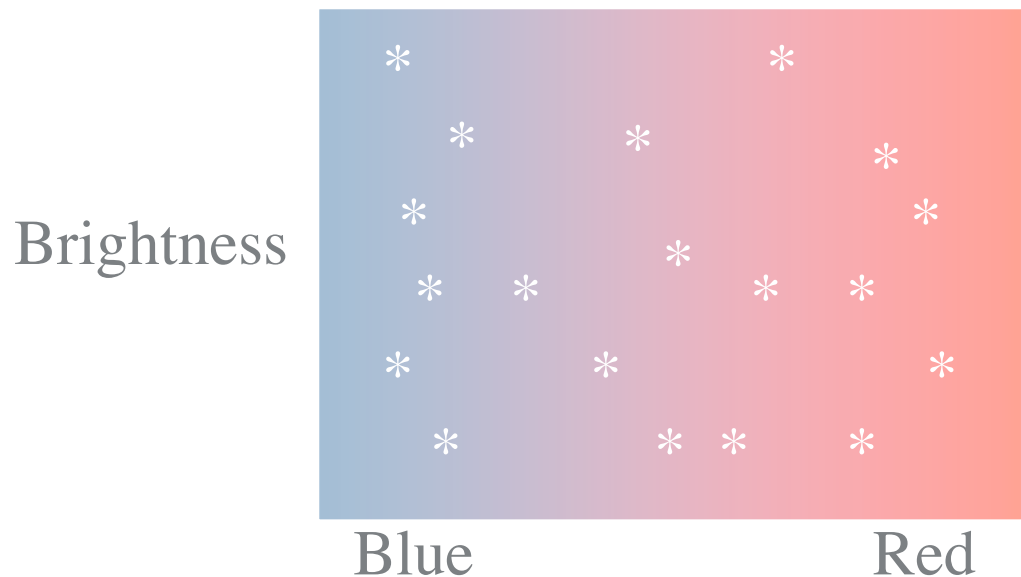


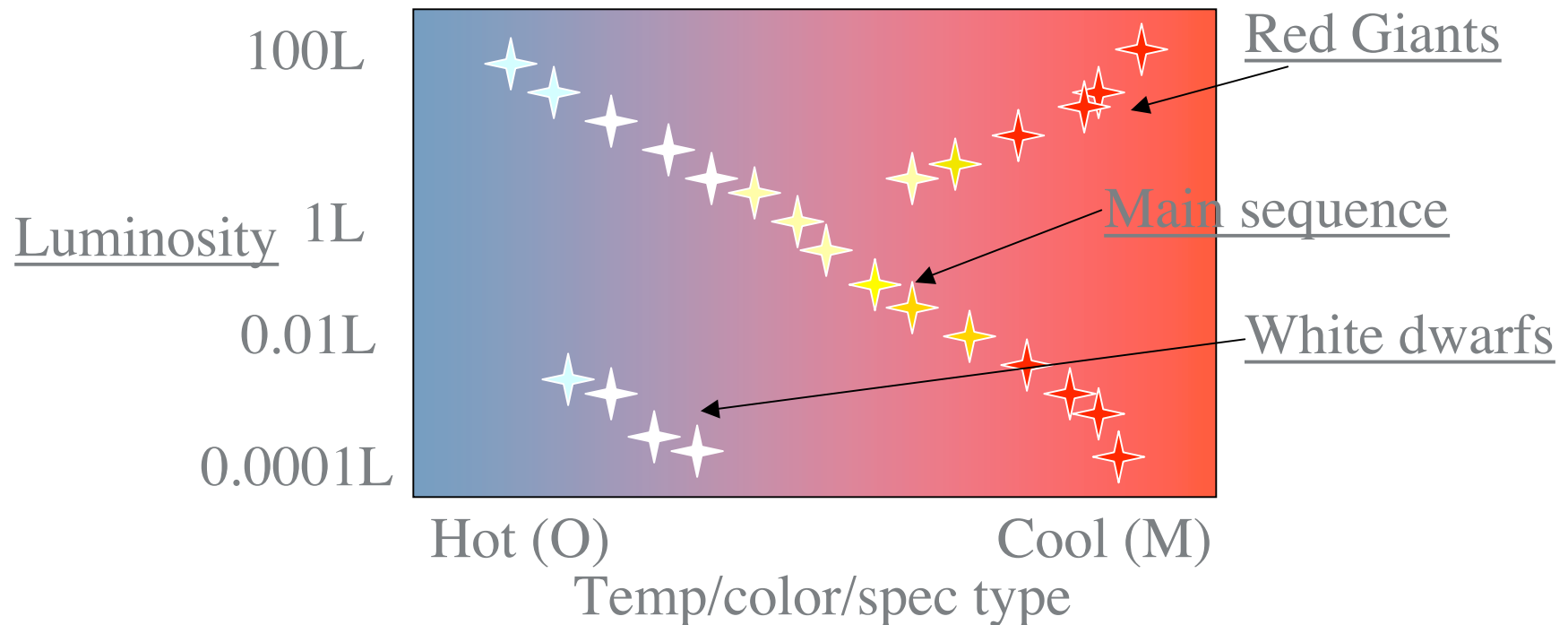
Properties of Stars: The H-R Diagram

- 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

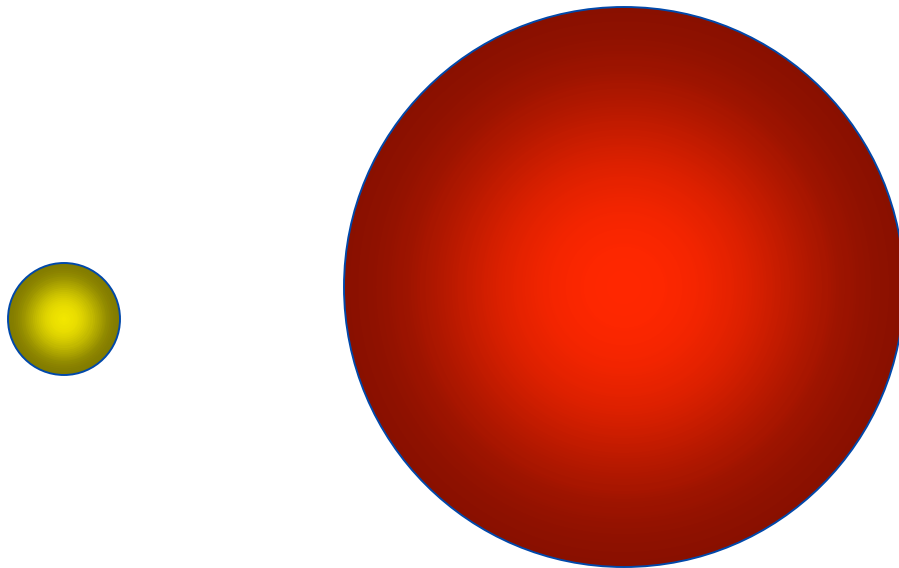
- For example, if you double the temperature of an object, the amount of energy it radiates increases by $2^4 = 2 \times 2 \times 2 \times 2 = 16$ (!)
- Think about the Sun and Betelguese:

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

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

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:

$$\frac{5500^4}{3400^4} = 6.8$$

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 27500 for the Betelguese surface area to give the Luminosity ratio measured for the two stars.

