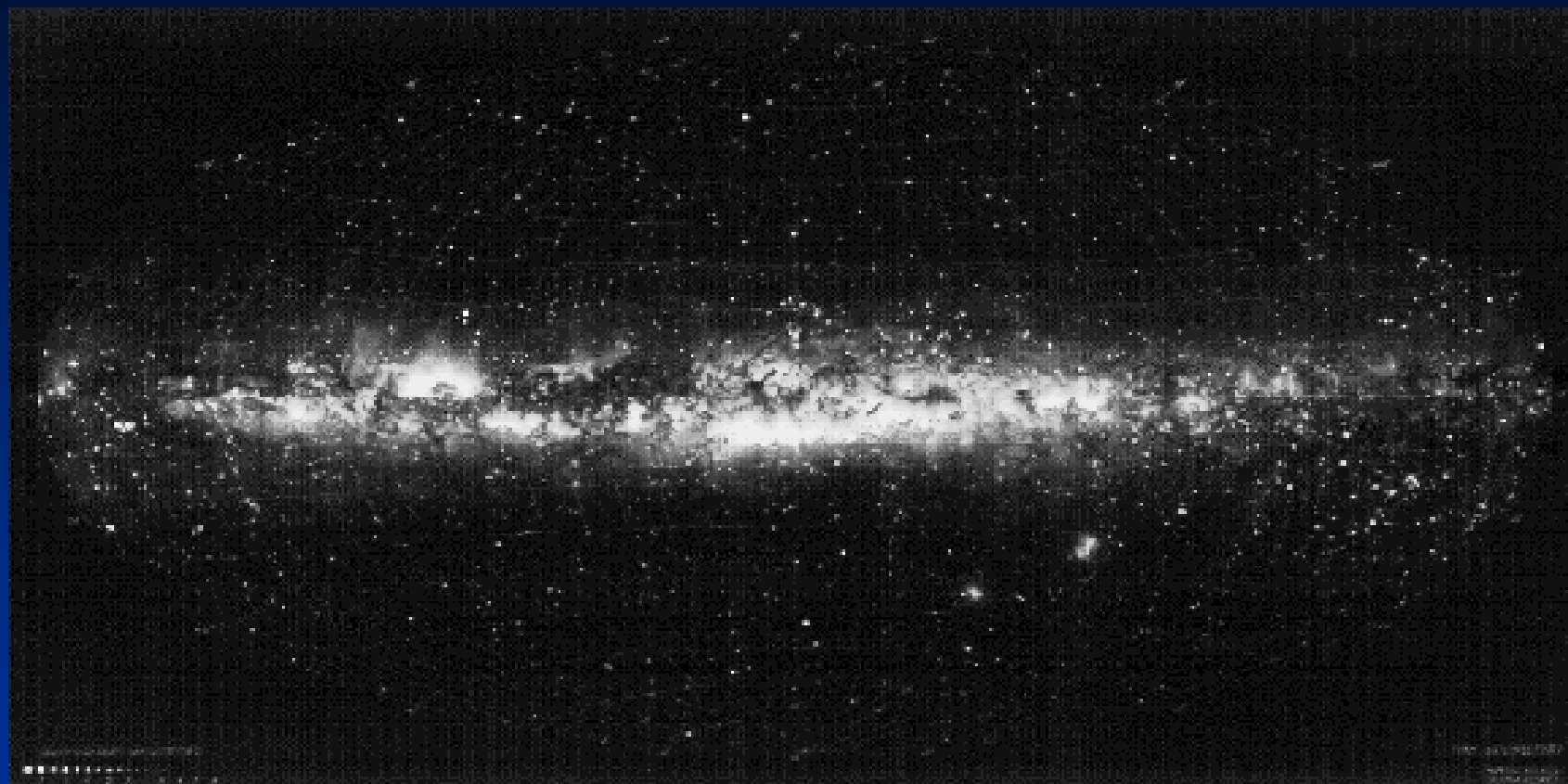
Announcements

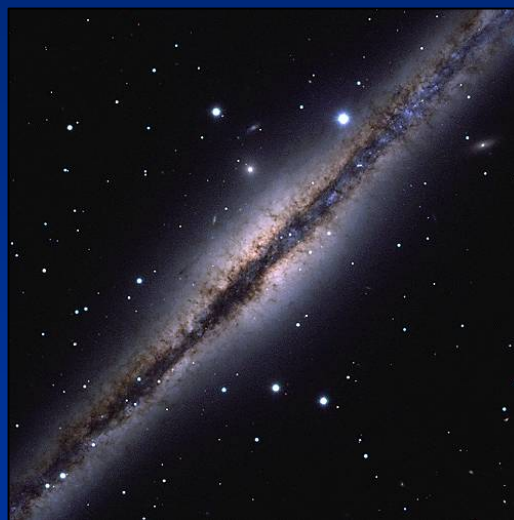
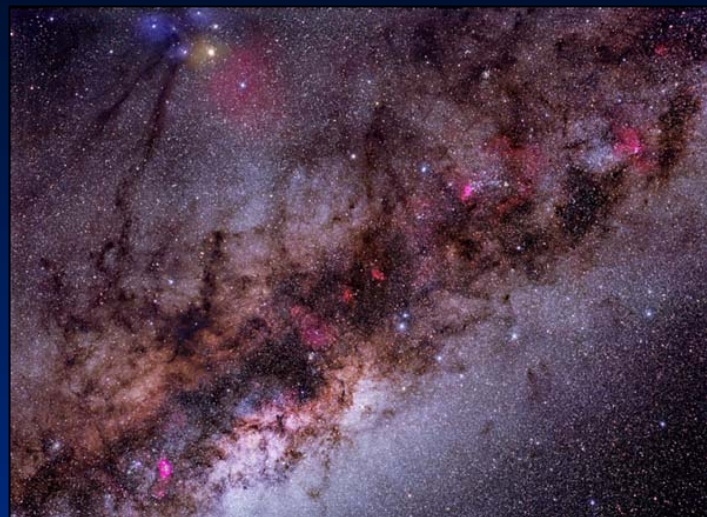
- Next section will be about the properties of stars and how we determine them.
- The spectral lab will be on April 22nd in class. Don't miss it!

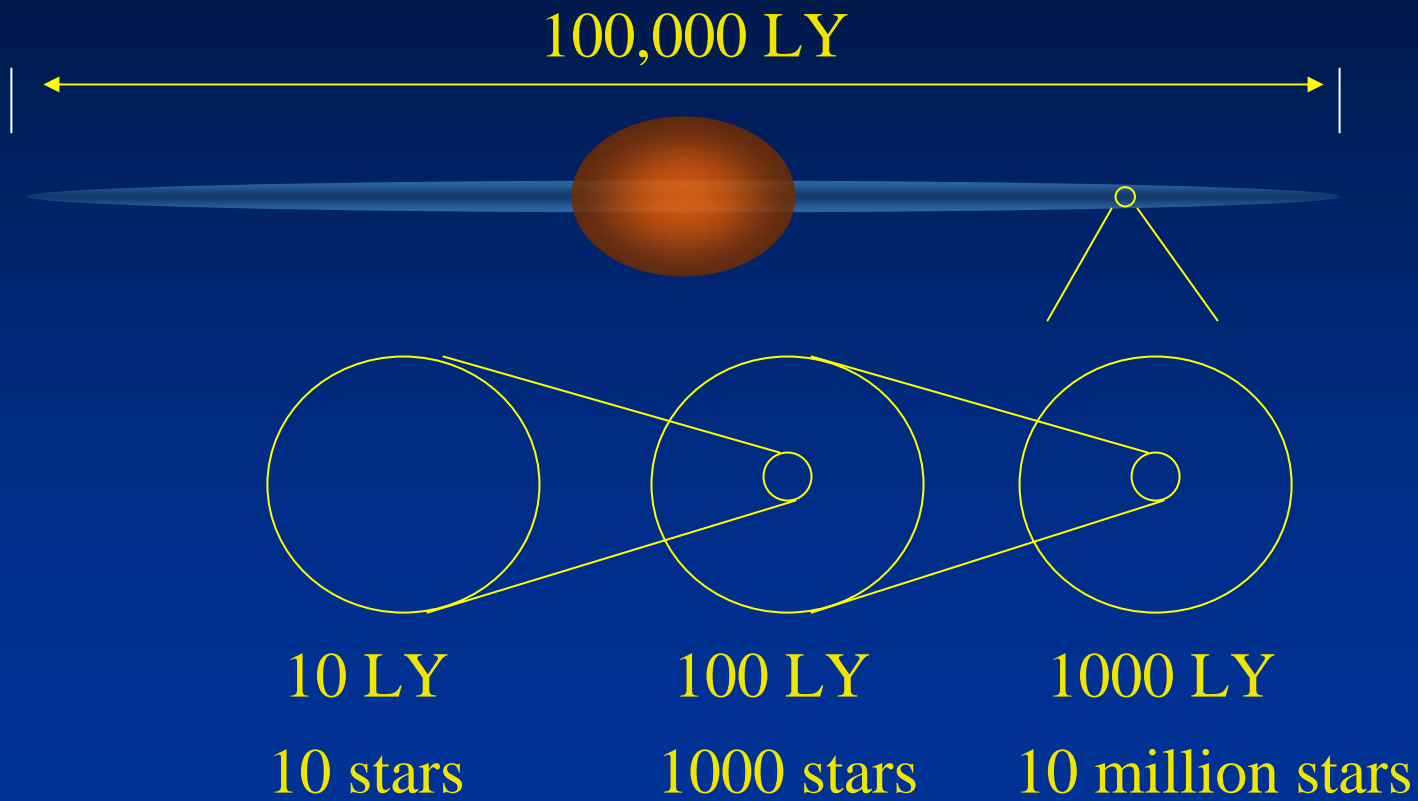
The Bigger Picture

- We live on the outskirts of a pretty good-sized spiral galaxy composed of about *100 billion* stars.
- There are only about 6000 stars that you can see with the unaided eye -- not even the tip of the iceberg.
- At a dark site, you can see a diffuse glow tracing and arc across the sky. This is the *Milky Way* and our galaxy is sometimes referred to as the *Milky Way Galaxy* (or just the Galaxy)



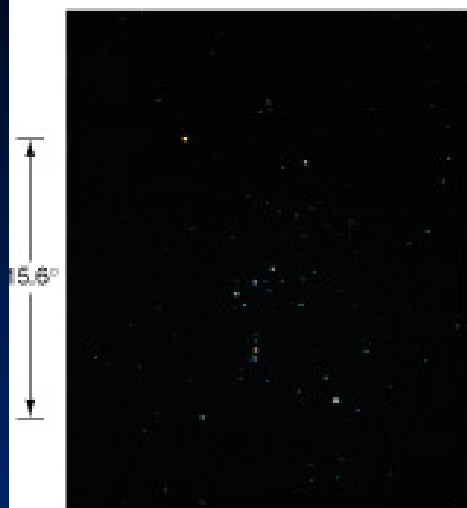






Stellar Constellations

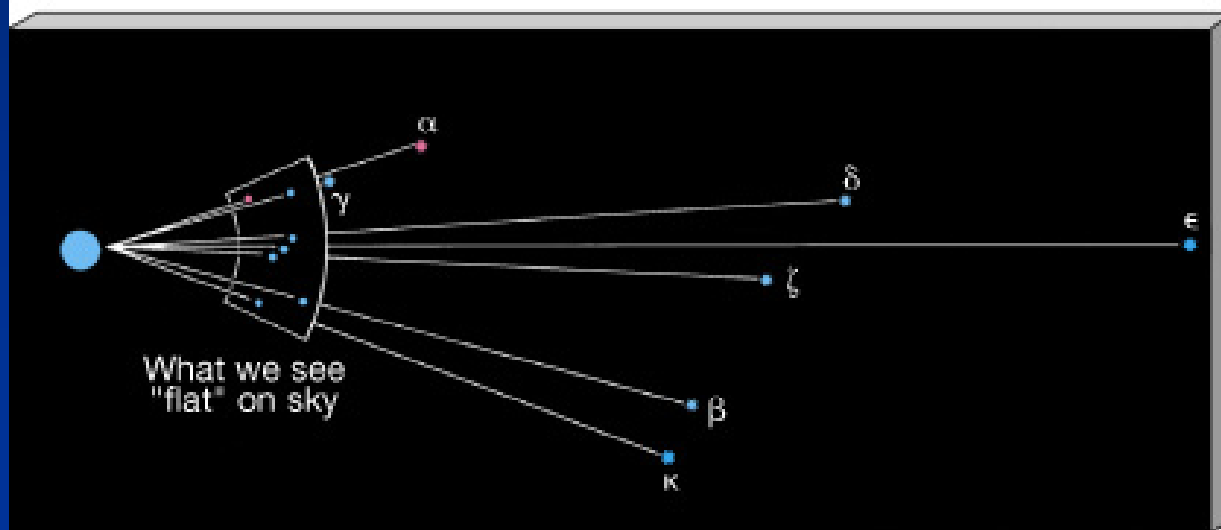
- These are just people connecting dots.
- The stars that make up constellations are in almost all cases only close together in **projection** on the sky. They are not physical groupings of stars.



(a)



(b)



(c)

What about Star Names?

- The brightest stars have lots of names, none official. There are some widely-used catalogues.
- A convention often used in astronomy is to use the Greek alphabet to identify the brightest stars in the constellations.

For example: Sirius = α Canis Majoris is the brightest star in the constellations Canis Major.

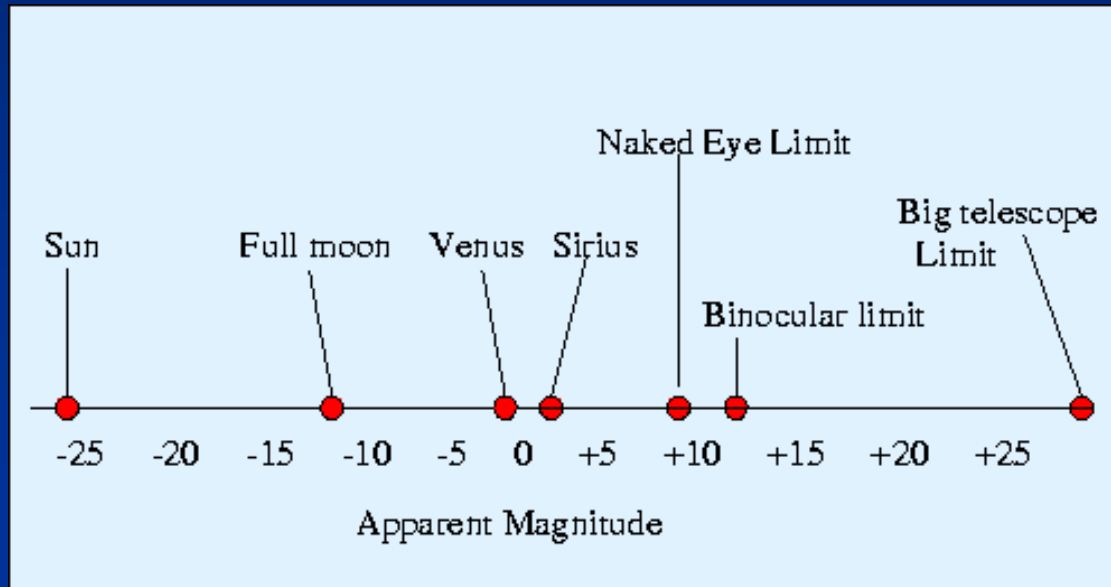
β Canis Majoris is the second brightest etc.

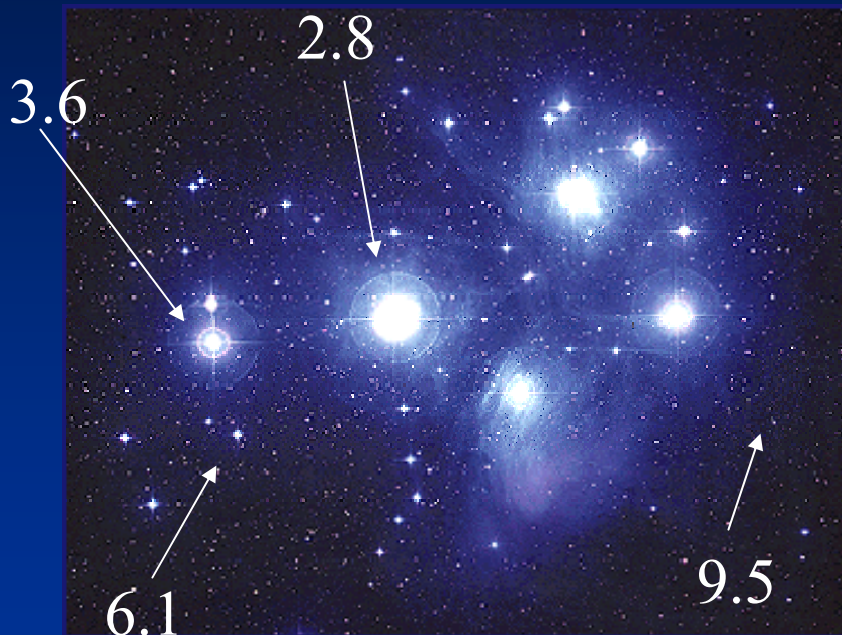
Stellar Properties

- *Brightness* - combination of distance and L
- *Distance* - this is crucial
- *Luminosity* - an important intrinsic property that is equal to the amount of energy produced in the core of a star
- *Radius*
- *Temperature*
- *Chemical Composition*

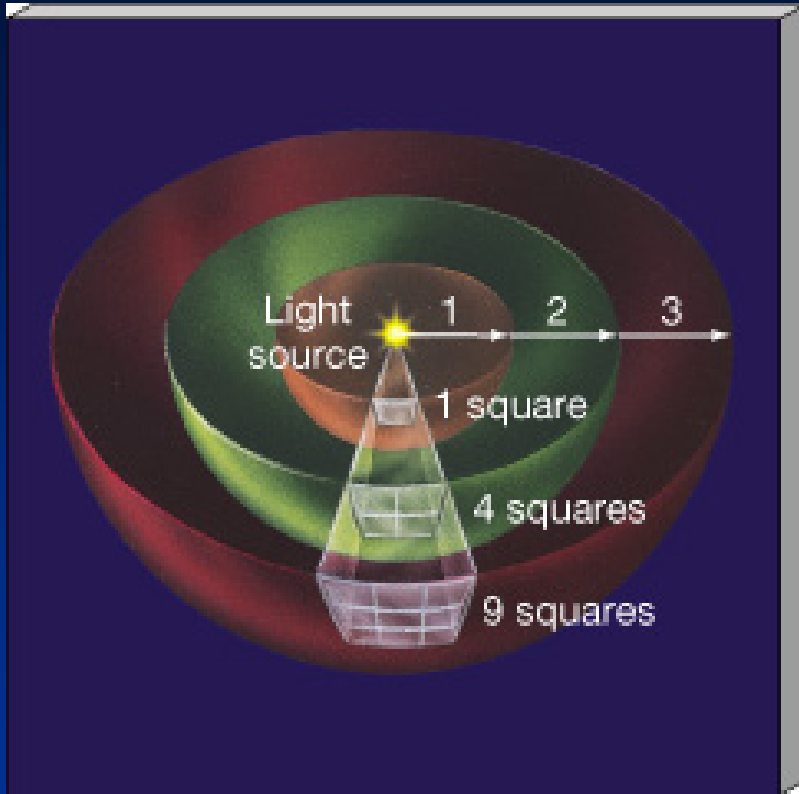
Stellar Brightness

- Will use brightness to be *apparent* brightness.
- This is not an INTRINSIC property of a star, but rather a combination of its Luminosity, distance and amount of dust along the line of sight.





- The apparent brightness scale is logarithmic based on 2.5, and it runs backward.
- Every 5 magnitudes is a factor of 100 in intensity. So a 10th magnitude star is 100x fainter than a 5th magnitude star



- The inverse square law is due to geometric dilution of the light. At each radius you have the same total amount of light going through the surface of an imaginary sphere. Surface area of a sphere increases like R^2 .
- The light/area therefore decreases like $1/R^2$

- Suppose we move the Sun to three times its current distance. How much fainter will the Sun appear?

Original distance

$$\frac{I}{I_0} = \frac{d_0^2}{d^2} = \left(\frac{d_0}{d}\right)^2 = \left(\frac{1}{3}\right)^2 = \frac{1}{9}$$

Original brightness

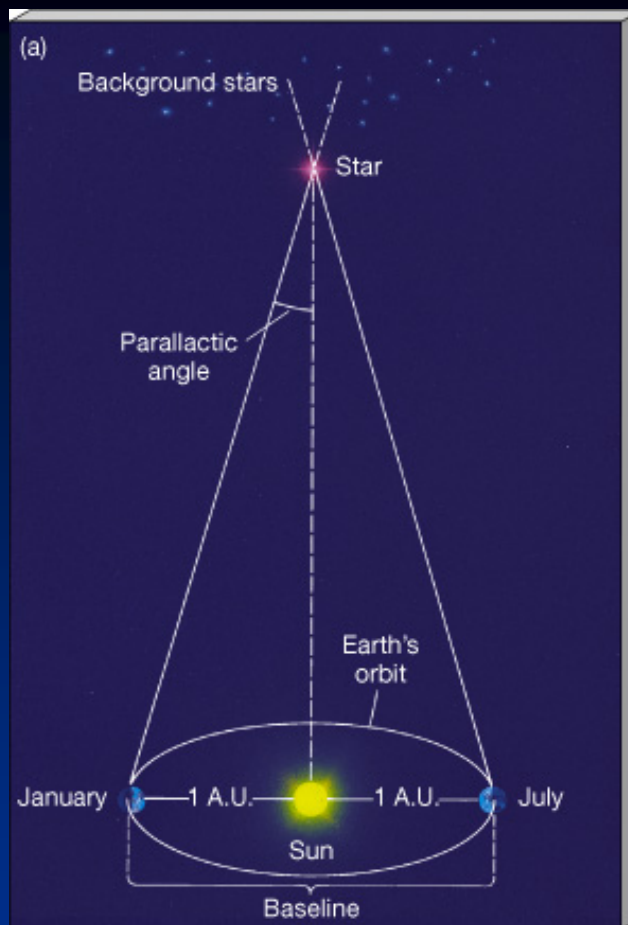
$$I = \frac{1}{9} I_0$$

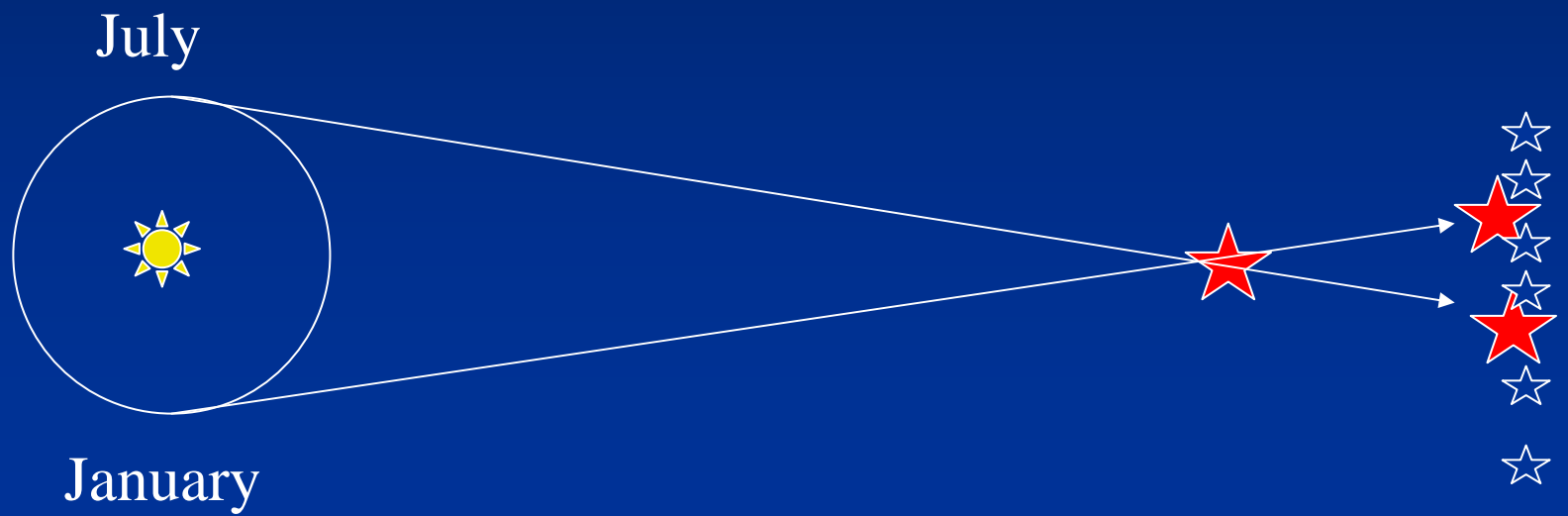
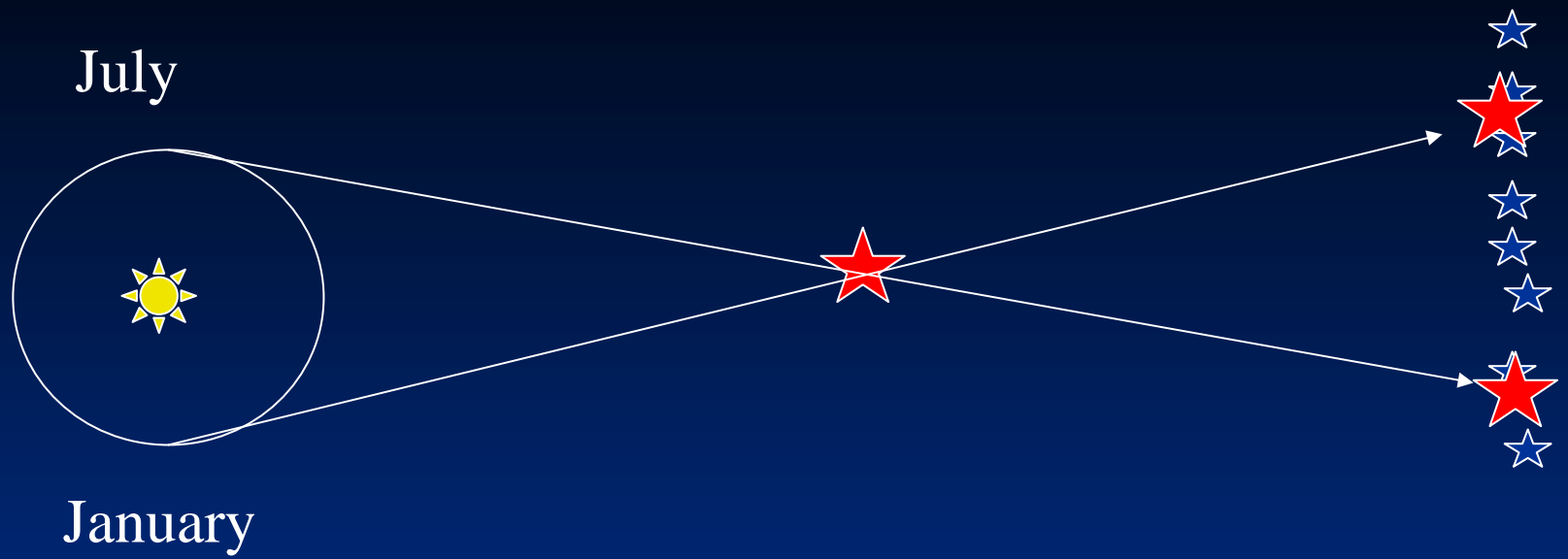
Stellar Distances

- 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.
- Put a finger in front of your nose and watch it move with respect to the back of the room as you look through one eye and then the other.

Stellar Distances

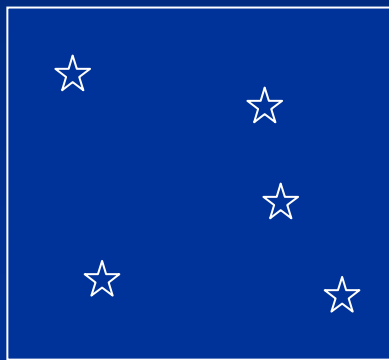
- For the experiment with your finger in front of your nose, the baseline for the parallax effect is the distance between your eyes.
- For measuring the parallax distance to stars, we use a baseline which is the *diameter of the Earth's orbit*.
- There is an apparent annual motion of the nearby stars in the sky that is really just a reflection of the Earth's motion around the Sun.



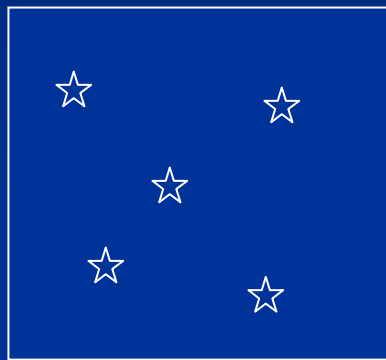


Stellar Parallax

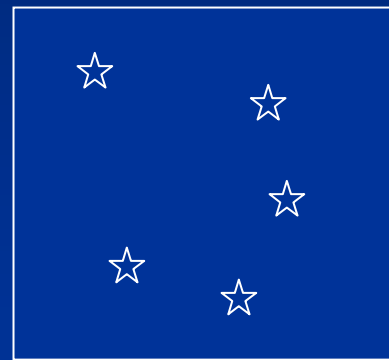
- Need to sort out parallax motion from proper motion -- in practice it requires years of observations.



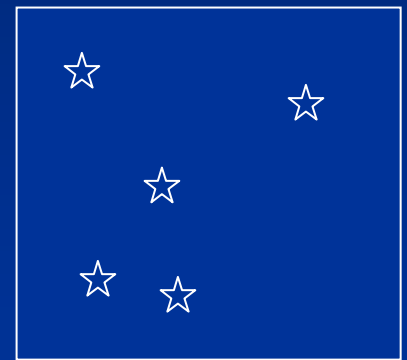
Jan 01



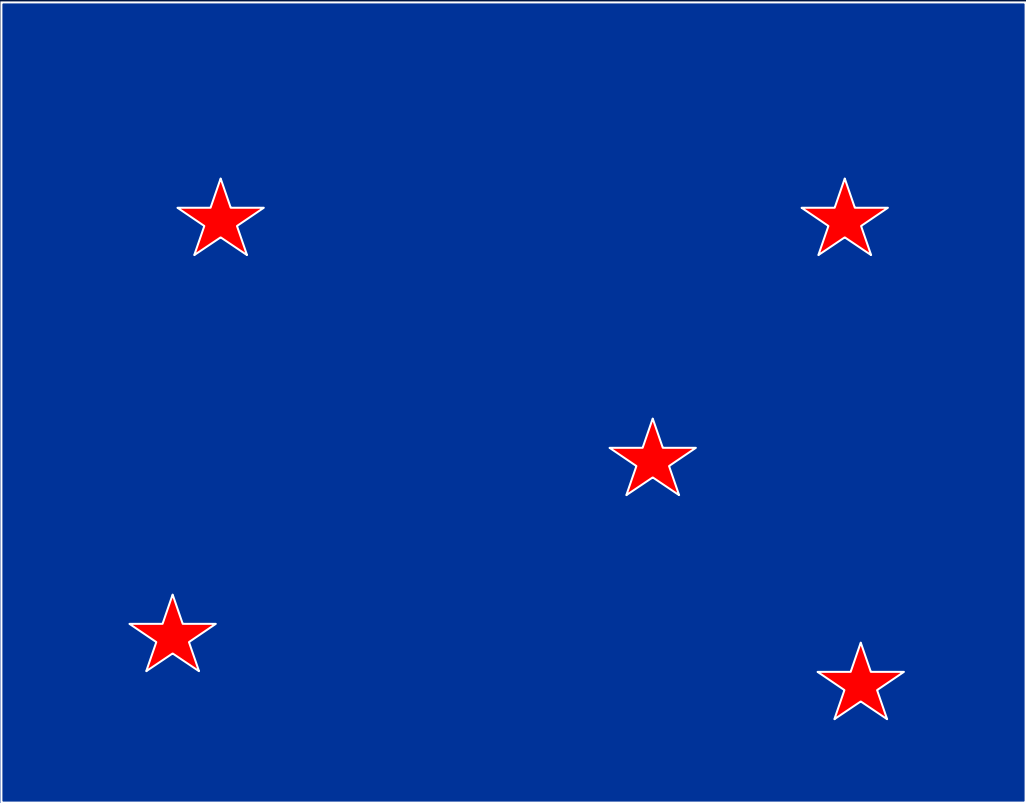
July 01

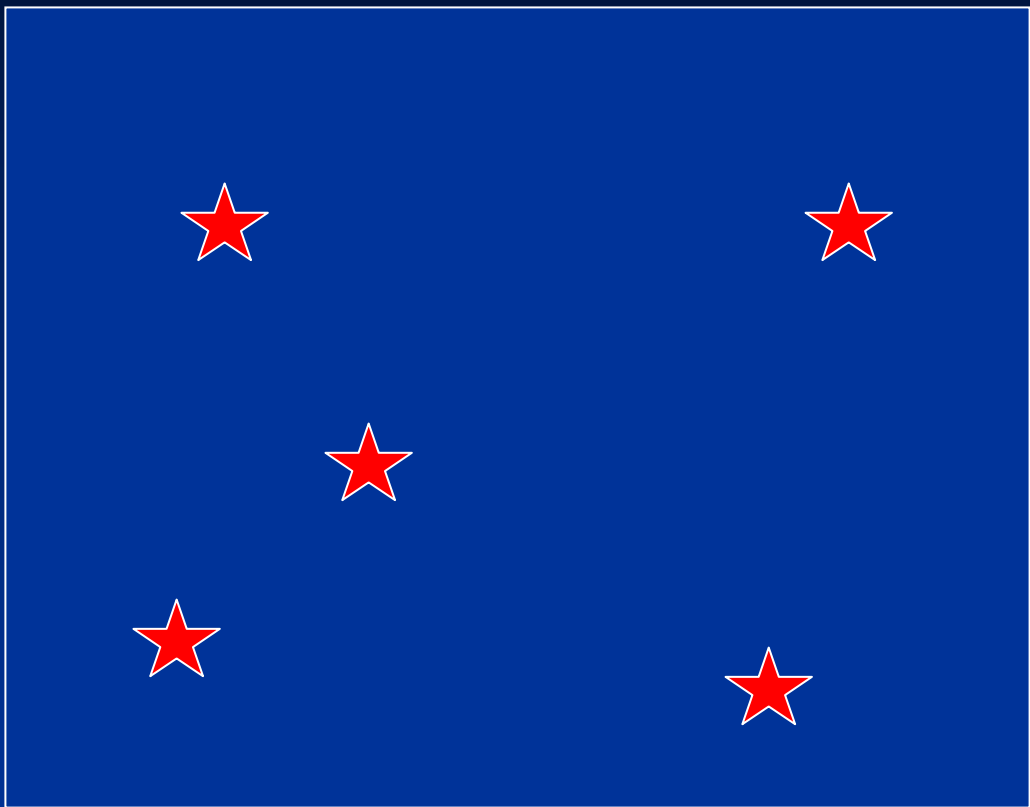


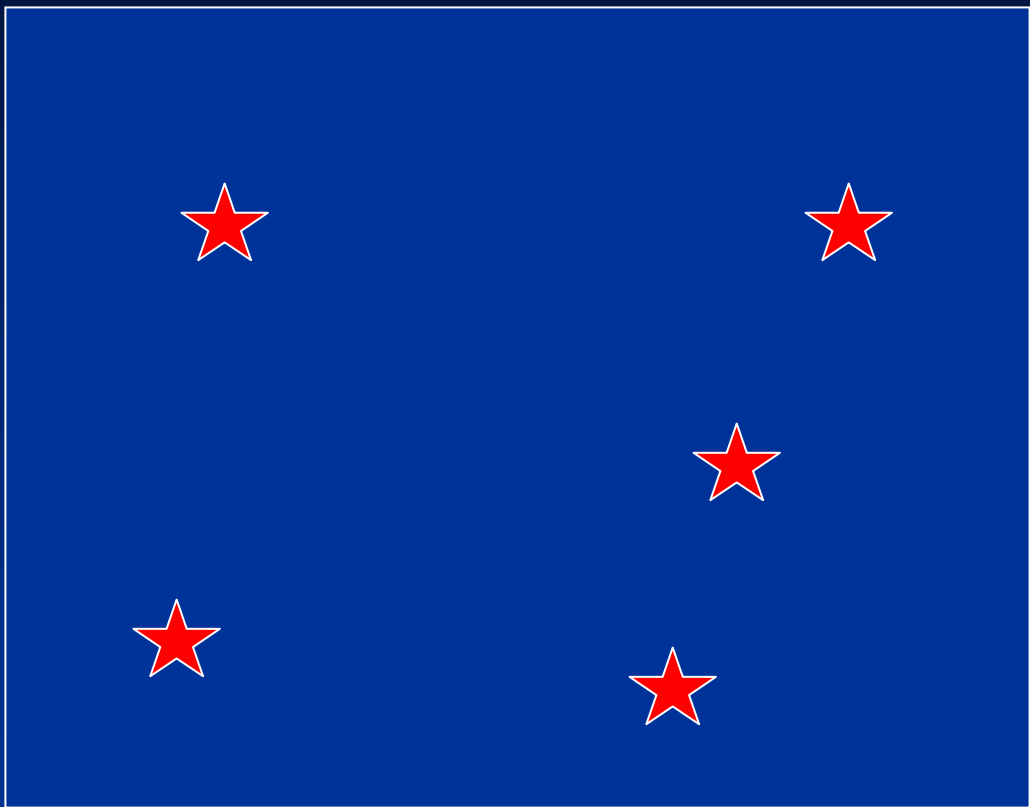
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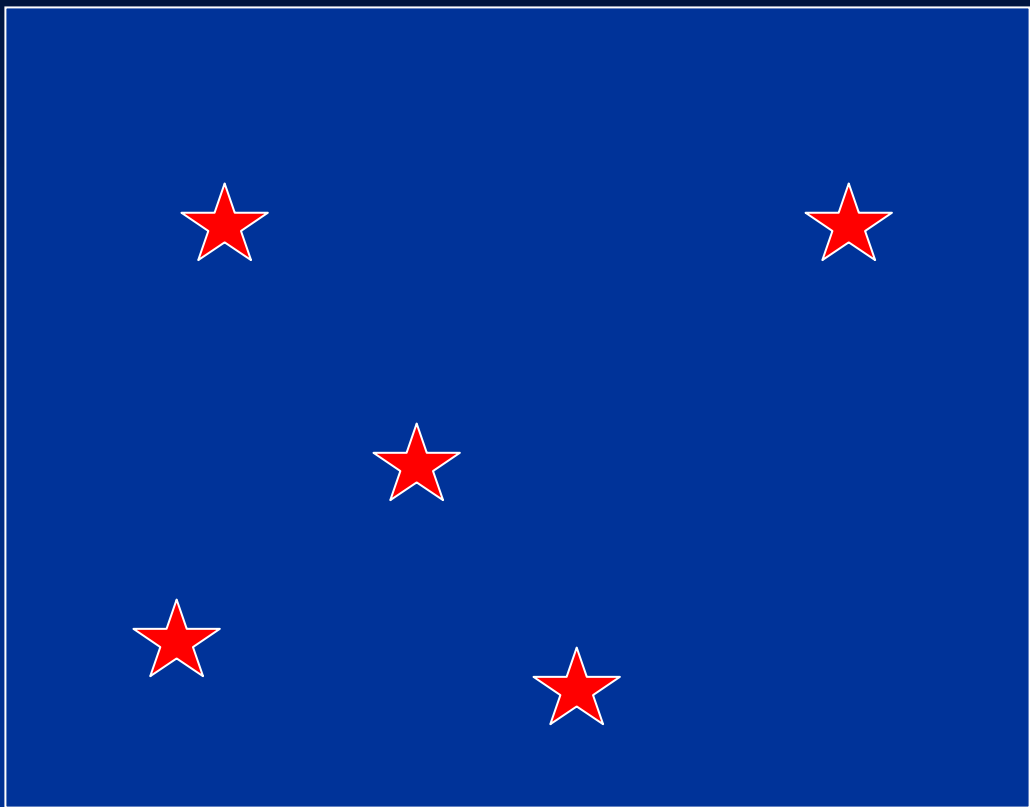


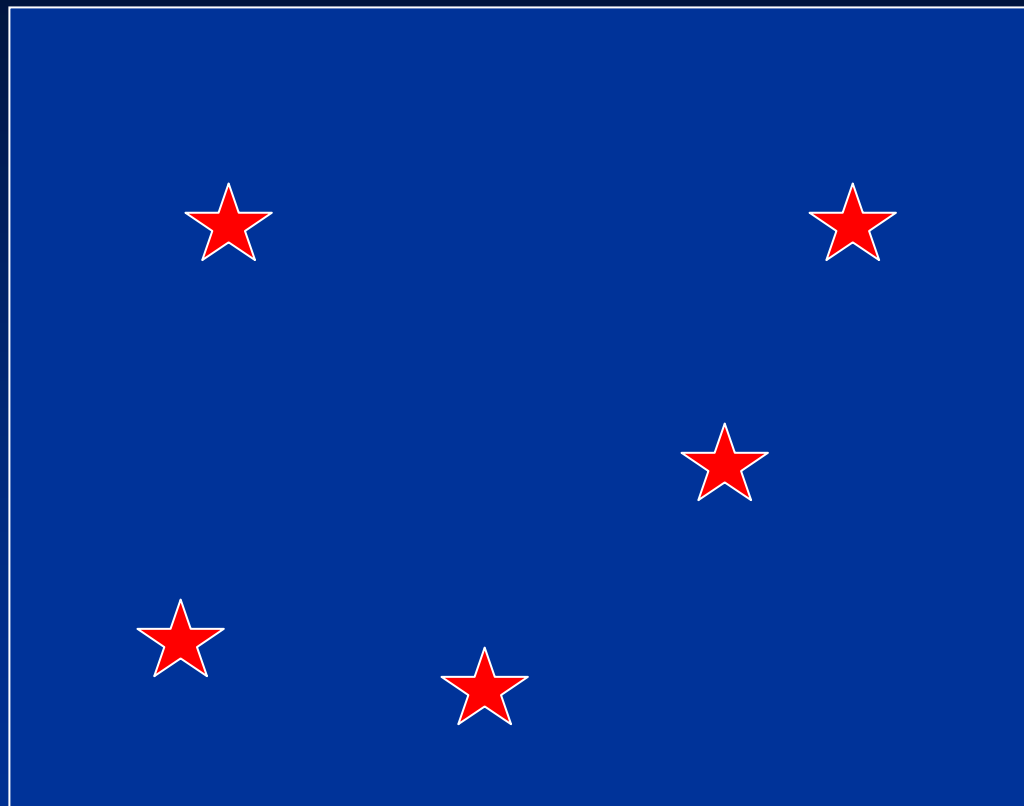
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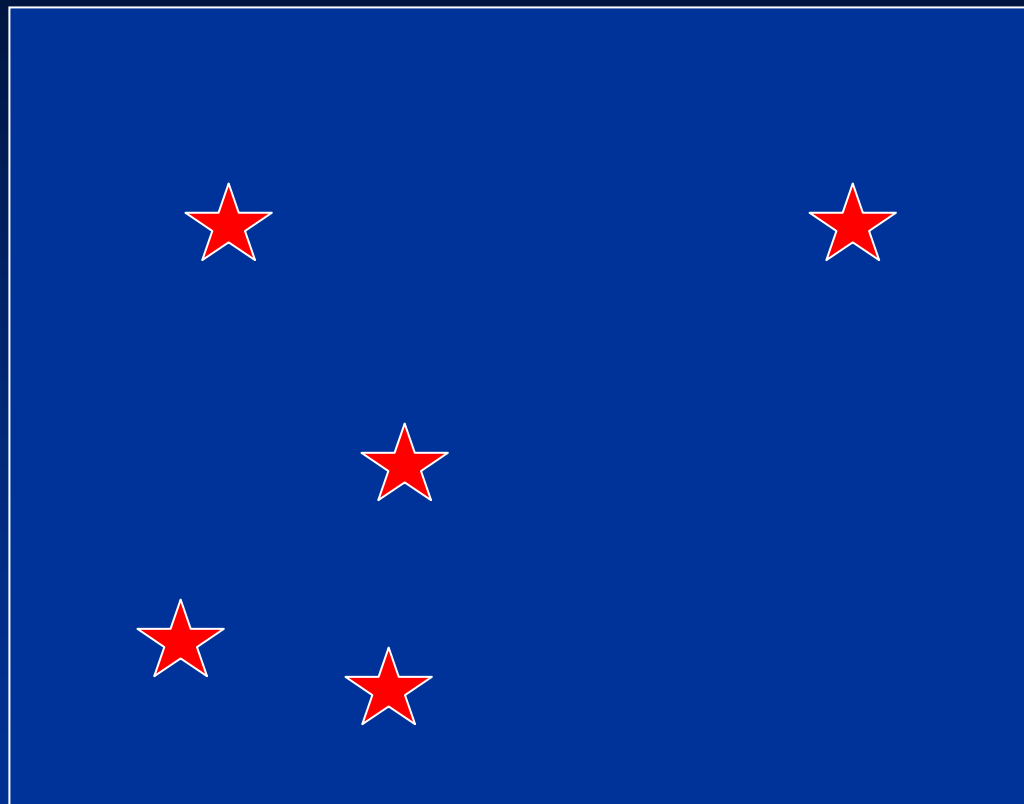