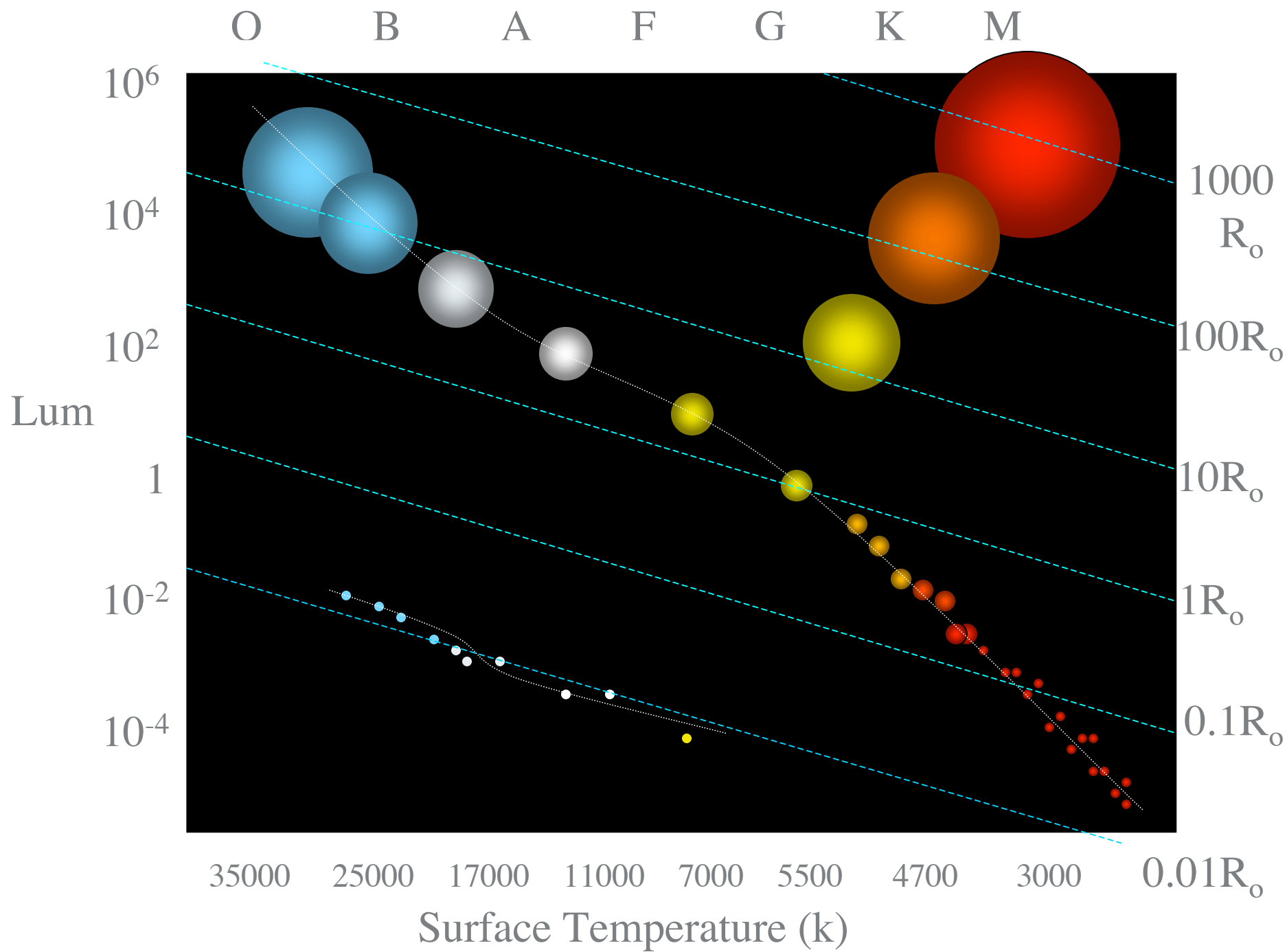
- Stated another way:

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

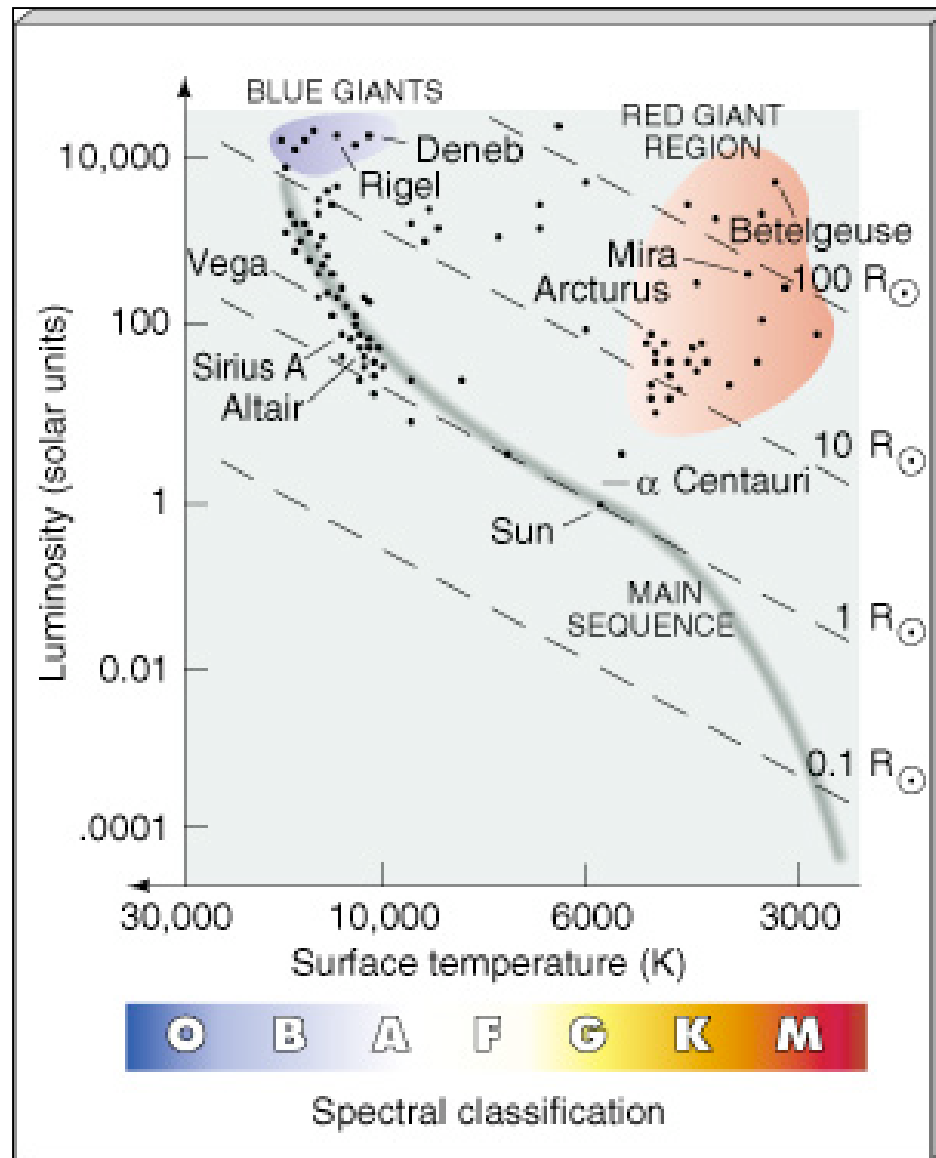
$$(\text{Area})_{\text{Betel}} = 27,500 \times \frac{(E/A)_{\text{Sun}}}{(E/A)_{\text{Betel}}} \times (\text{Area})_{\text{Sun}}$$