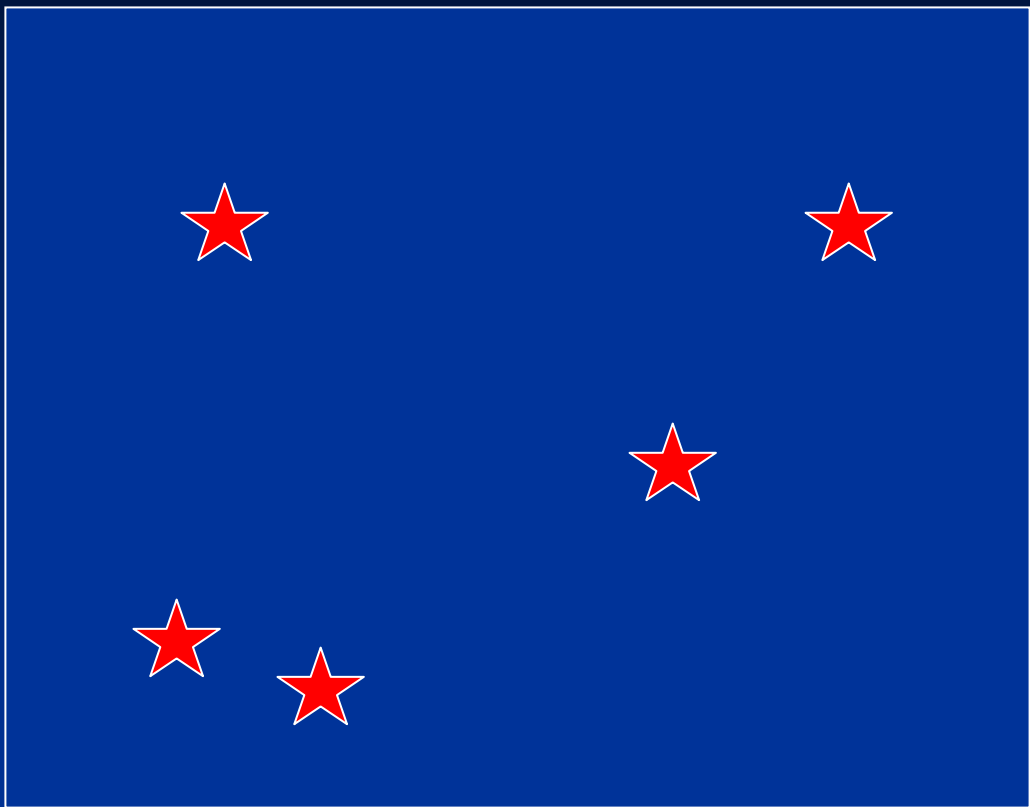


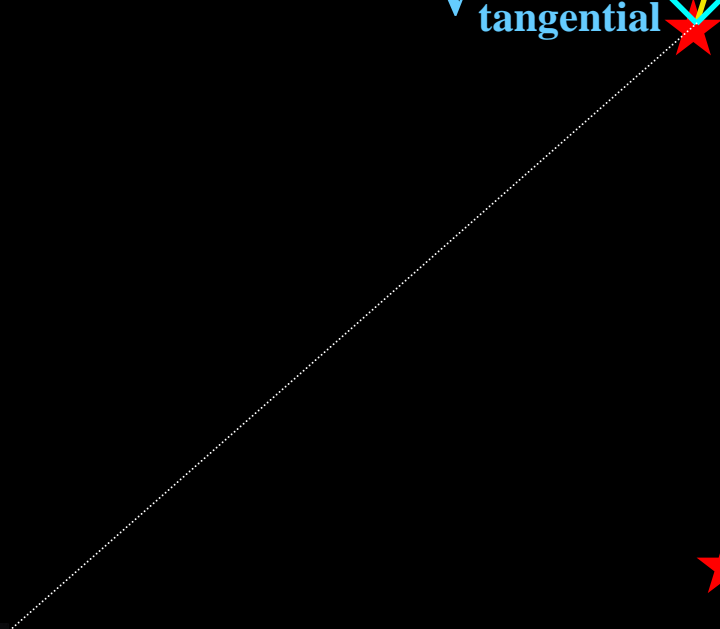












$V_{\text{tangential}}$

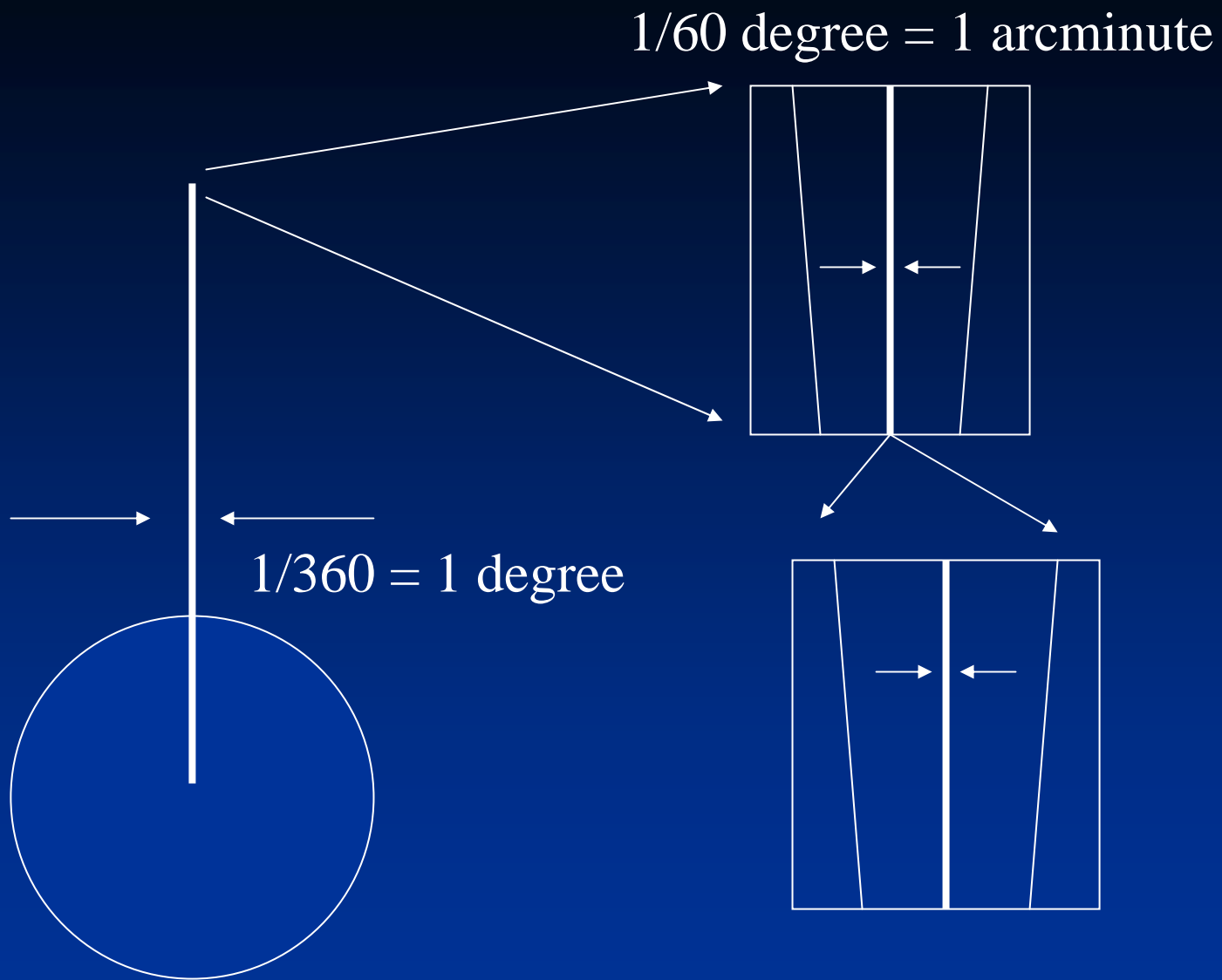
V_{radial}

V



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.



$1/60 \text{ arcminute} = 1 \text{ arcsecond}$

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

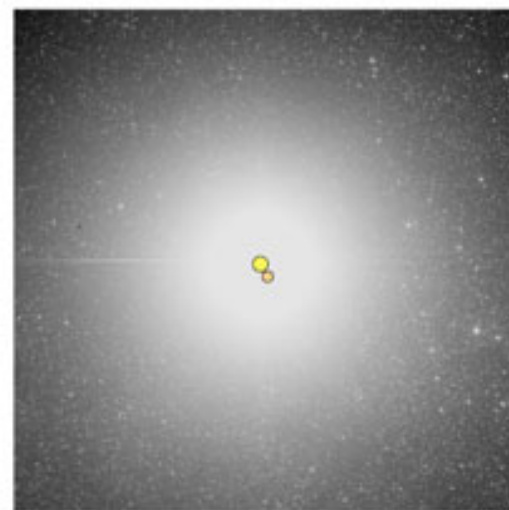
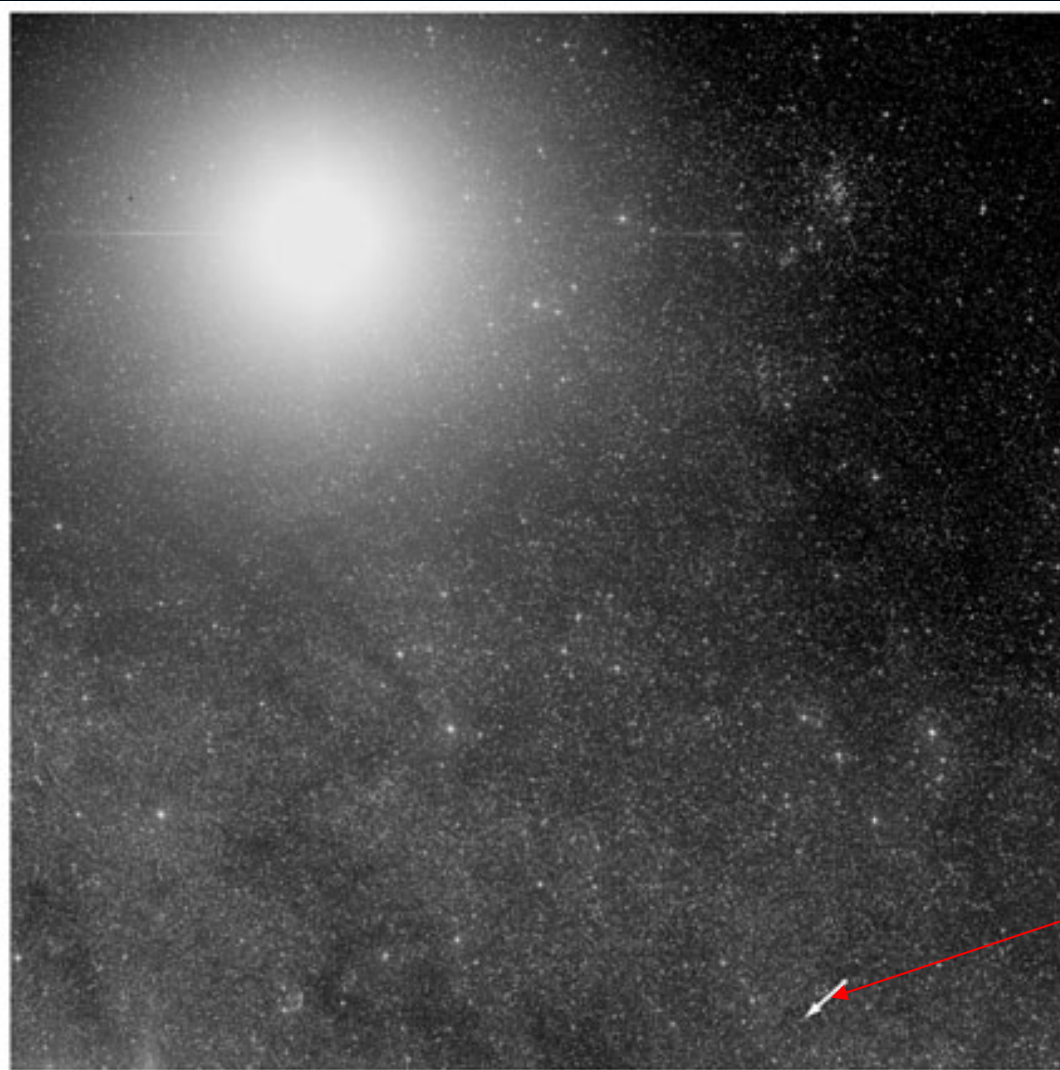
- Stellar parallax is usually called $\underline{\pi}$
- The distance to a star in parsecs is:

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

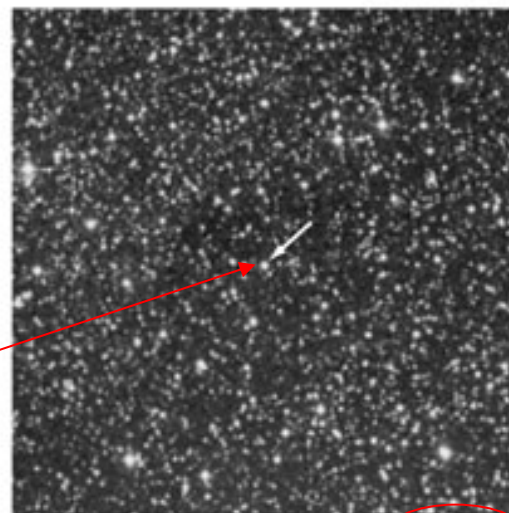
1 parsec = 3.26 light-years = 3.09×10^{13} km

- 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:

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



α Cen A & B



Proxima

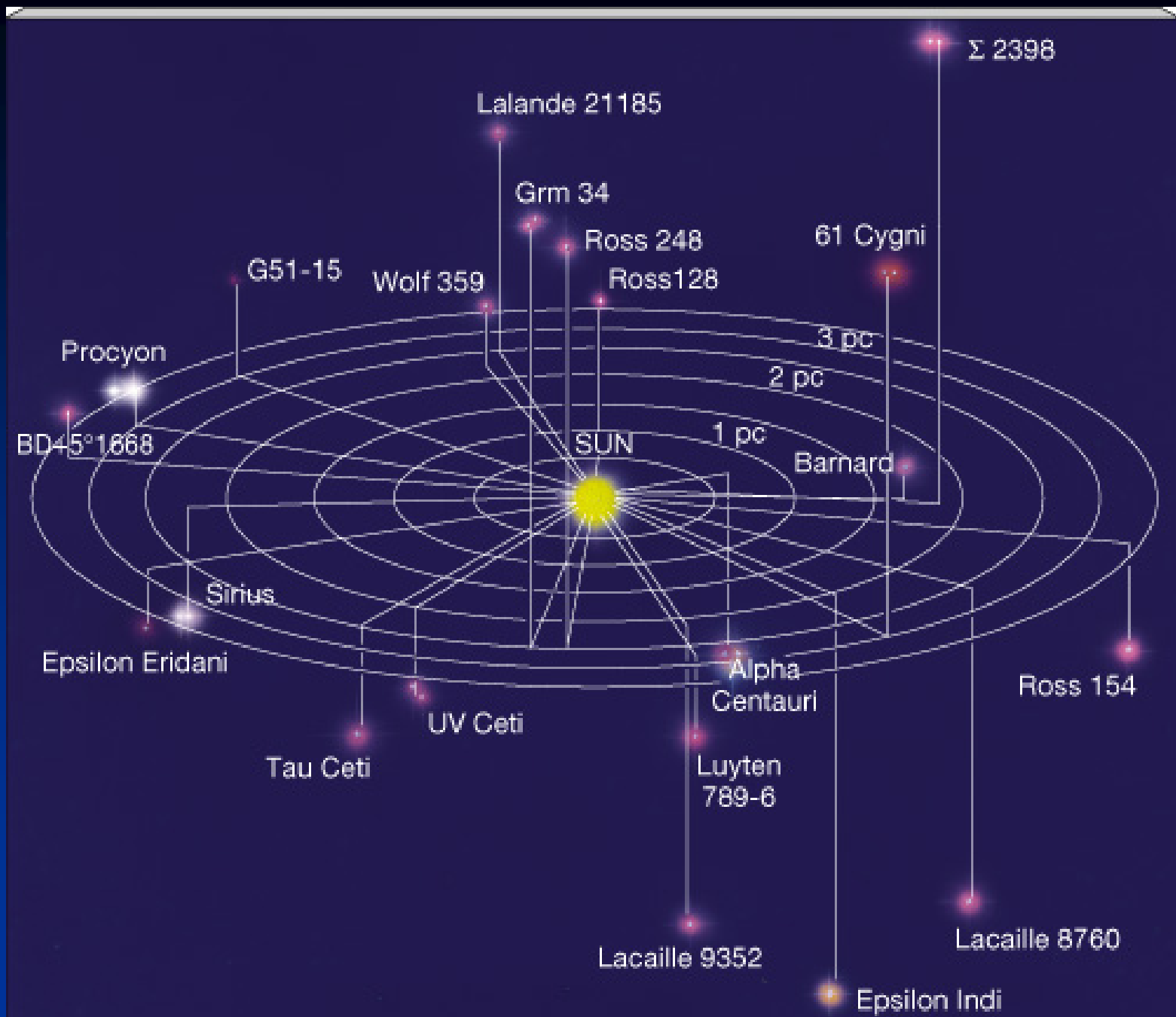
Stellar parallax

- 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.

- Parallax-based 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. A satellite called Hipparcos measured parallaxes for about 100,000 stars (pre-Hipparcos, this number was more like 2000 stars).

The Nearest Stars

Name	Parallax arcsec	Distance pc	Apparent magnitude	Luminosity (L_{\odot})
Proxima Cen	0.77	1.3	11.05	0.00006
α Cen A	0.75	1.3	-0.01	1.6
α Cen B	0.75	1.3	1.33	0.45
Barnard's star	0.545	1.8	9.45	0.000045
Wolf 359	0.421	2.4	13.5	0.00002
BD +36° 2147	0.397	2.5	12.52	0.0055
Luyten 726-8A	0.387	2.6	12.52	0.00006
Luyten 726-8B	0.387	2.6	13.02	0.00004
Sirius A	0.377	2.6	-1.46	23.5
Sirius B	0.377	2.6	8.3	0.003
Ross 154	0.345	2.9	10.45	0.00048



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

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?

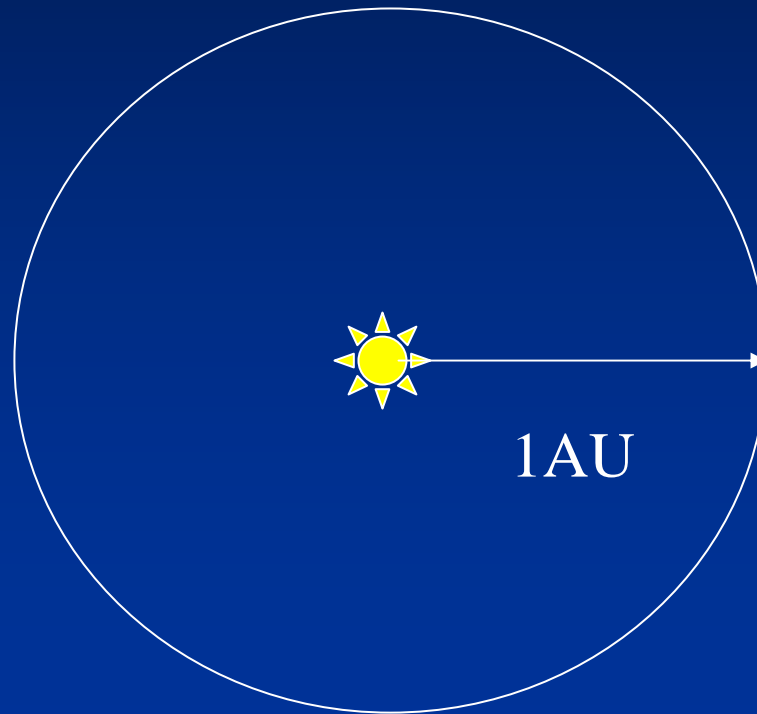
- On a sunny day, the amount of solar energy crashing into the roof of this building is the solar constant times the surface area of the roof.