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

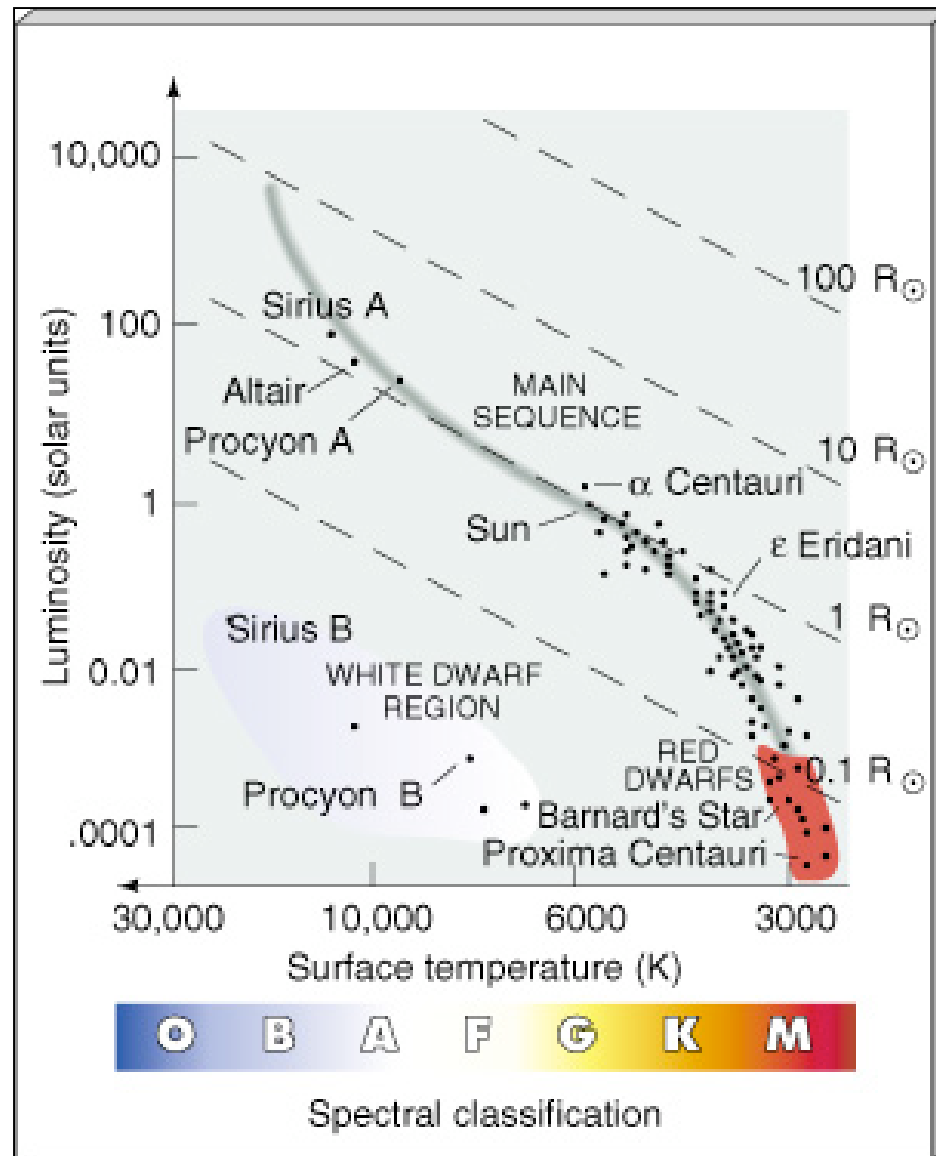
- Surface area goes like R^2 , so Betelguese has a radius that is >400 times that of the Sun!