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

- 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 $4 \pi R^2$

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:

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

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

$$1.4 \times 10^6 \frac{\text{ergs}}{\text{cm}^2 \bullet \text{sec}} \times 2.8 \times 10^{27} \text{ cm}^2 = 3.9 \times 10^{33} \frac{\text{ergs}}{\text{sec}}$$

Solar Luminosity

- $L_{\odot} = 3.9 \times 10^{33} \text{ ergs/sec}$
- At Enron rates, the Sun would cost
 $10^{20} \text{ \$/second}$

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

A. $3.9 \times 10^{33} \text{ ergs/sec}$

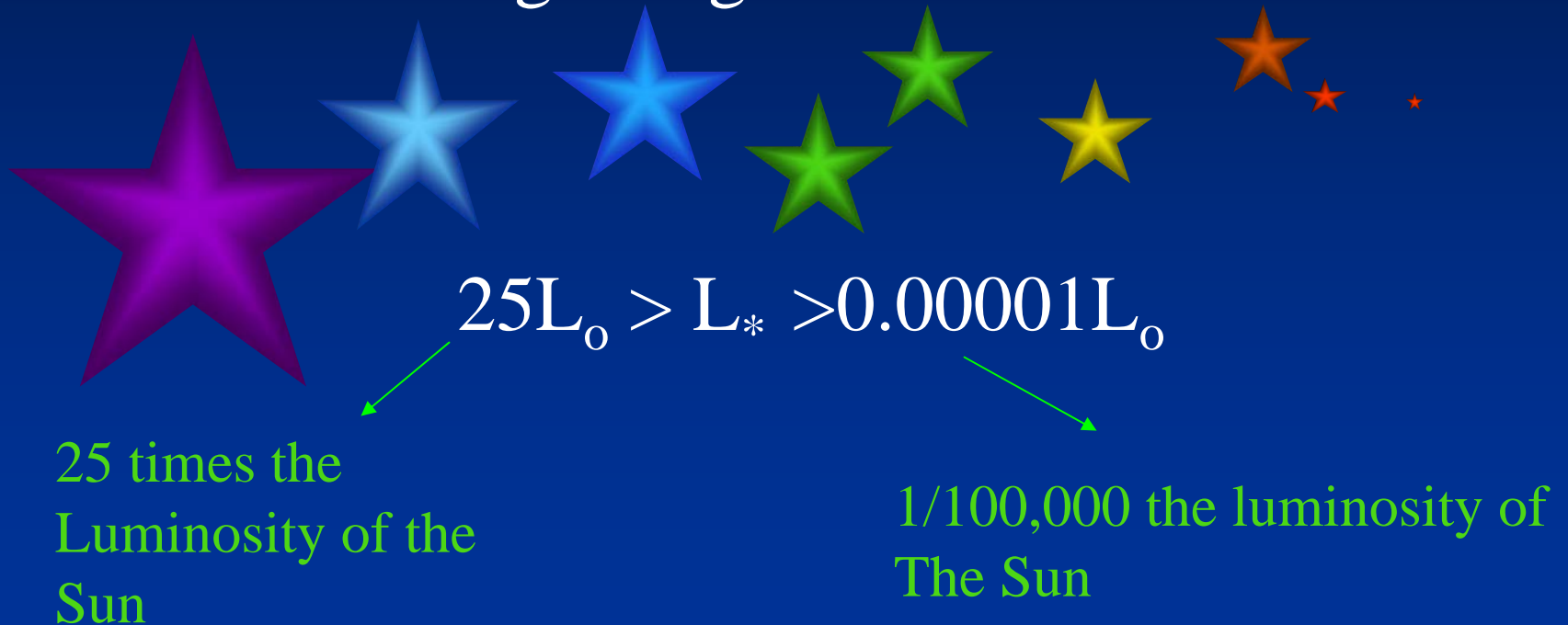
- What is the Solar Luminosity at the surface of the Earth?

- What is the Solar Luminosity at the surface of the Earth?
- 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 the other stars?
- Apparent brightness is easy to measure, for stars with parallax measures we have the distance. Brightness + distance + inverse square law for dimming allow us to calculate intrinsic luminosity.

- For the nearby stars (to 100 parsecs) we discover a large range in L.



Stellar Luminosity

- When we learn how to get distances beyond the limits of parallax and sample many more stars, we will find there are stars that are stars that are 10^6 *times* the luminosity of the Sun.
- This is an enormous range in energy output from stars. This is an important clue in figuring out how they produce their energy.

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 **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.

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c. Compare the apparent brightness of the two stars.

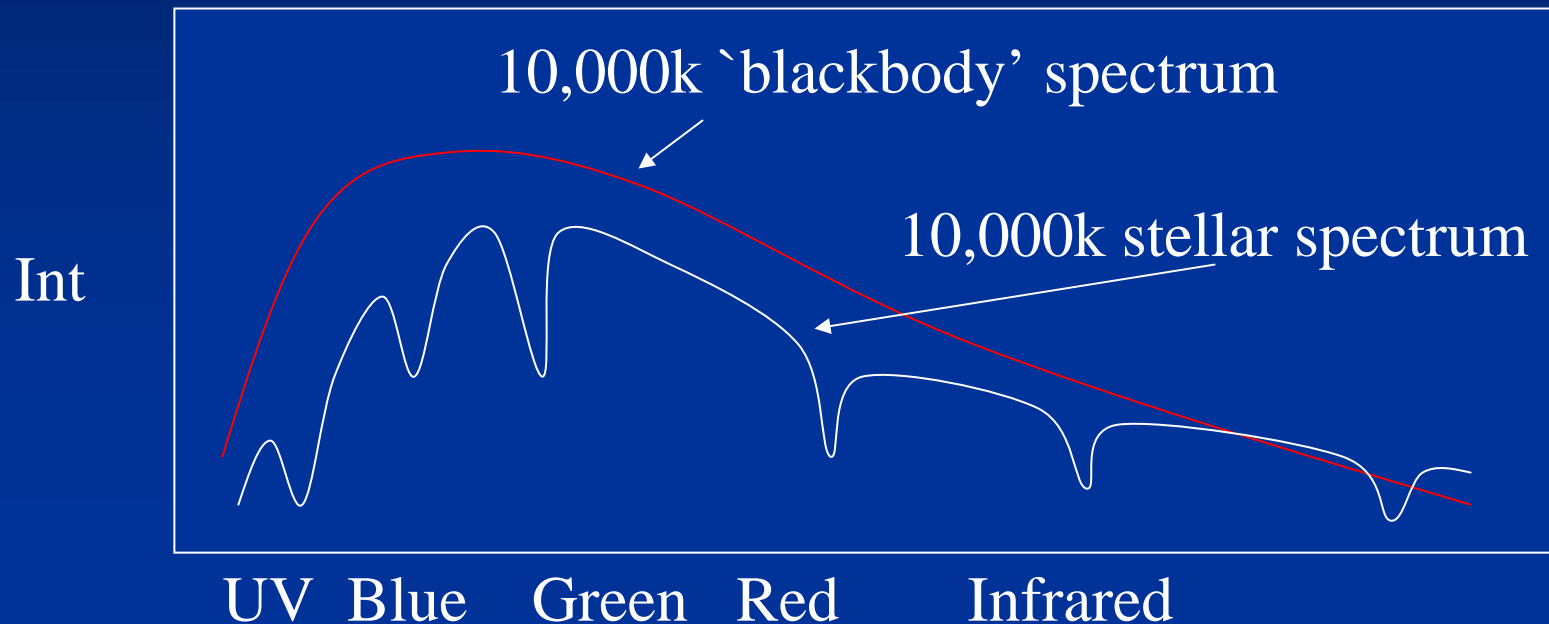
Star B is twice as far away, same L. If there is no dust along the the line of sight to either star, B will be $1/4$ as bright.

Next stellar property: Temperature

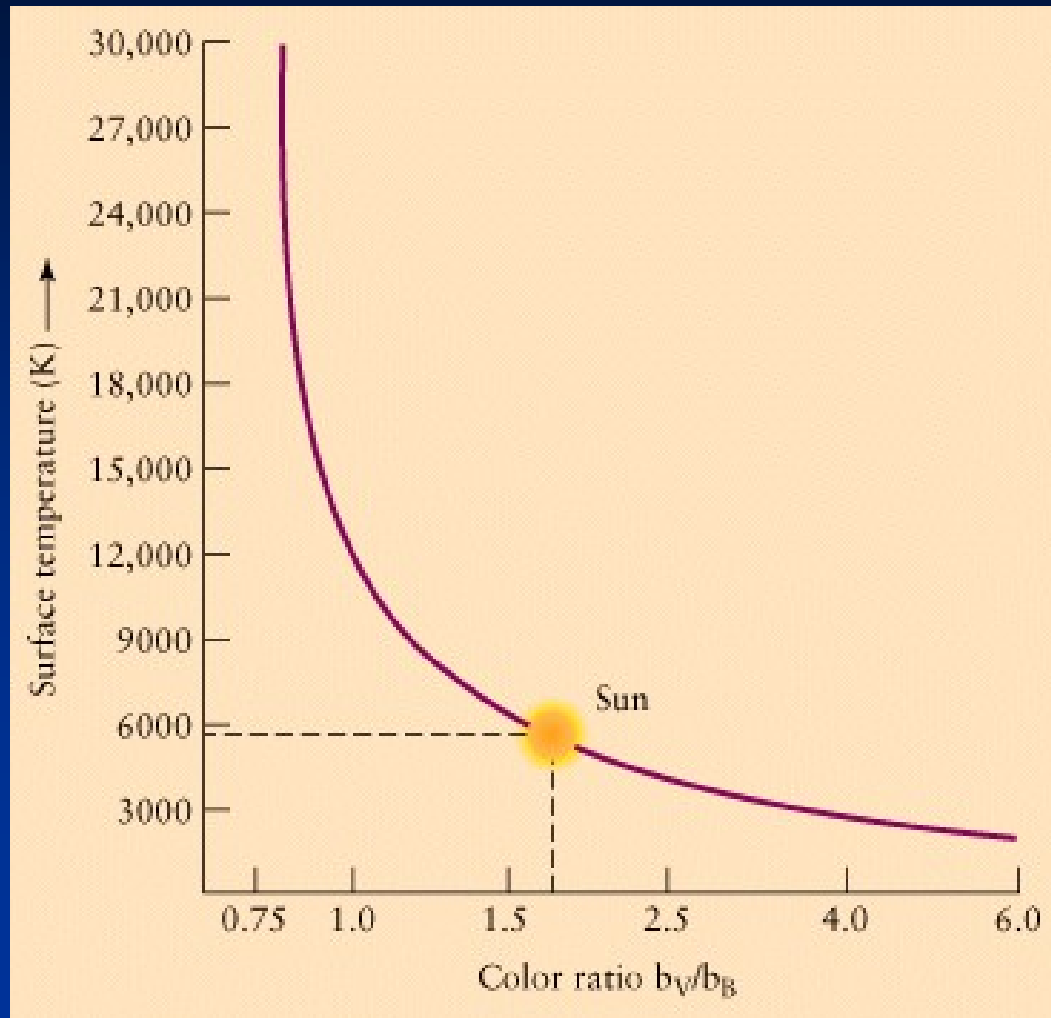
- We have already talked about using colors to estimate temperature and even better, Wien's law.
- In practice, there are some problems with each of these methods...

Stellar Temperatures

- Wien's law works perfectly for objects with Planck spectra. Stars don't quite have Planck-like spectra.

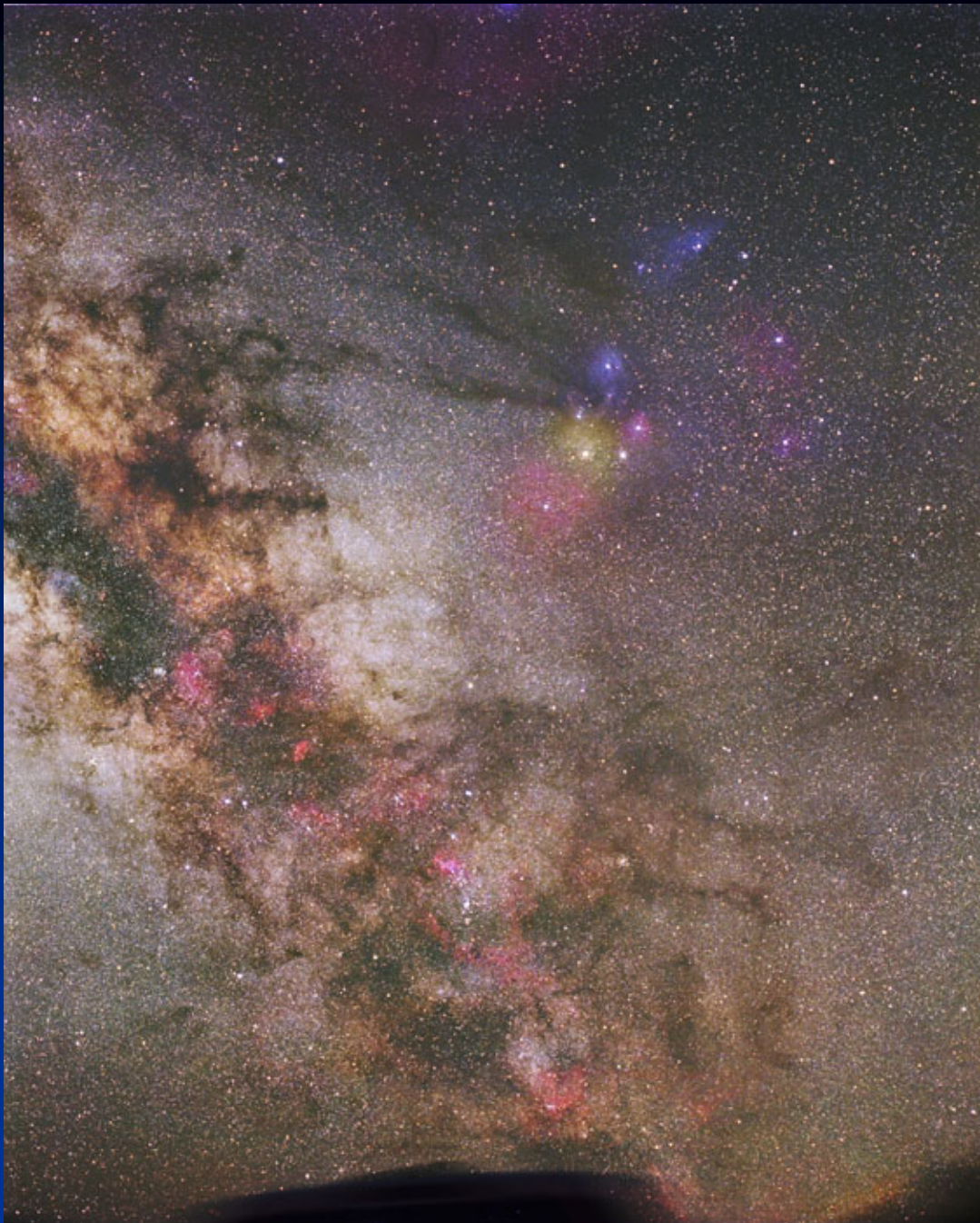


Star colors have been calibrated to temperature, but lose sensitivity above about 12000K when using visible-light colors.



Stellar Temperatures

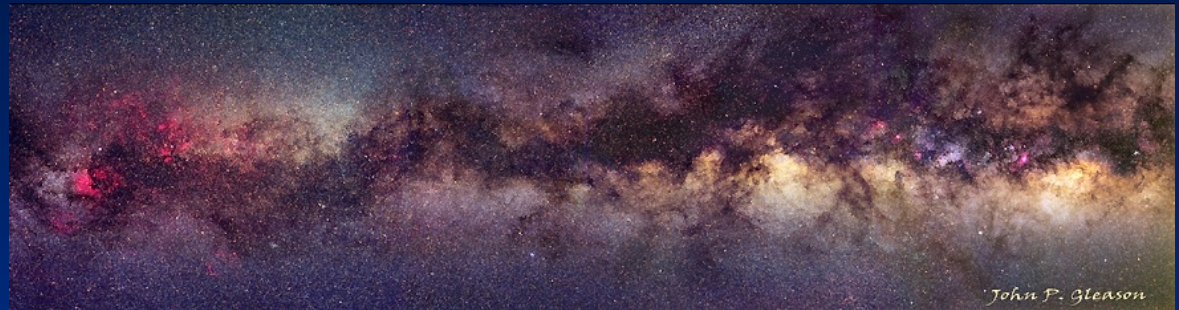
- Another problem with using colors is that there is dust between the stars. The dust particles are very small and have the property that they scatter blue light more efficiently than red light. This is called *'interstellar reddening'*.
 - Most stars appear to be REDDER than they really are (cooler)
 - Stars of a given luminosity appear FAINTER than you would calculate given their distance and the inverse square law.



In some regions of
the Galaxy there is
LOTS of dust.

The properties of dust are such that it has **MUCH** less effect at infrared wavelengths.

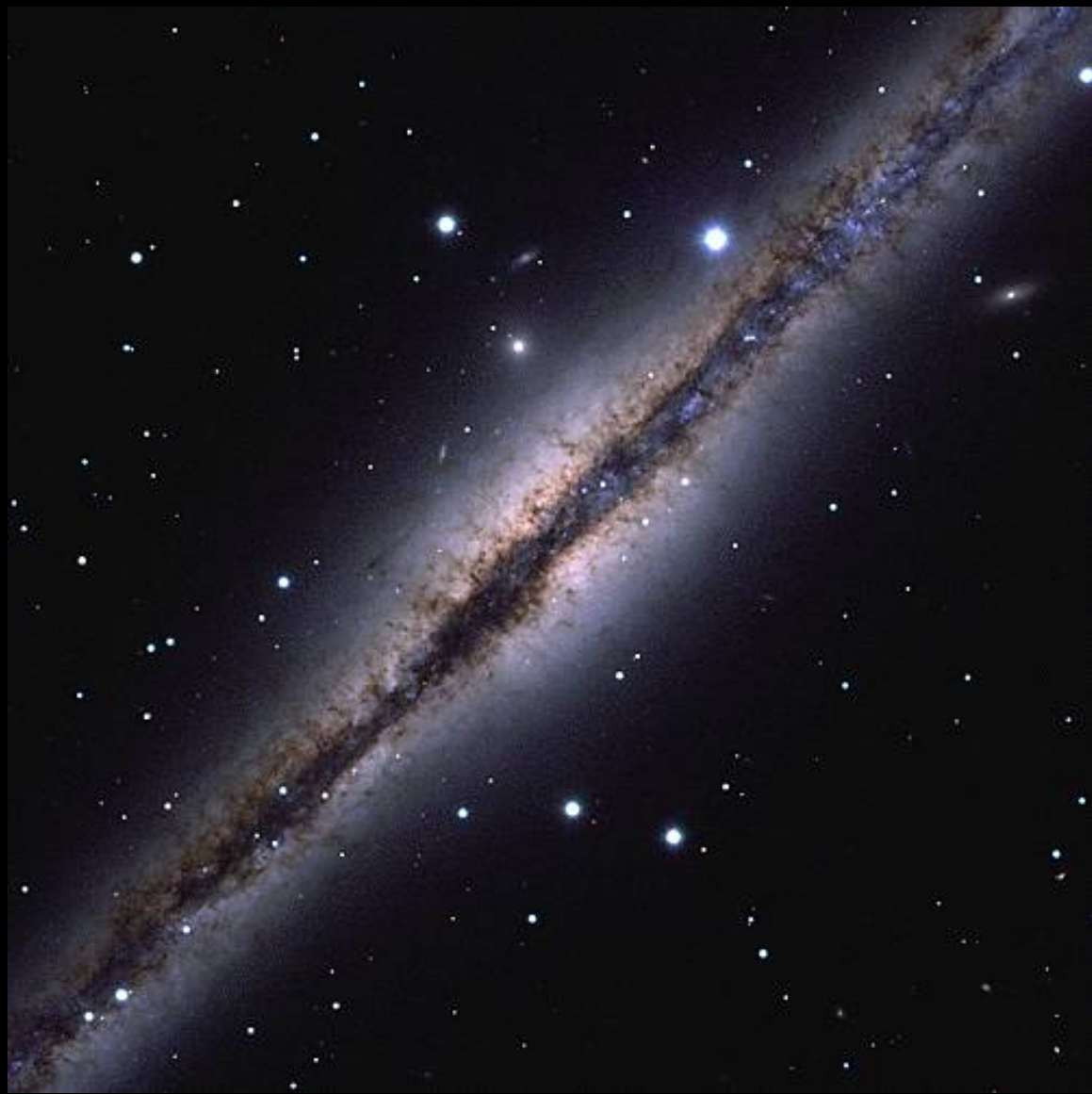
Visible Light



Infrared









Stellar Temperatures

- Despite these complications, we often use colors to estimate stellar temperatures, but there can be confusion.
- Fortunately, there is another way to estimate stellar temperatures which also turns out to be the answer to a mystery that arose as the first spectra of stars were obtained.
- **Stellar spectral types**

Spectral Types

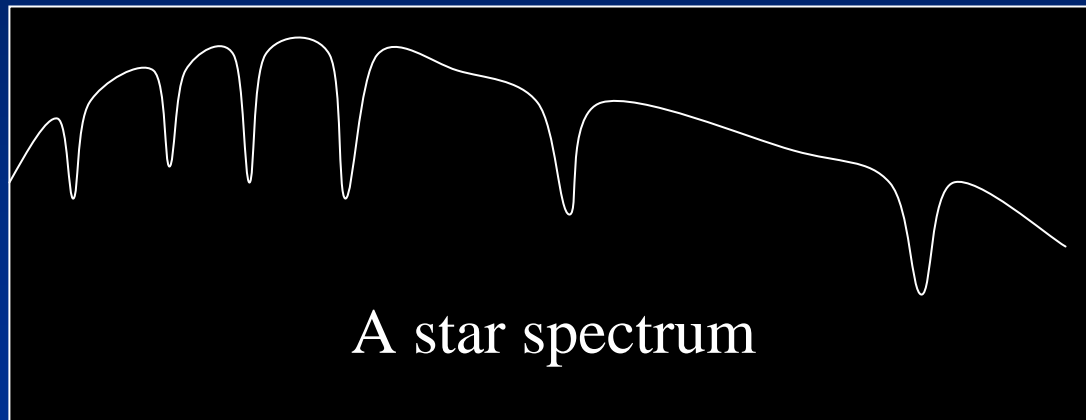
- Long ago it was realized that different stars had dramatically different absorption lines in their spectra. Some had very strong absorption due to hydrogen, some had no absorption due to hydrogen, some were in between.
- With no knowledge of the cause, stars were classified based on the strength of the hydrogen lines in absorption:
 - A star -- strongest H lines
 - B star -- next strongest
 - and so on (although many letters were skipped)

Spectral Types

Microsoft 'rainbow' is not astronomically correct...



Intensity

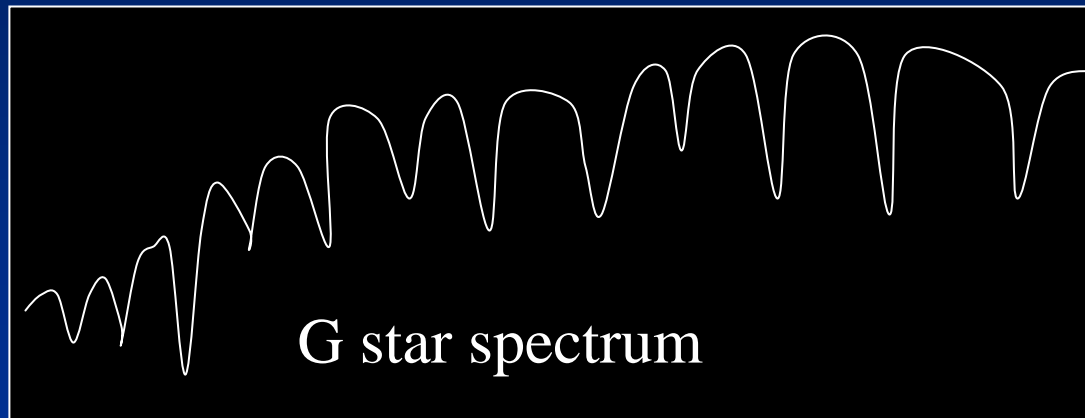


Wavelength

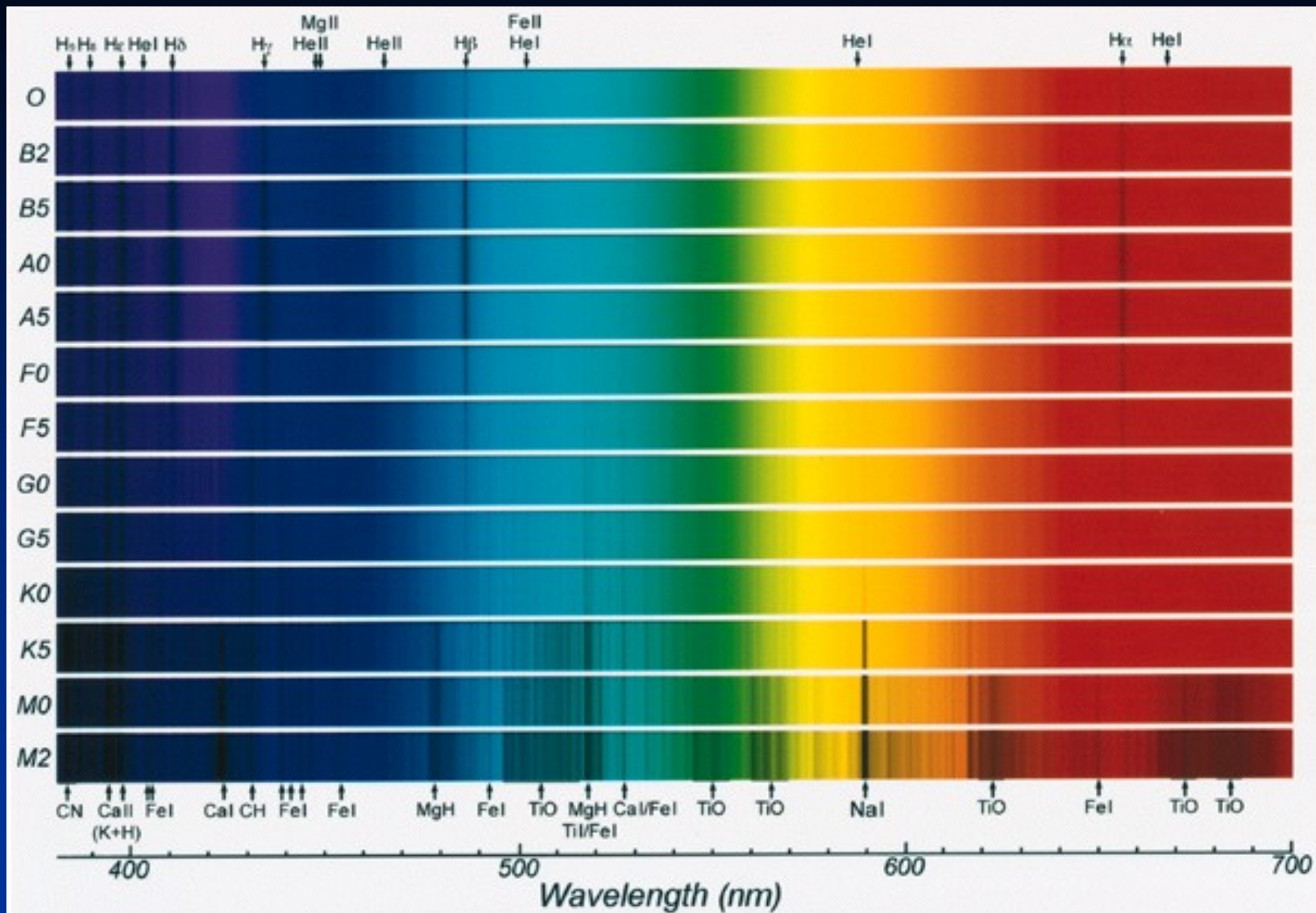
Spectral Types



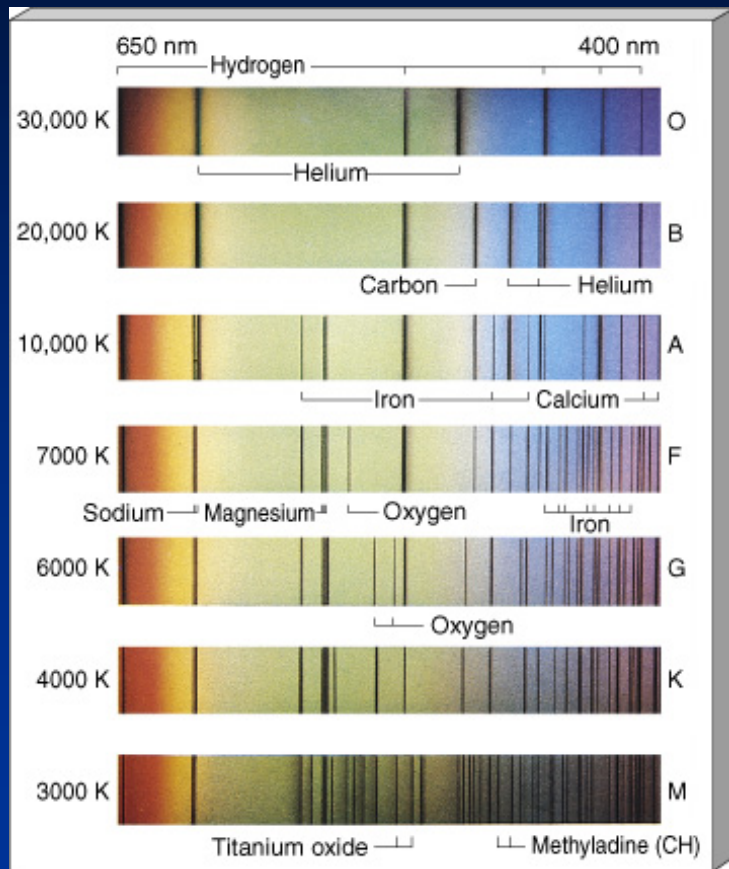
Intensity



Wavelength

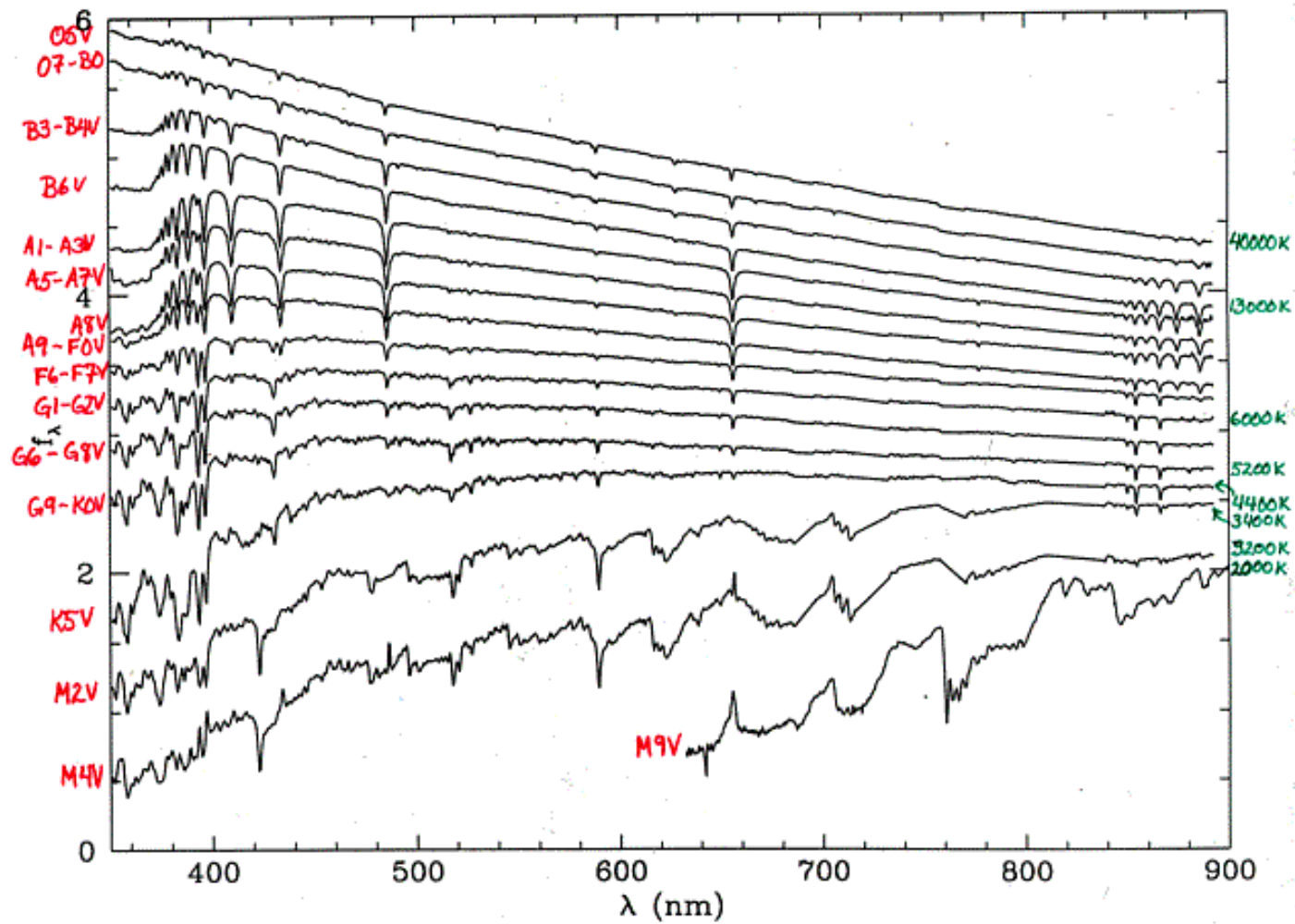


Spectral Types

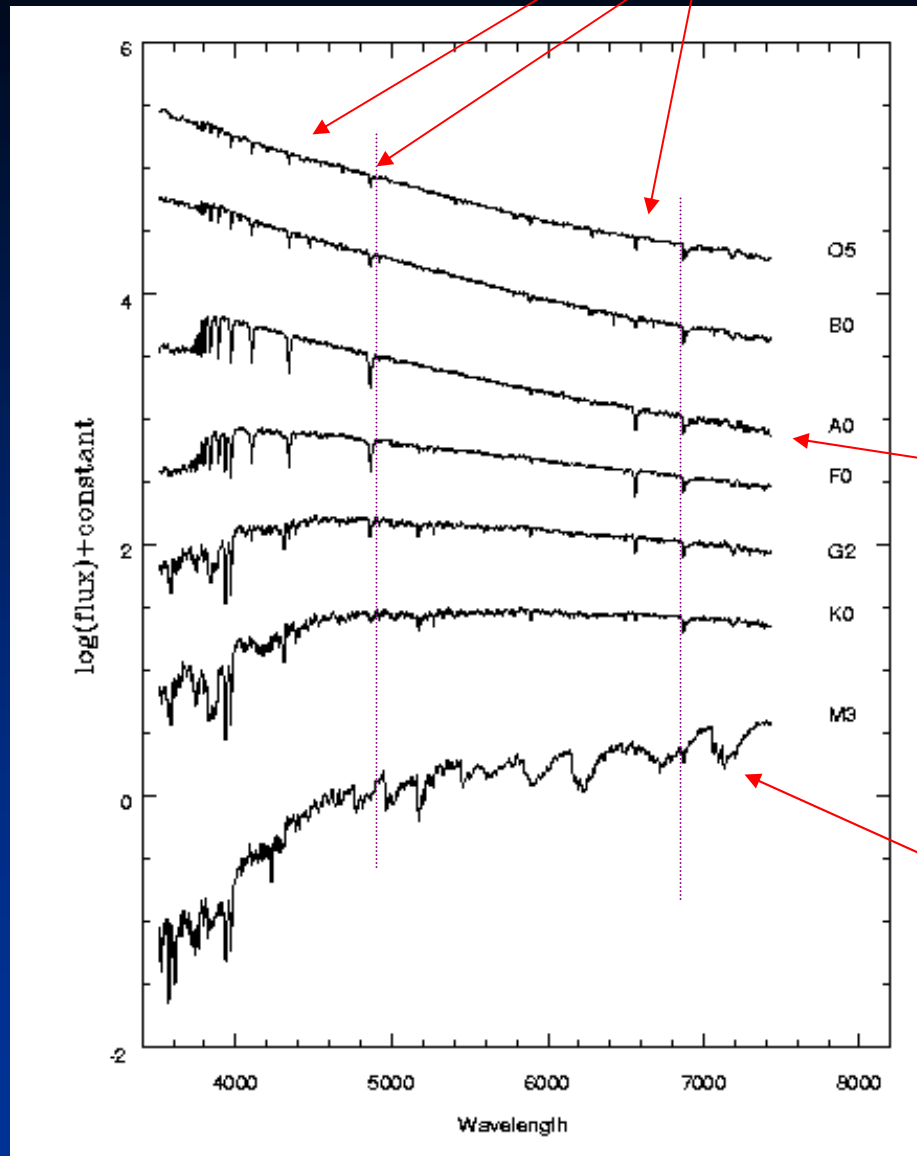


- The A stars show only strong absorption lines due to Hydrogen
- Other spectral types show weaker H lines and generally lines from other elements.
- For M stars, there are also lines from molecules.

Optical Stellar Spectra from O5V to M9V



Note the
Difference in
Spectral shape



Hydrogen lines

H lines at
Max strength

Molecular
lines

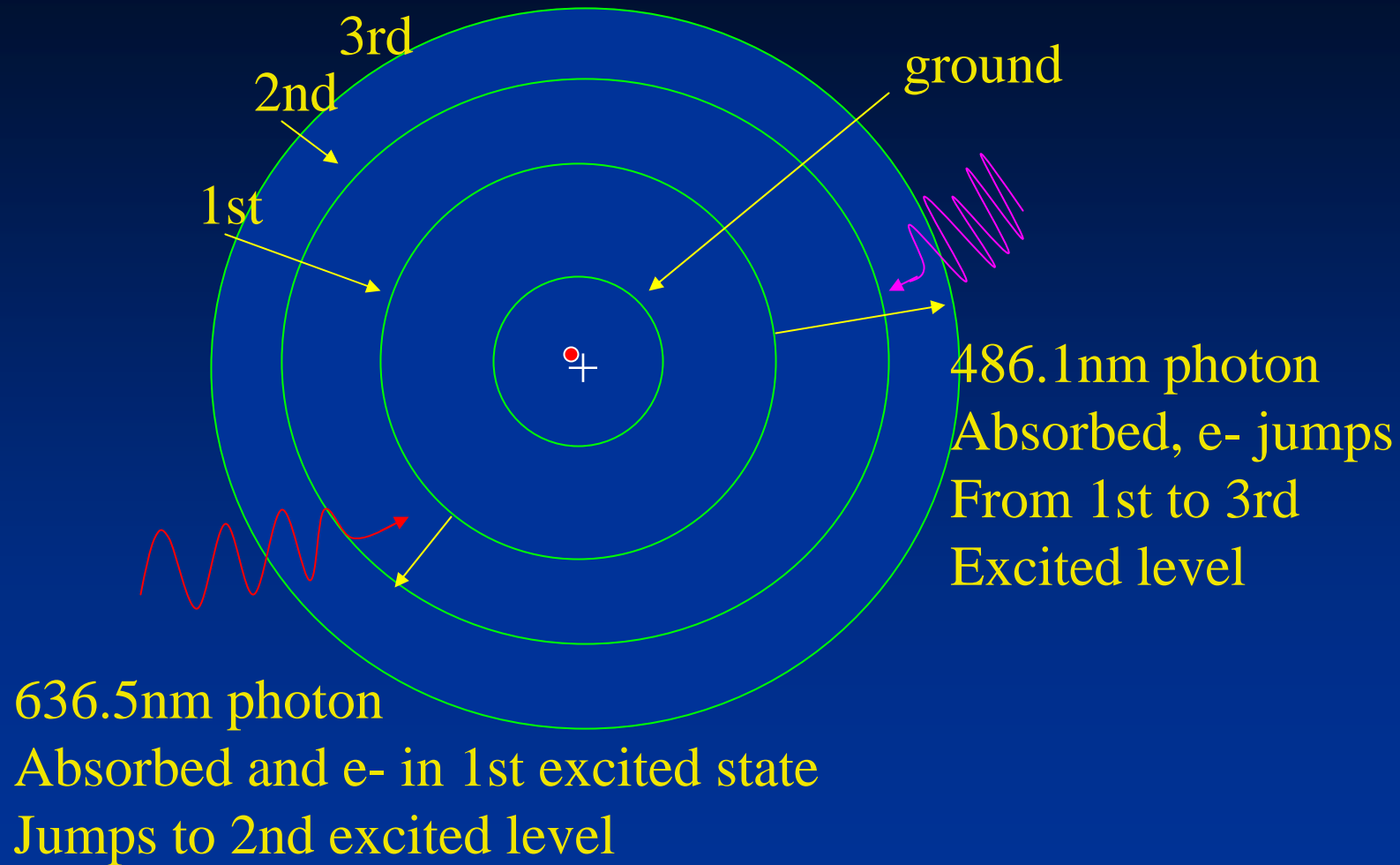
Spectral Type Explanation

- The different spectral types were recognized in the early 1800s.
- Why do some stars show strong absorption due to hydrogen and others don't.
- The obvious solution would be to imagine that it is due to differences in the chemical composition of stars. **Nope!**

Spectral Type Explanation

- Think about how absorption lines are produced. Hydrogen lines in the visible part of the spectrum (known as the Balmer Series) are created when a photon is absorbed by bouncing an electron from the 1st excited level to a higher excited level.
- Photons with just the right energy to move an electron from the 1st excited state to the 2nd excited state have a wavelength of 636.5nm. This is in the red part of the spectrum and this absorption line is called $H\alpha$

Hydrogen atom energy level diagram



- For one of the visible-light transitions to happen, there must be some H atoms in the gas with their electrons in the 1st excited state.

Hydrogen Line formation

- Imagine a star with a relatively cool (4000k) atmosphere. Temperature is just a measure of the average velocity of the atoms and molecules in a gas. For a relatively cool gas there are:
 - (1) Few atomic collisions with enough energy to knock electrons up to the 1st excited state so the majority of the H atoms are in the ground state
 - (2) Few opportunities for the H atoms to catch photons from the Balmer line series.
- So, even if there is lots of Hydrogen, there will be few tell-tale absorptions.

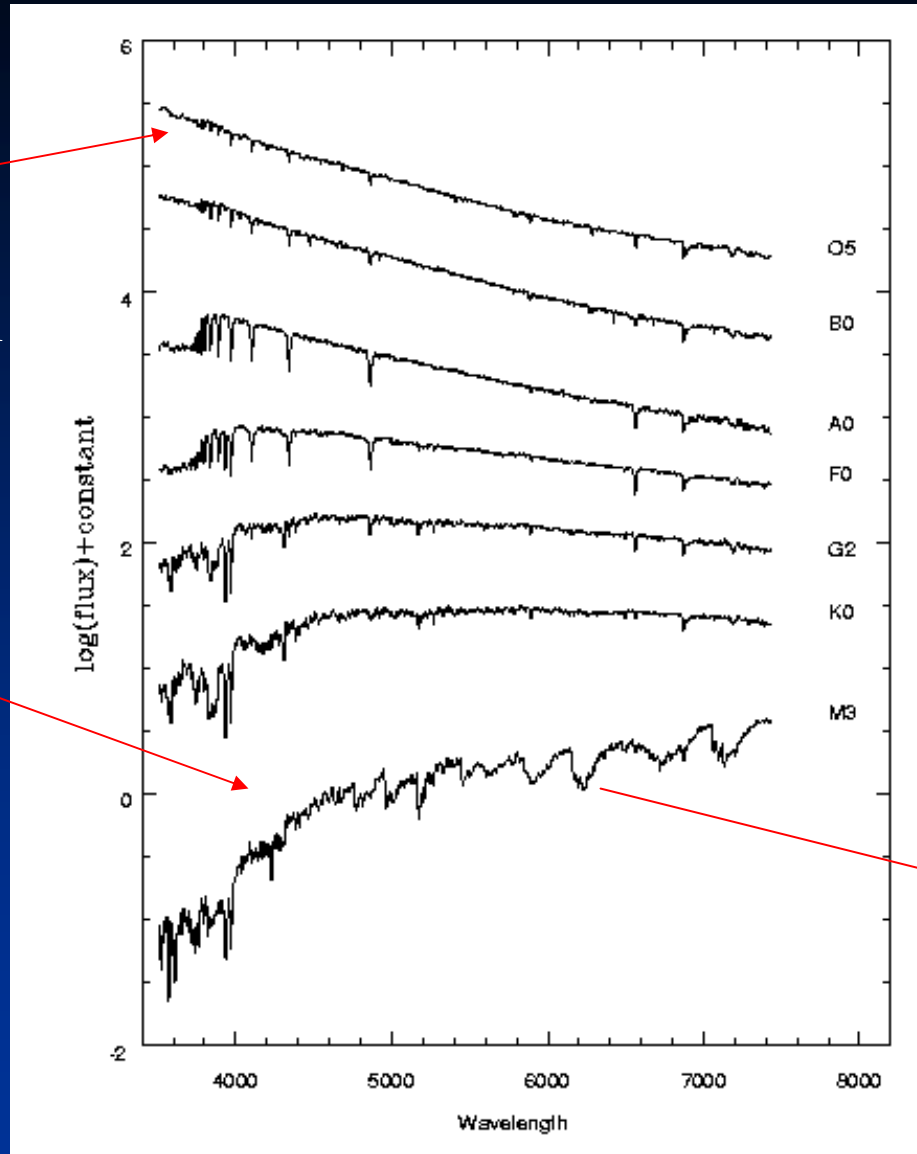
Hydrogen Line Formation

- Now think about a hot stellar atmosphere (say 40000k). Here the collisions in the gas are energetic enough to *ionize* the H atoms.
- Again, even if there is lots of hydrogen, if there are few H atoms with electrons in the 1st excited state, there will be no evidence for the hydrogen in the visible light spectrum.

- Therefore, the spectral sequence is a result of stars having different Temperature.