H-R Diagram for the Brightest Stars

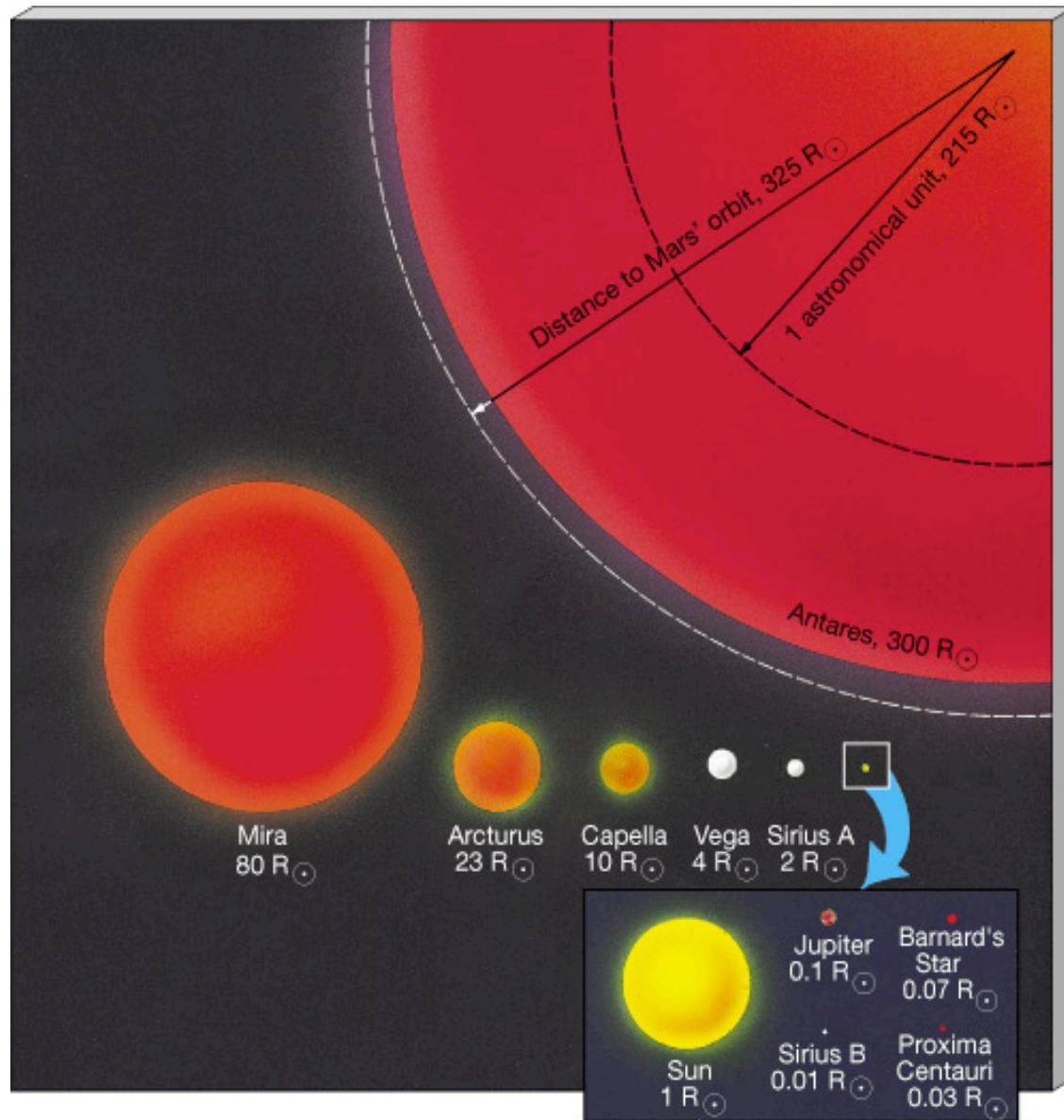


H-R Diagram for the Nearest Stars



Stellar Radius

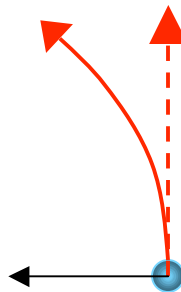
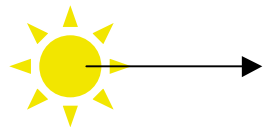
- The range in stellar radius seen is from 0.01 to about 1000 times the radius of the Sun.



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:

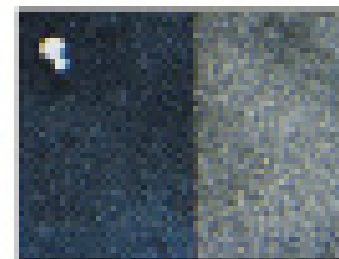
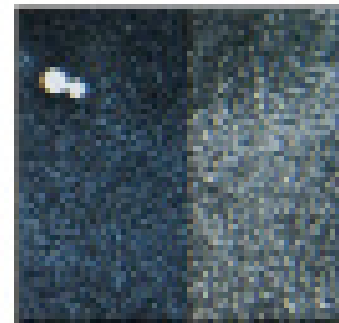
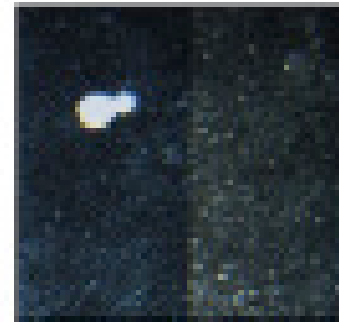
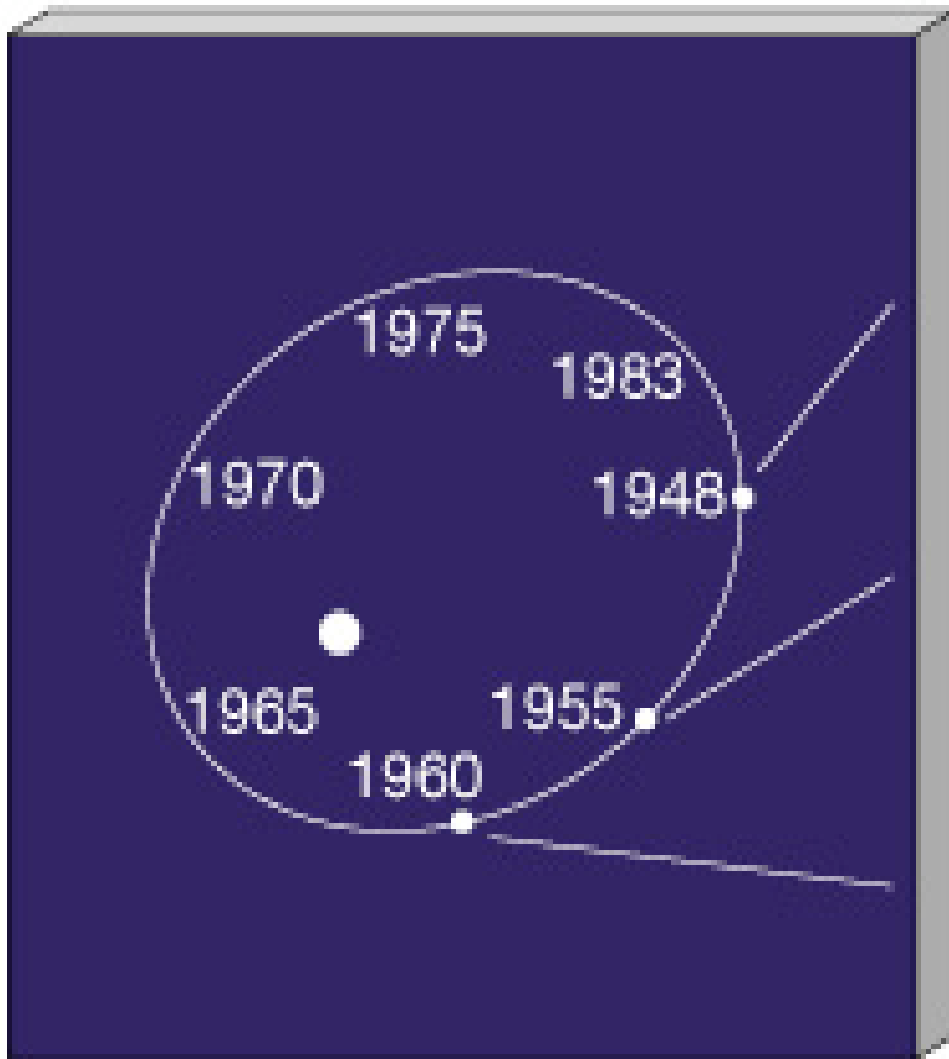
$$\text{Mass}_o = 2 \times 10^{33} \text{ Grams} = 300,000 M_{\text{Earth}}$$