Wien's Law
Tells you these
Are hot. Spectrum
Peaking at short
wavelengths

Moving down
The sequence
The wavelength
Of the peak of
The spectrum
Moves redward



Too hot O
B
Just right A
F
G
K
Too cold M

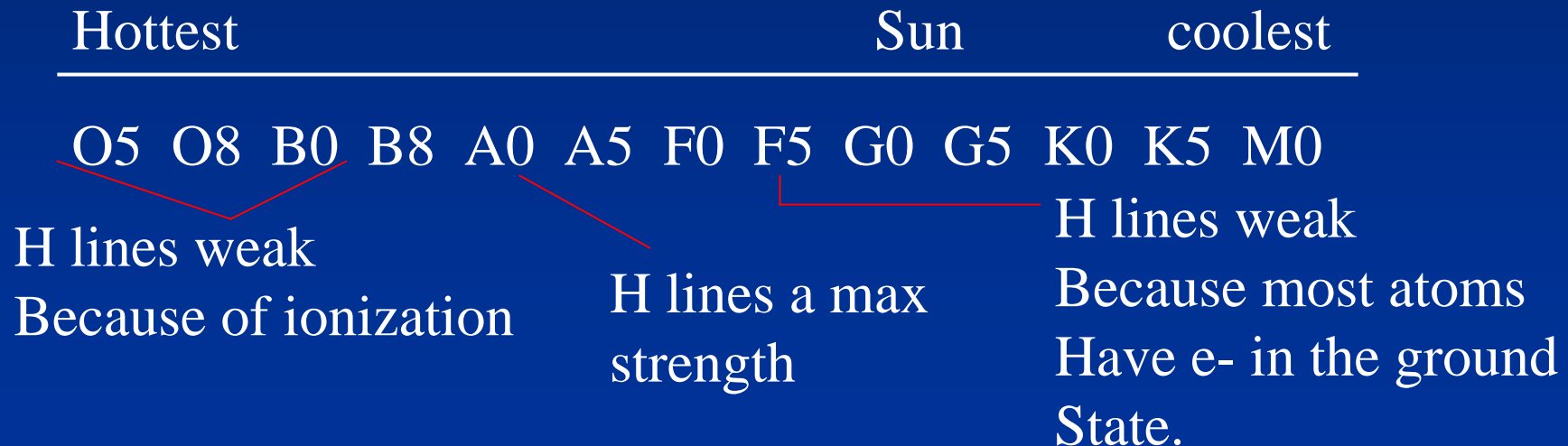
Only see
molecules in
cool gases

- Given the temperature of a gas, it is possible to calculate the fraction of atoms with electrons in any excitation level using an equation called the Boltzmann Equation.

- It is also possible to calculate the fraction of atoms in a gas that are ionized at any temperature using an equation called the Saha Equation.
- The combination of Boltzmann and Saha equations and hydrogen line strength allow a very accurate determination of stellar temperature.

Spectral Sequence

- Temperature effects are far and away the most important factor determining spectral types. Once this was recognized, the sequence was reorganized by temperature.



Spectral Sequence

- There are some additional spectral types added - L and T are extremely cool stars; R, N and S for some other special cases. The usual sequence is OBAFGKMRNS and there are some awful mnemonic devices to remember the temperature sequence.

OBAFGKMRNS

- Oh Be A Fine Girl Kiss Me

OBAFGKMRNS

- Oh Be A Fine Girl Kiss Me
- Oh Bother, Another F is Going to Kill Me

OBAFGKMRNS

- Oh Be A Fine Girl Kiss Me
- Oh Bother, Another F is Going to Kill Me
- Old Boring Astronomers Find Great Kicks
Mightily Regaling Napping Students

OBAFGKMRNS

- Oh Be A Fine Girl Kiss Me
- Oh Bother, Another F is Going to Kill Me
- Old Boring Astronomers Find Great Kicks
Mightily Regaling Napping Students
- Obese Balding Astronomers Found Guilty
Killing Many Reluctant Nonscience
Students

OBAFGKMRNS

- Oh Backward Astronomer, Forget Geocentricity; Kepler's Motions Reveal Nature's Simplicity

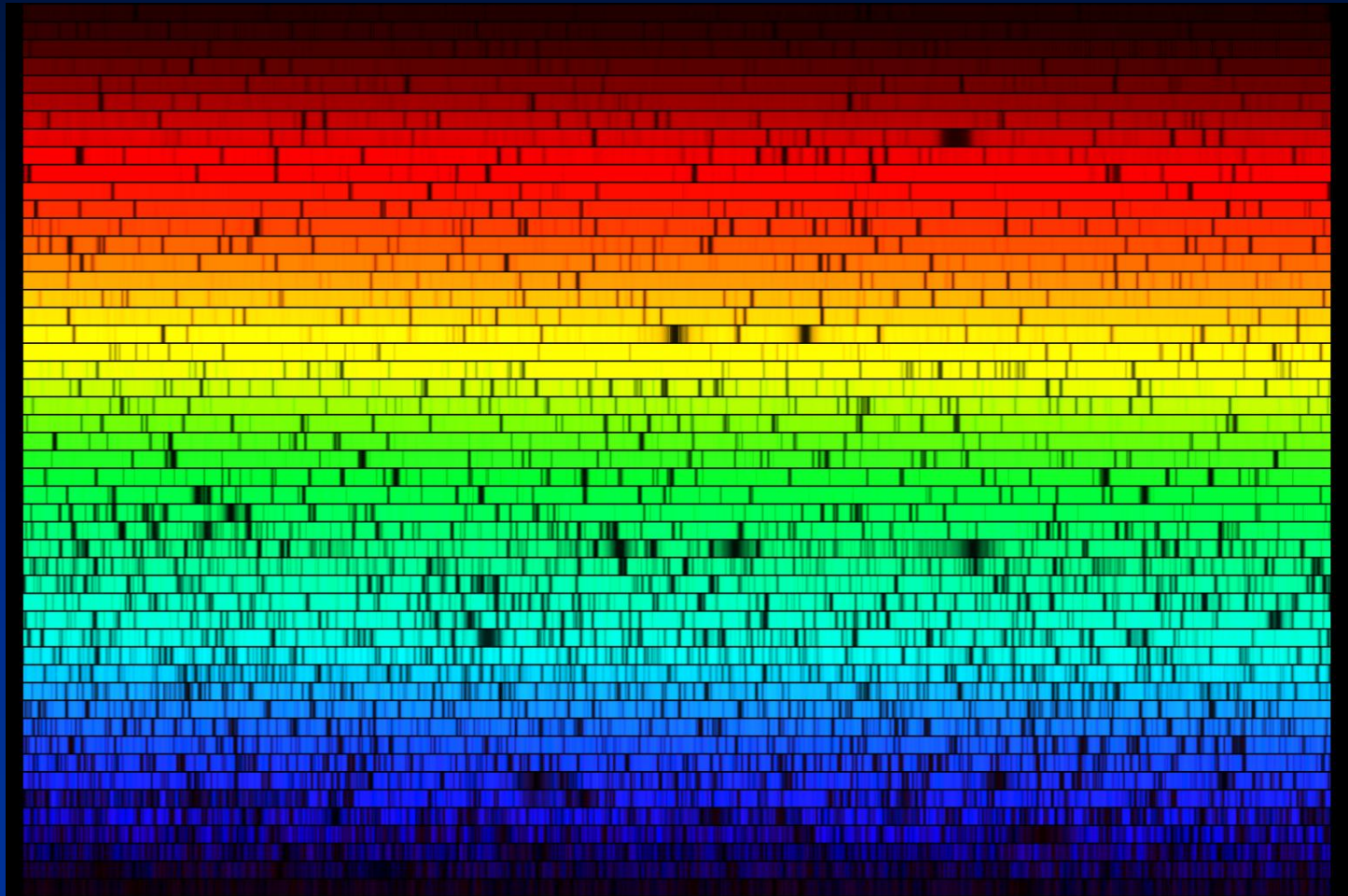
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- Oh Backward Astronomer, Forget Geocentricity; Kepler's Motions Reveal Nature's Simplicity
- Out Beyond Andromeda, Fiery Gases Kindle Many Radiant New Stars

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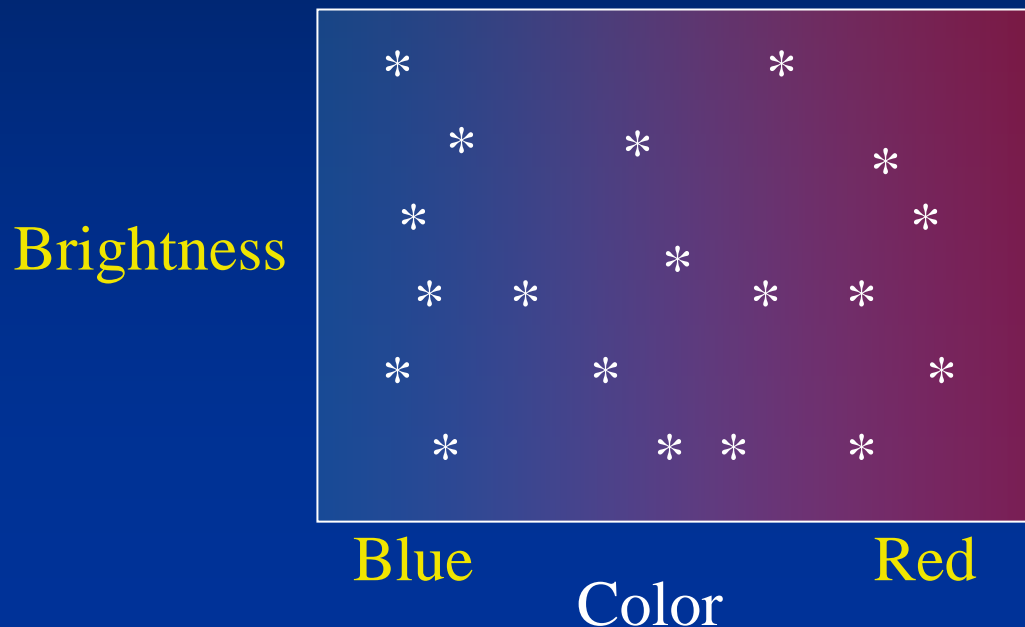
- Oh Backward Astronomer, Forget Geocentricity; Kepler's Motions Reveal Nature's Simplicity
- Out Beyond Andromeda, Fiery Gases Kindle Many Radiant New Stars
- Only Bungling Astronomers Forget Generally Known Mnemonics

Solar Spectrum (G2 star)



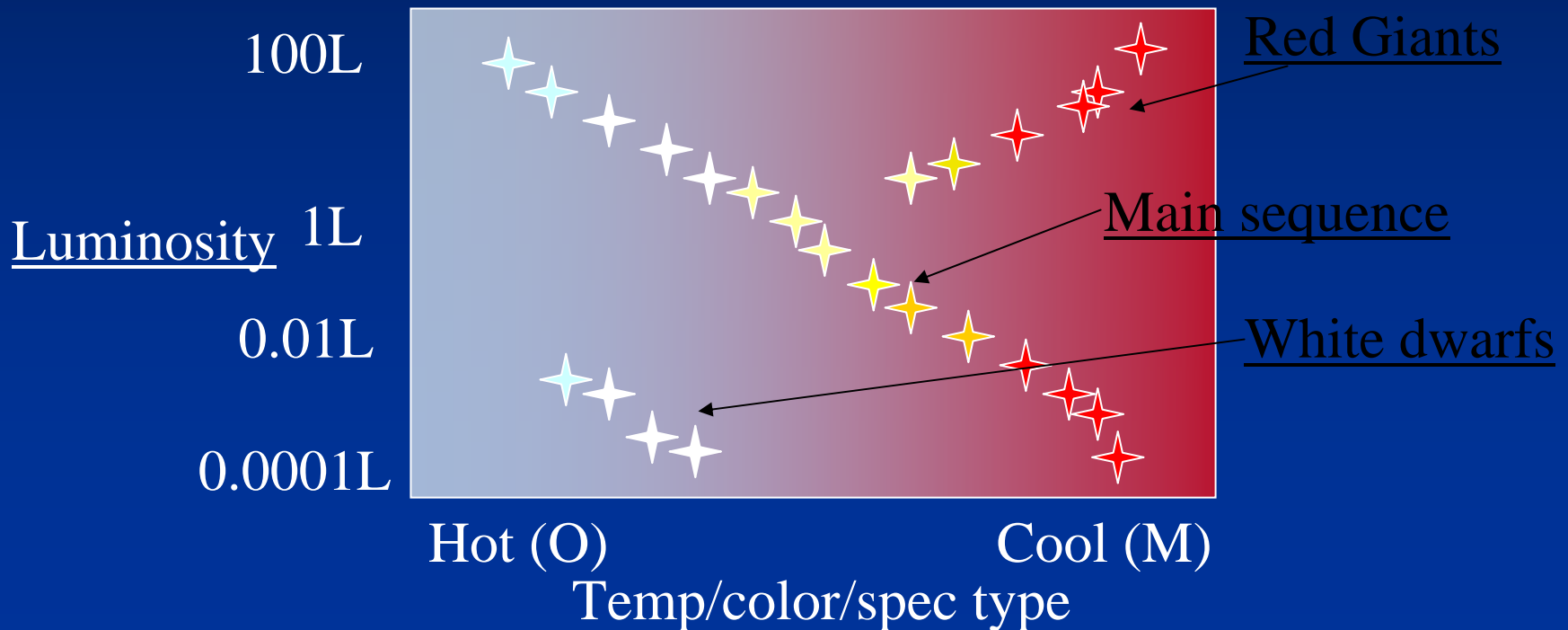
Properties of Stars: The H-R Diagram

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



H-R Diagram

- But a plot of Luminosity vs color (or spectral type 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.
- For now, we will use the H-R Diagram to determine one more property of stars.

Stellar Radius

- With another physics principle first recognized in the 19th century we can determine the sizes of stars.
- Stephan's Law
$$\frac{\text{Energy}}{\text{area}} = \sigma T^4$$
- 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

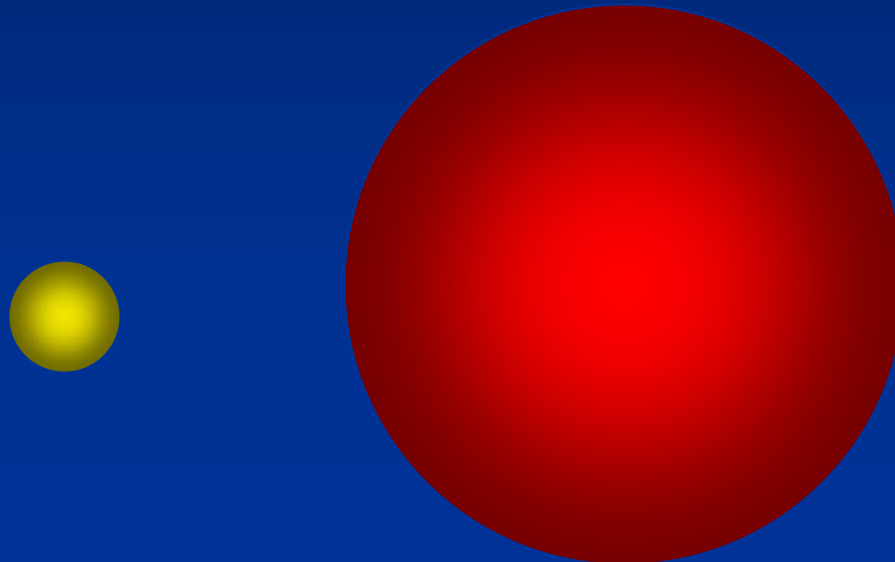
- For example, if you double the temperature of an object, the amount of energy it radiates increases by $2^4 = 2 \times 2 \times 2 \times 2 = 16$ (!)
- Think about the Sun and Betelgeuse:

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

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

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 Betelgeuse 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 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 luminosity, need another factor of 27500 for the Betelguese surface area to give the Luminosity ratio measured for the two stars.

- Stated another way:

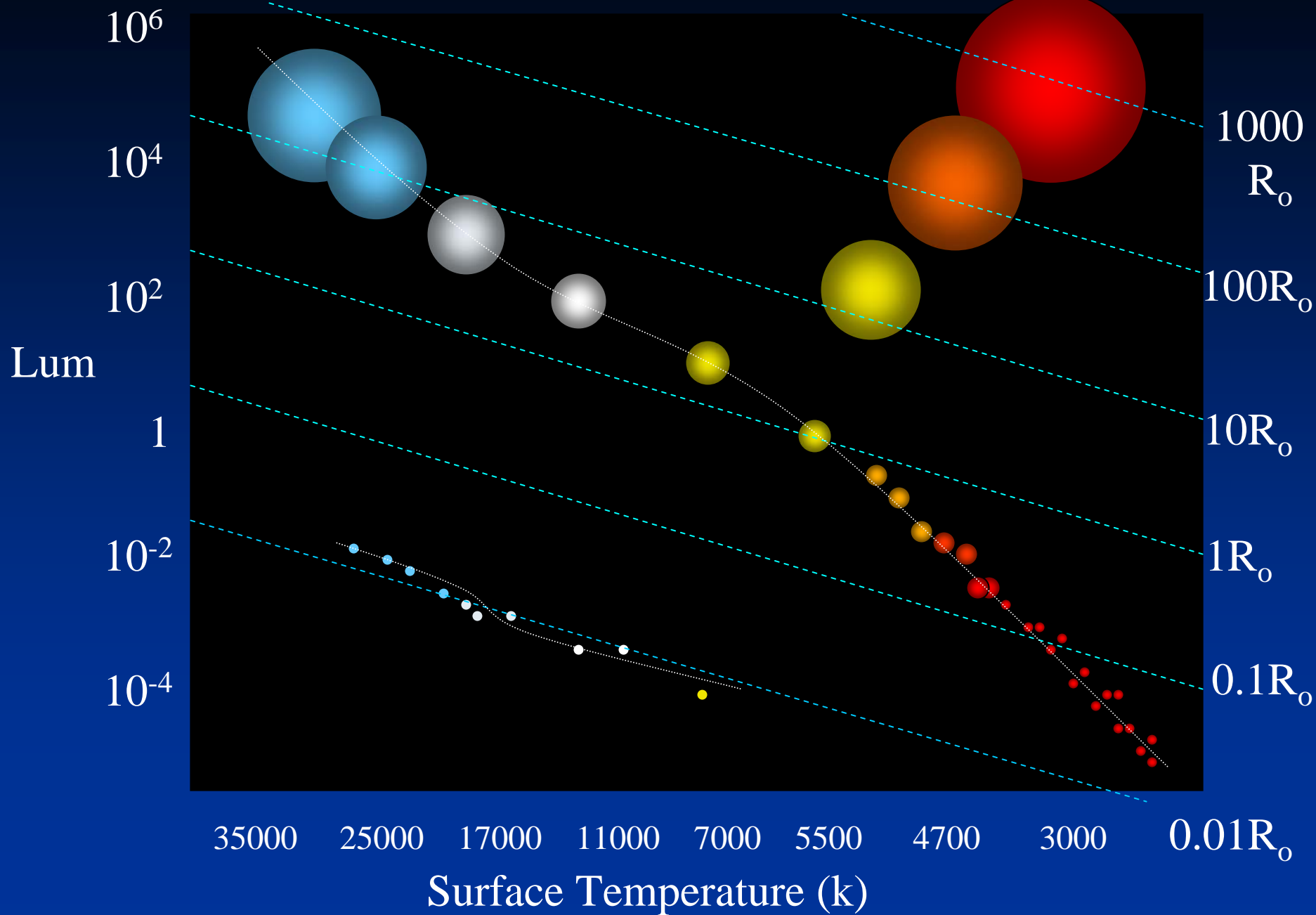
$$\left(\frac{\text{Energy}}{\text{Area}} \right)_{\text{Betel}} \times (\text{Area})_{\text{Betel}} = 27,500 \times \left(\frac{\text{Energy}}{\text{Area}} \right)_{\text{Sun}} \times (\text{Area})_{\text{Sun}}$$

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

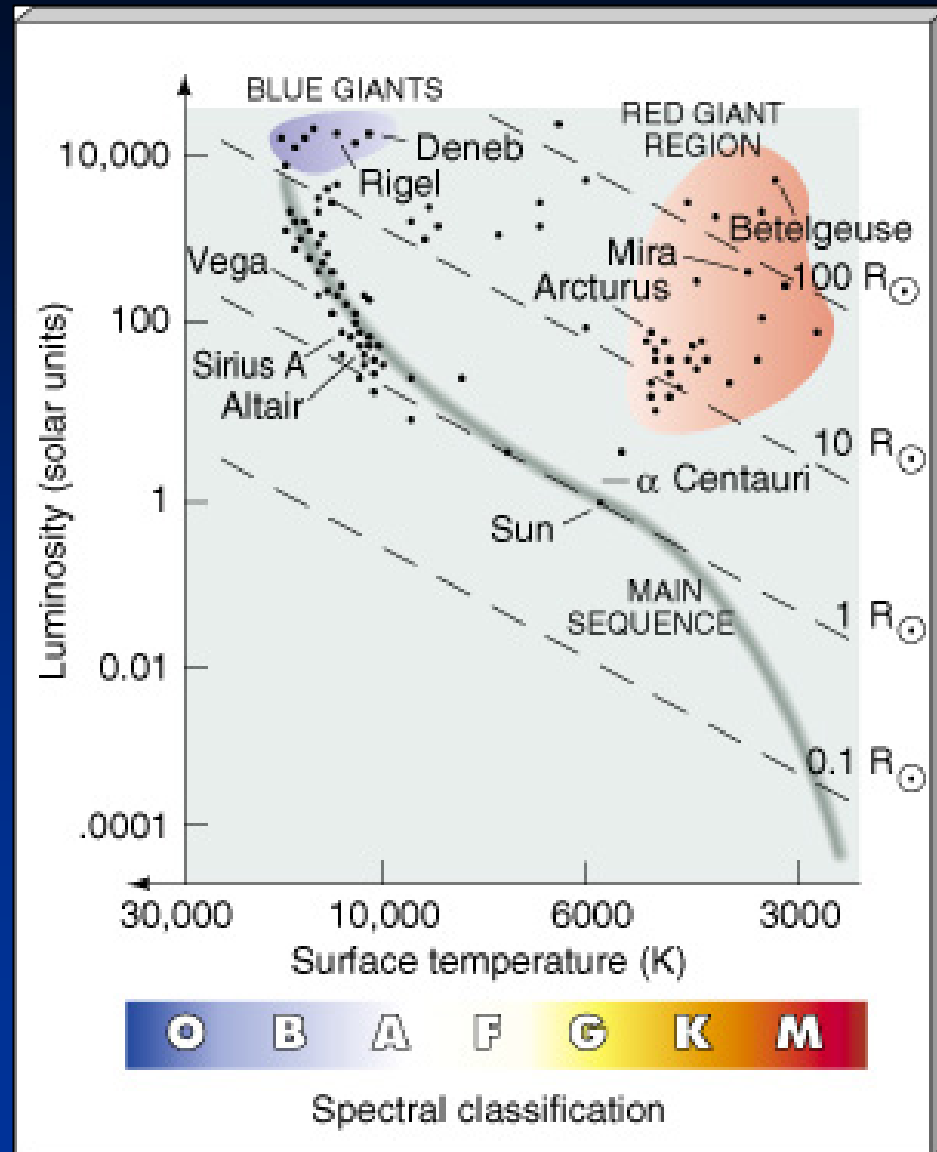
$$(\text{Area})_{\text{Betel}} = 27,500 \times 6.8 \times (\text{Area})_{\text{Sun}} = 187,000 (\text{Area})_{\text{Sun}}$$

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

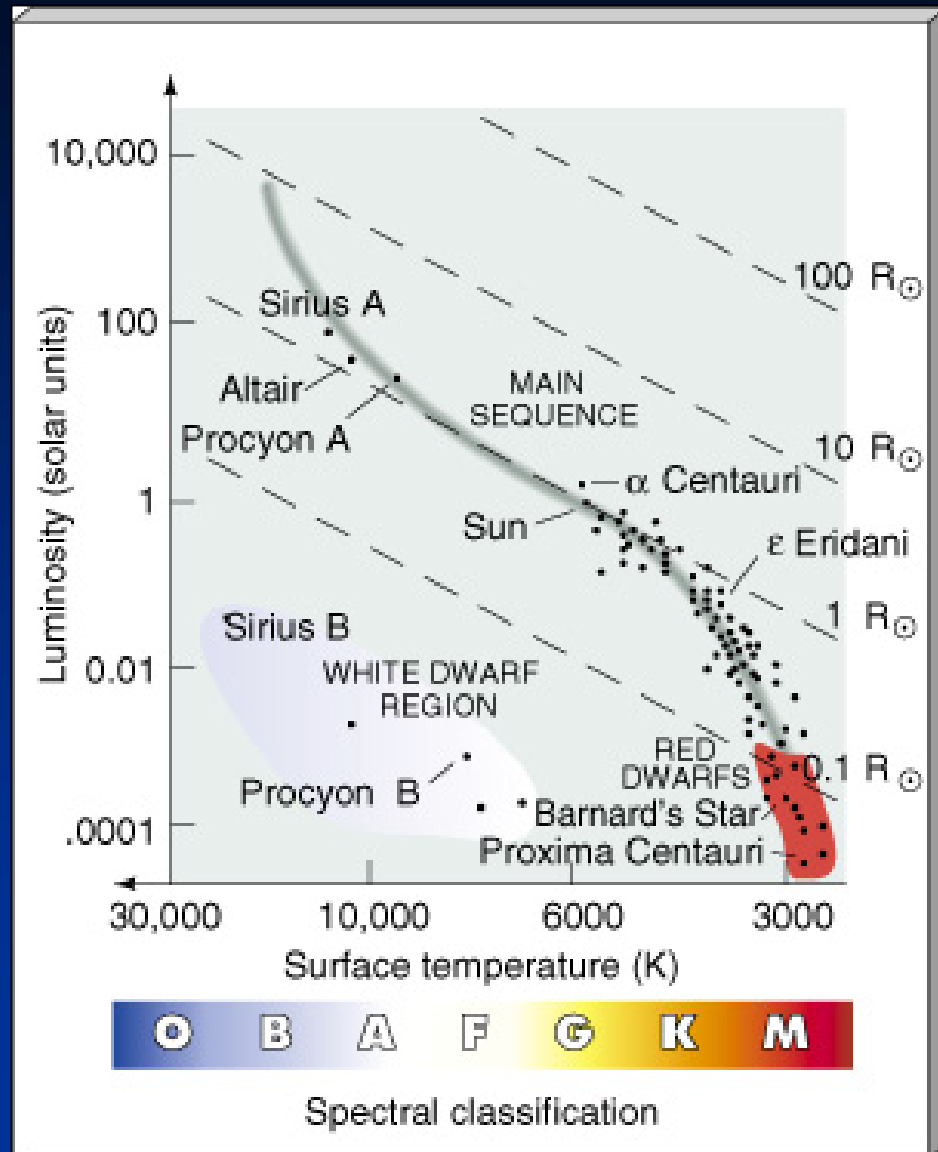
O B A F G K M



H-R Diagram for the Brightest Stars

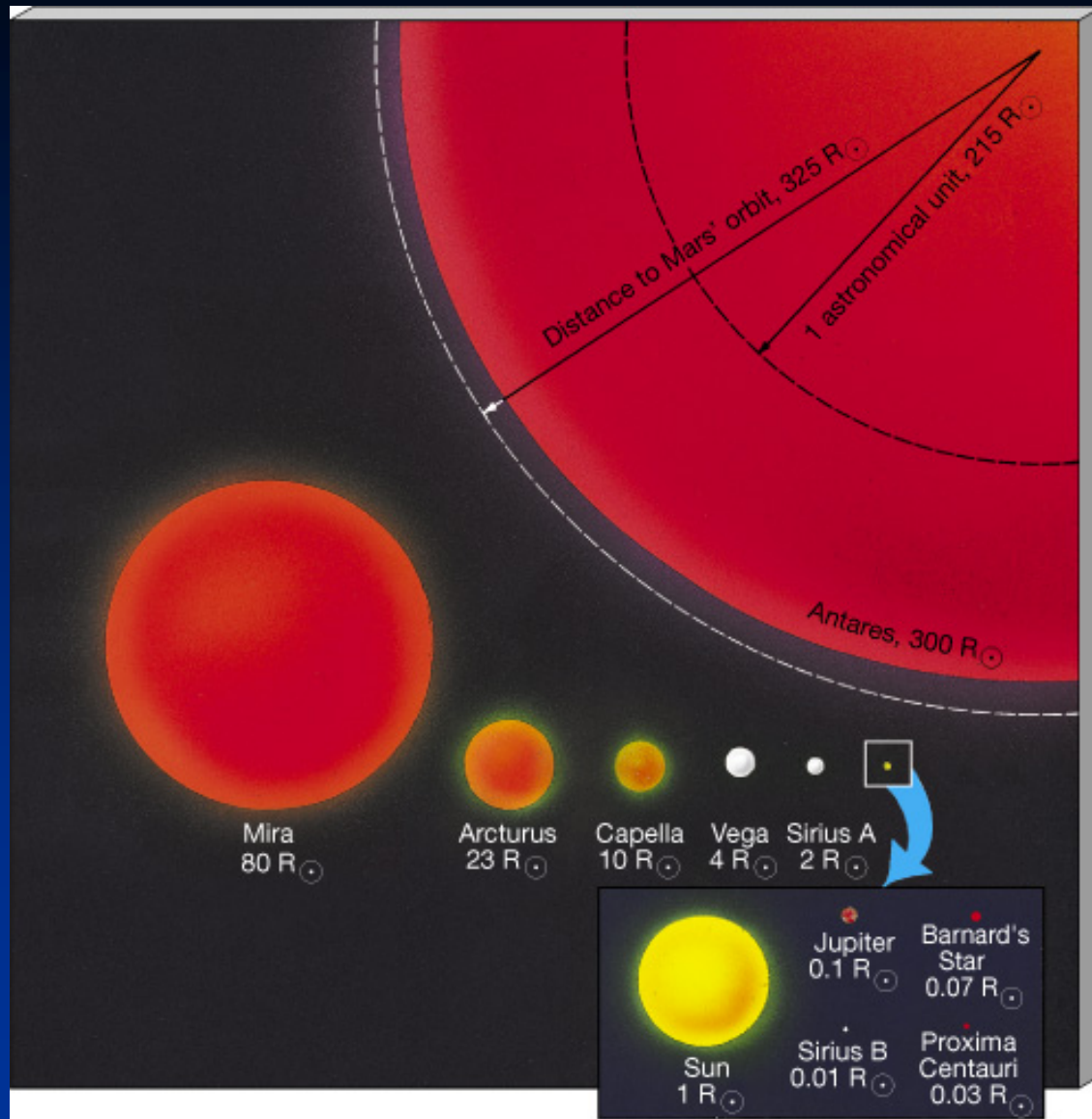


H-R Diagram for the Nearest Stars



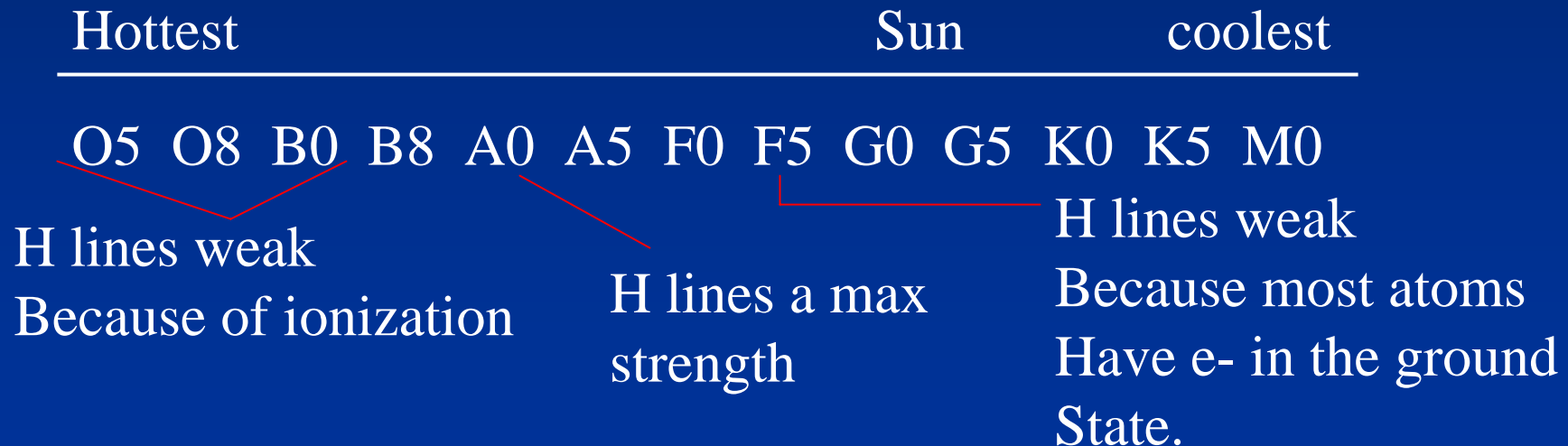
Stellar Radius

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



Spectral Sequence

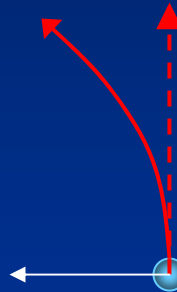
- Temperature effects are far and away the most important factor determining spectral types. Once this was recognized, the sequence was reorganized by temperature.



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:

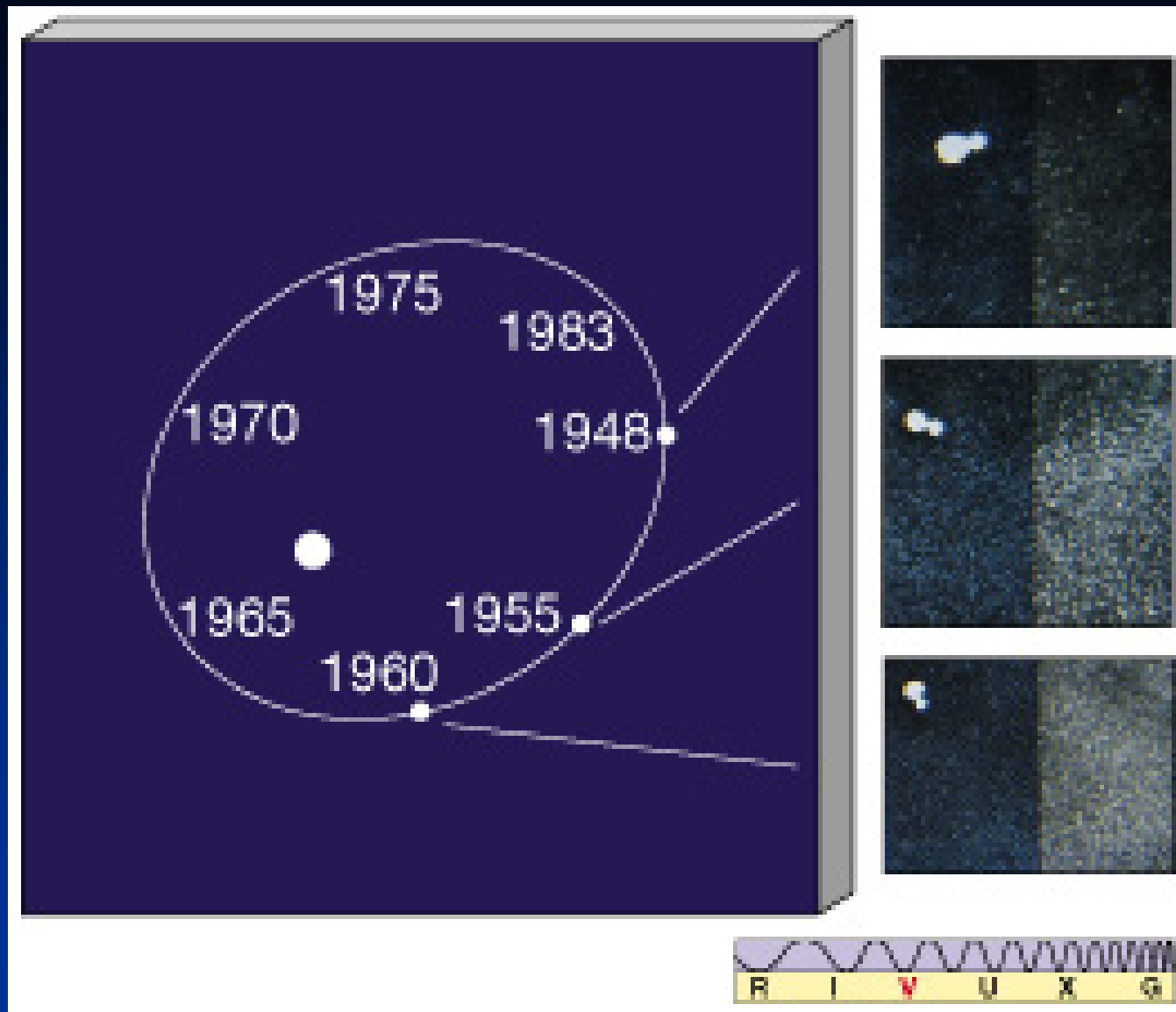
$$\text{Mass}_o = 2 \times 10^{33} \text{ Grams} = 300,000 M_{\text{Earth}}$$

Stellar Mass

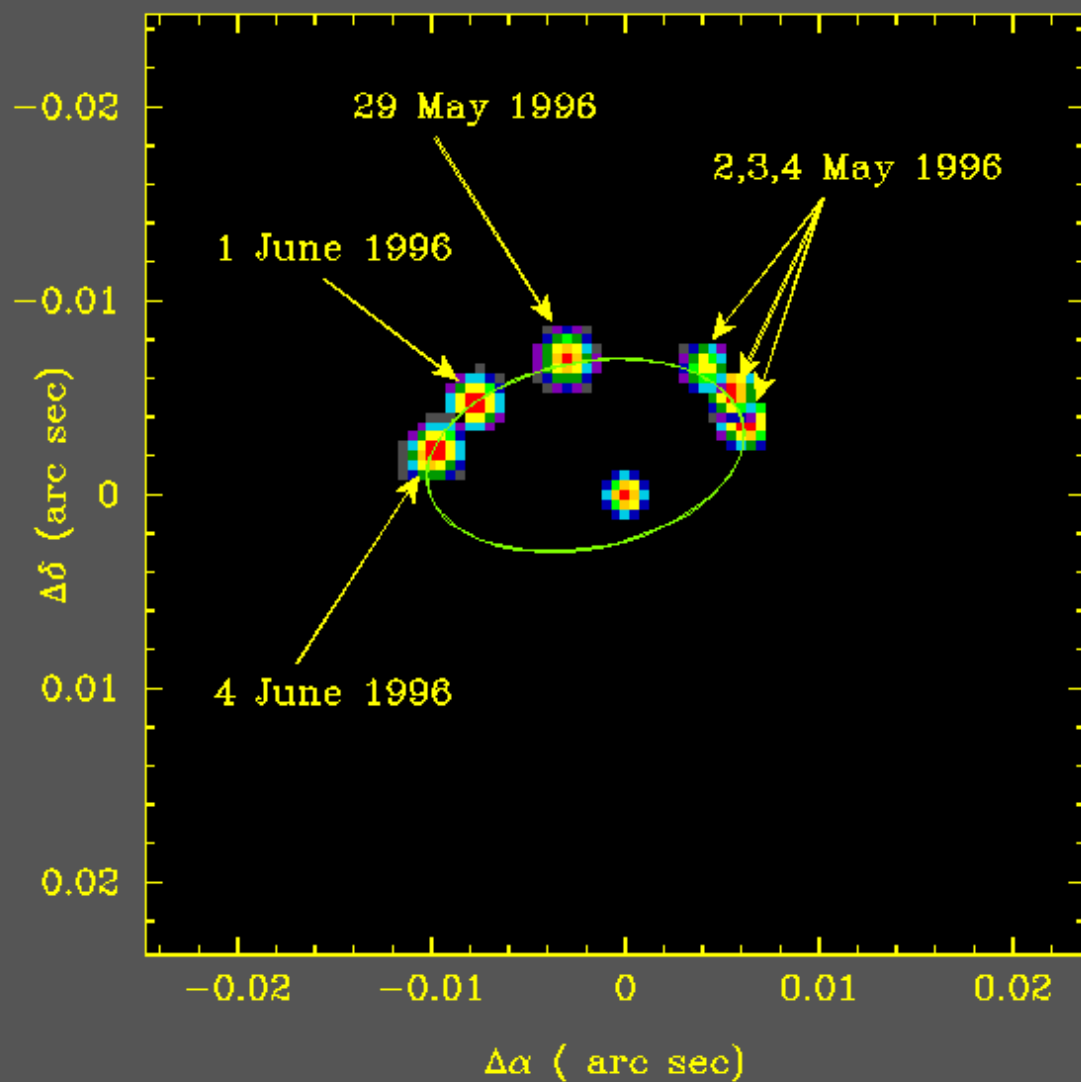
- Interesting note. The mean Density of the Sun is only 1.4 grams/cm^3
- To measure the masses of other stars, we need to find some binary star systems.
- Multiple star systems are common in the Galaxy and make up at least $1/3$ of the stars in the Galaxy.

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 loooooong time scale. Timescales for the orbits are 10s of year to 100s of years.



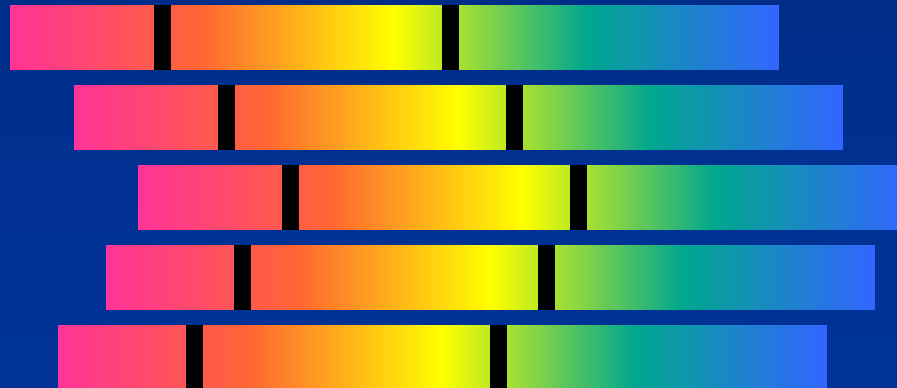
ζ^1 Ursae Majoris



Stellar Mass

(3) Spectroscopic binary -- now it is getting interesting. There are three subclasses:

(3a) Single-lined spectroscopic binary. Sometimes you take spectra of a star over several nights and discover the positions of the spectral lines change with time.



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.

Stellar Mass: Binary Systems

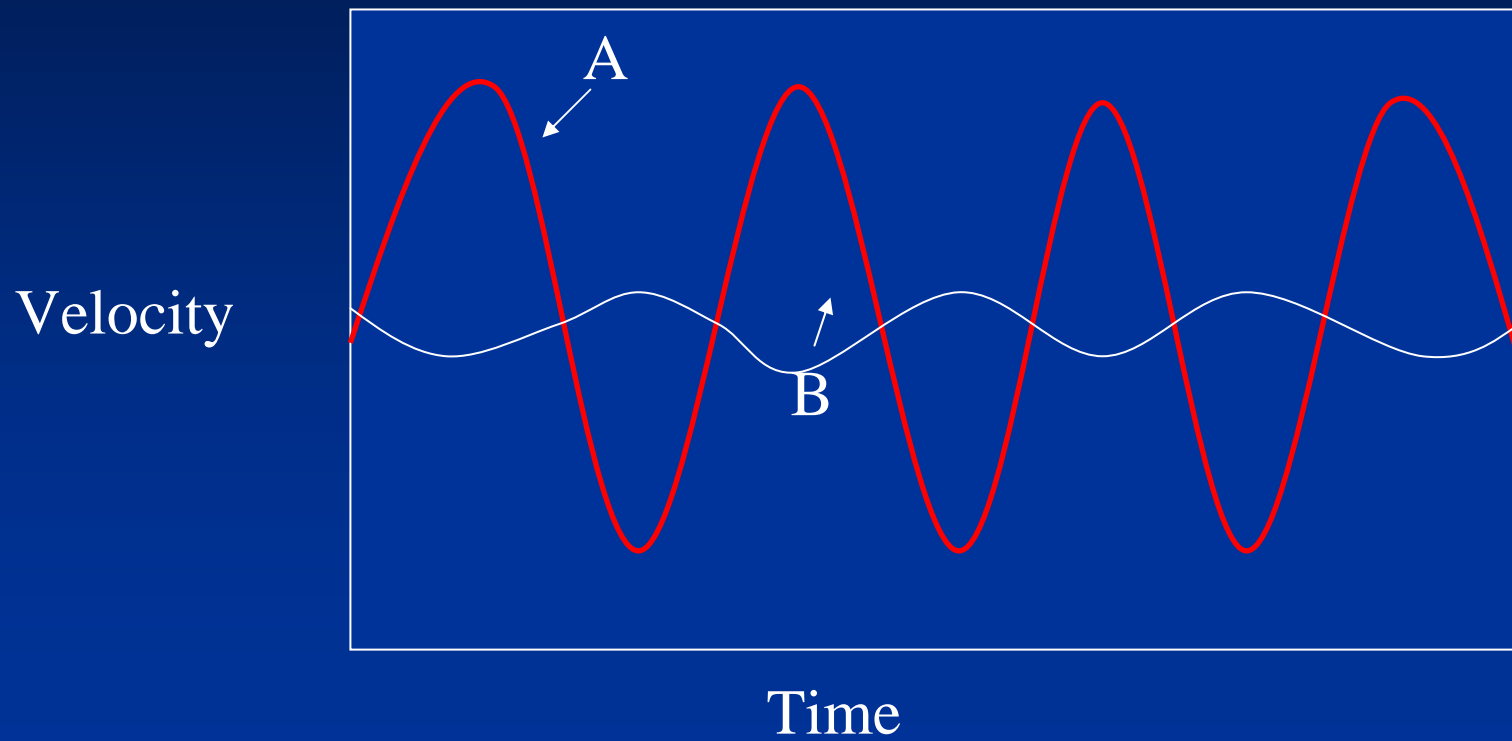
- So for a single-lined SB we measure one component of the motion of one component of the binary system.
- (3b) **Double-lined Spectroscopic Binary.** Take a spectrum of an apparently single star and see two sets of absorption lines with each set of lines moving back and forth with time. This is an opportunity to measure the mass of each component in the binary by looking at their relative responses to the mutual gravitational force.



← Blue

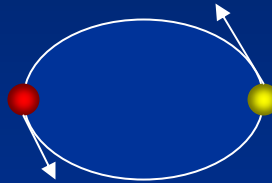
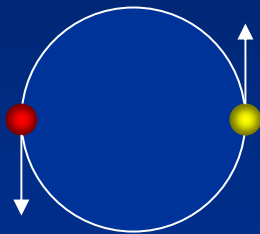
Red →

DLSB



Stellar Masses

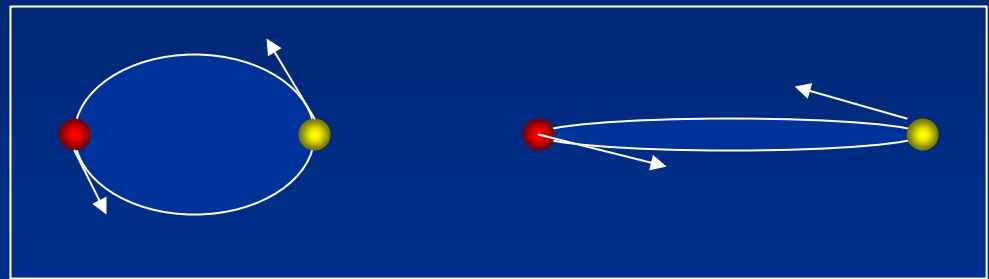
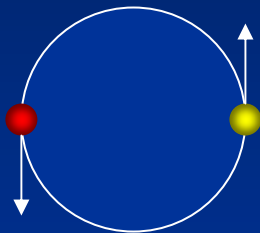
- With Double-lined Spectroscopic Binary stars you can determine the mass of each member of the binary to within a factor of the **inclination of the orbit**.



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

Stellar Masses

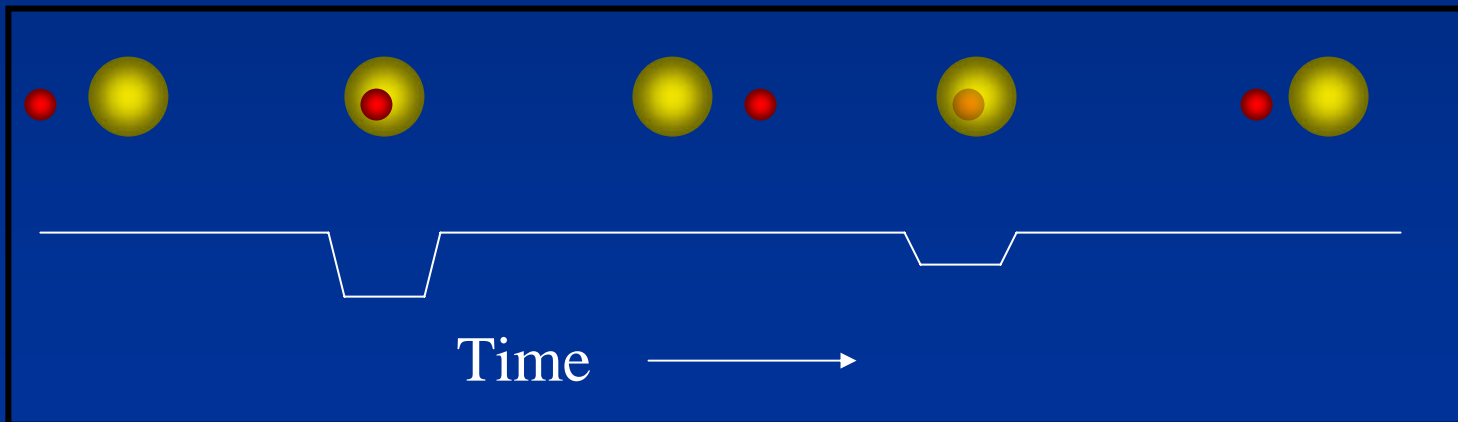
- With Double-lined Spectroscopic Binary stars you can determine the mass of each member of the binary to within a factor of the **inclination of the orbit**.



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

Double-Lined Eclipsing Binary

- The last category of binary star is the DLEB. 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.

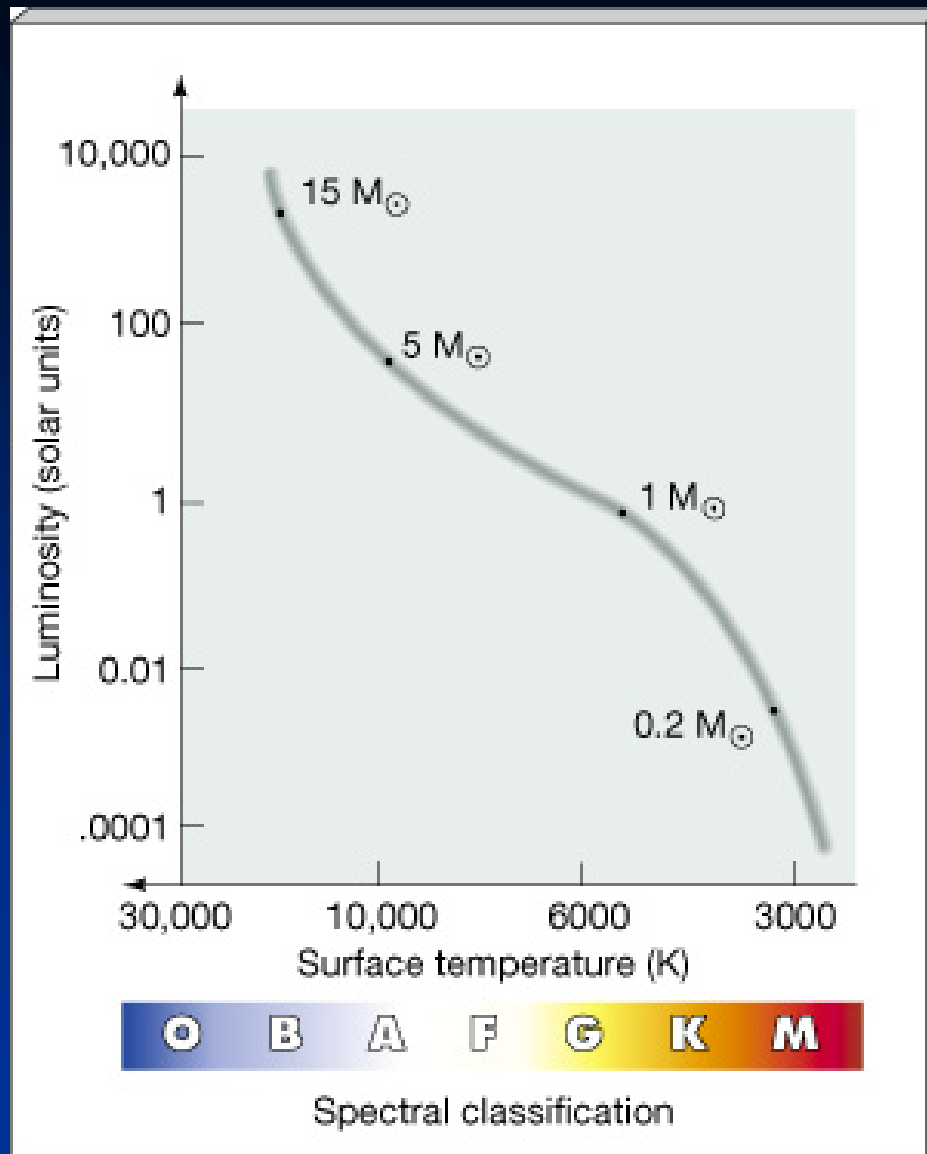


Mass-Luminosity Relation

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

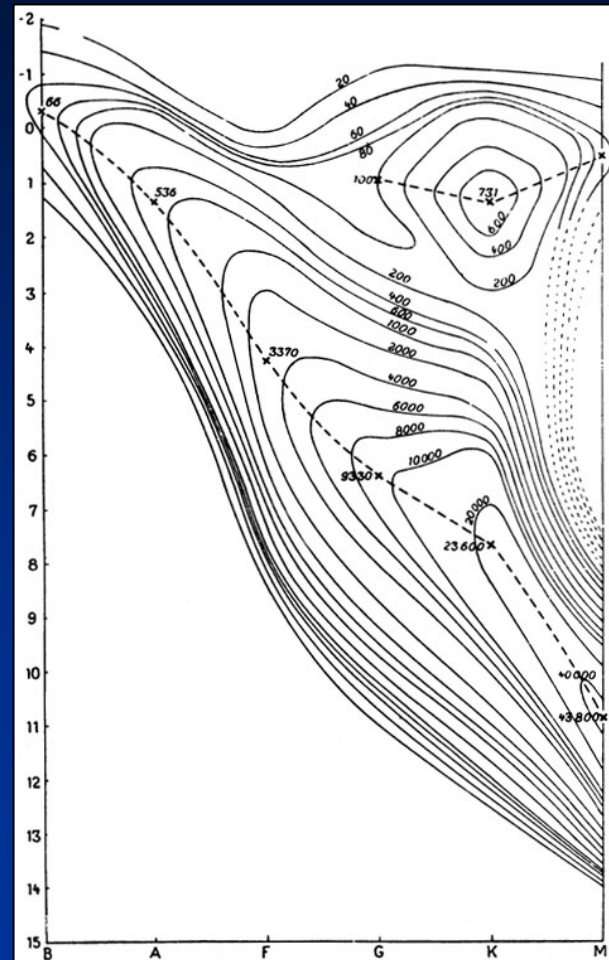
$$L \propto M^{3.5}$$

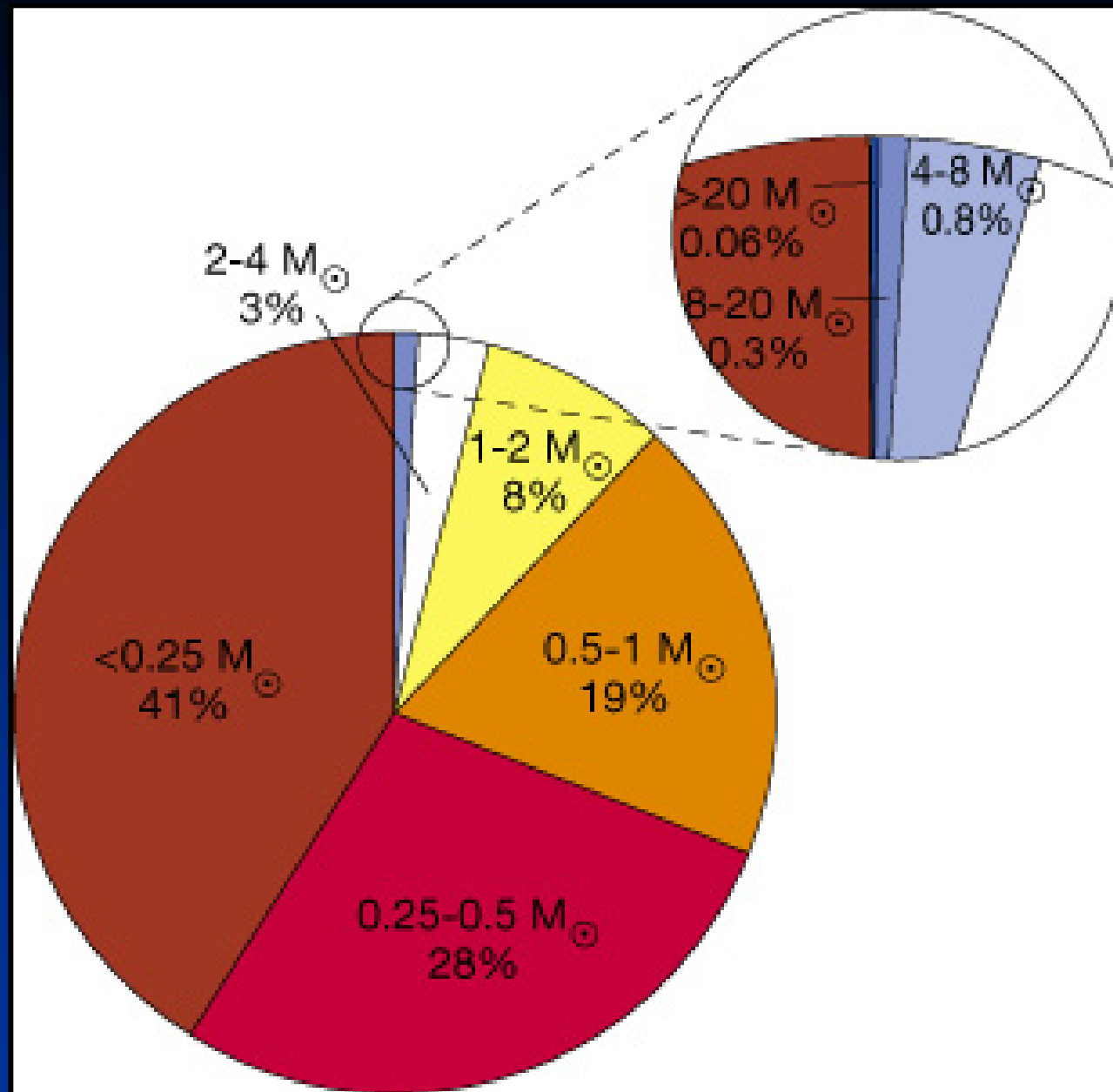
- *The main-sequence in the H-R Diagram is a mass sequence.*
- Temp, Luminosity and Mass all increase and decrease together.



Distribution of Stars by Mass

- The vast majority of stars in the Galaxy are low-mass objects.
- This distribution is shown in the Hess Diagram.



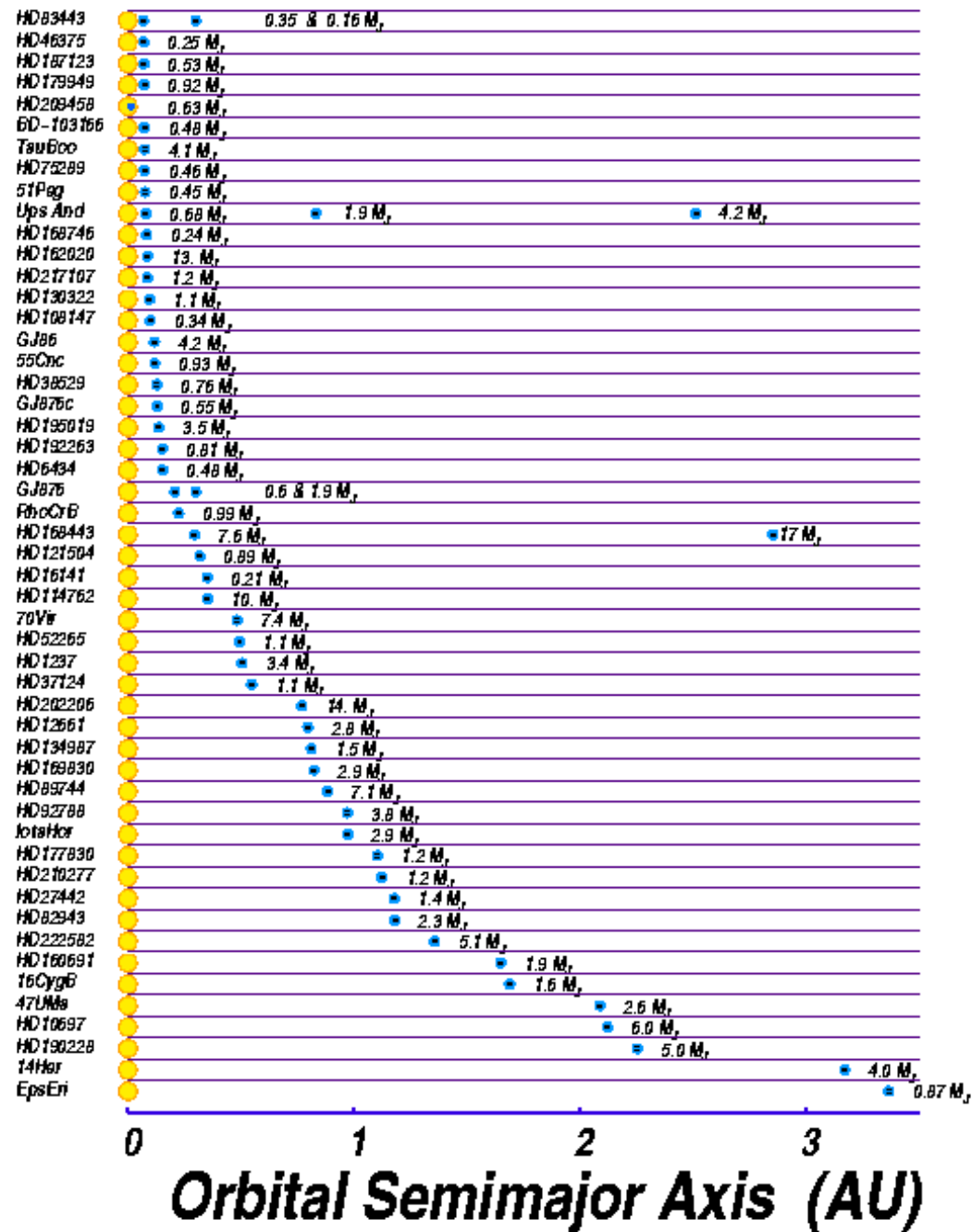


Stellar Mass

- The two limits on stellar ($0.08M_{\odot}$ and $80M_{\odot}$) are well understood and we will get back to these next section when we talk about the energy source for stars.
- Note that all the extra-solar planets that are being discovered at a rate of about 10 per year are detected by the Doppler shift of the stars around which they orbit. These are essentially single-lined spectroscopic binaries.

Extrasolar Planets

- Typical velocity amplitudes for binary stars are 20km/sec. This is pretty easy to measure. The motion of a star due to orbiting planets is generally <70 m/sec and typically <10 m/sec. This is VERY difficult!
- UCSC students Geoff Marcy, Debra Fisher and UCSC faculty member Steve Vogt have discovered the large majority of known extra solar planets! About 1/2 from Mt Hamilton, 1/2 from Keck.



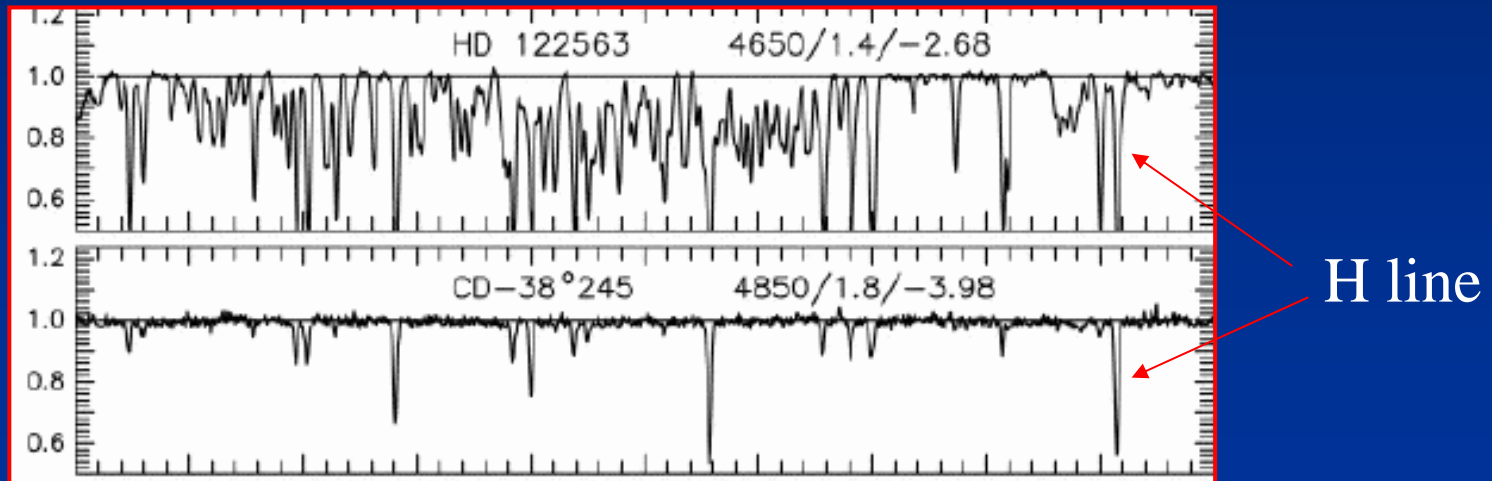
Chemical Composition

- We can also determine the abundances of many elements in stars by using the `atomic fingerprints' seen in spectral absorption lines.
- This is a tricky business! We already know that the strength and even presence of absorption lines is strongly temperature dependent. To use absorption line strengths to measure abundances in a star requires that we first determine:
 - (1) the star's temperature (could use the strength of the hydrogen lines)
 - (2) the star's surface density (astronomers have ways to do this using `ionization equilibrium')

Once these are known, we can then estimate the abundance of any elements that have absorption lines in a stellar spectrum!

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 heavier than H and He 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	$10^{-5}L_{\odot}$ - 10^6L_{\odot}
Radius	Stephan's Law	$0.01R_{\odot}$ - $800R_{\odot}$
Mass	Binary orbits	$0.08M_{\odot}$ - $80M_{\odot}$