Stellar Mass

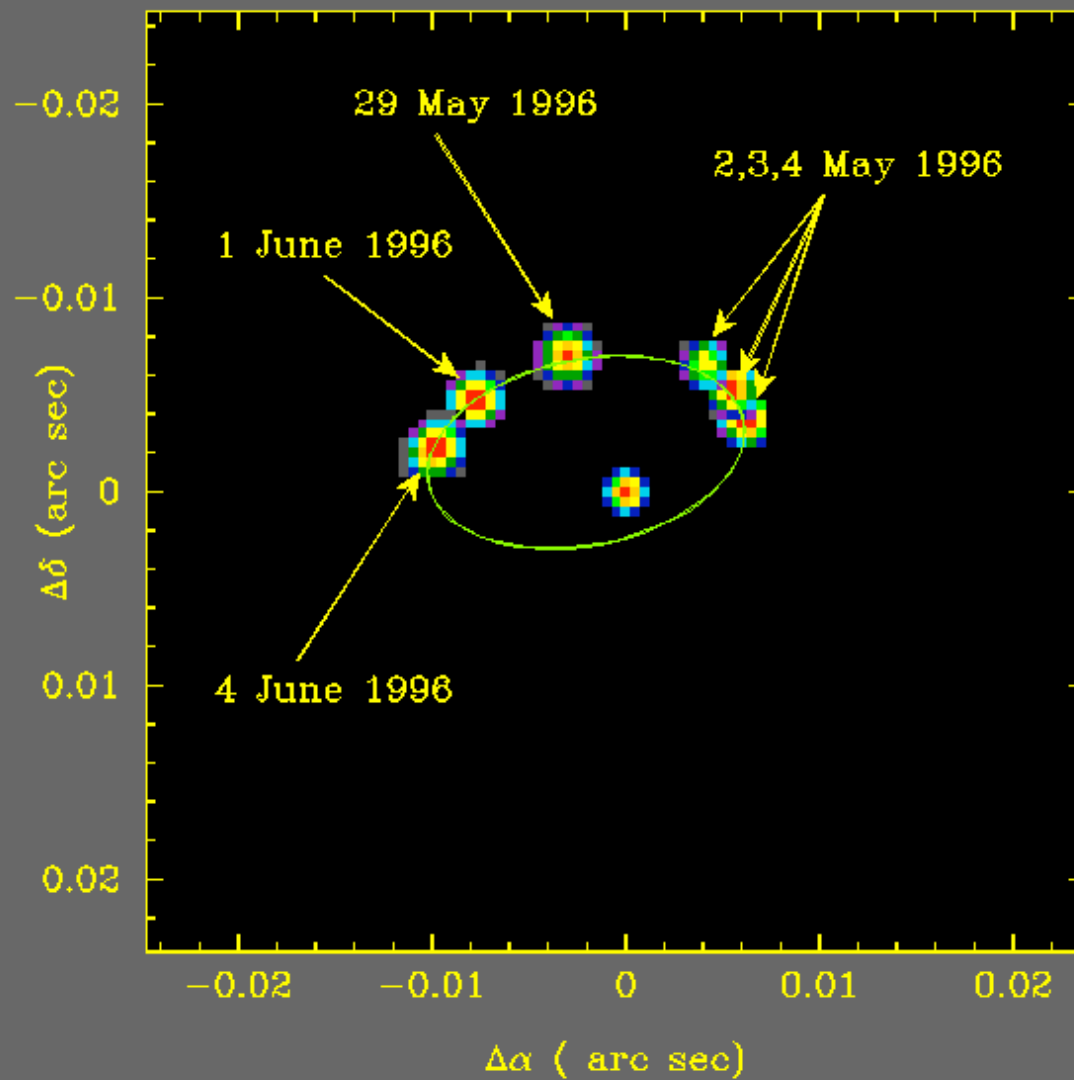
- Interesting note. The mean Density of the Sun is only 1.4 grams/cm^3
- To measure the masses of other stars, we need to find some binary star systems.
- Multiple star systems are common in the Galaxy and make up at least $1/3$ of the stars in the Galaxy.

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.



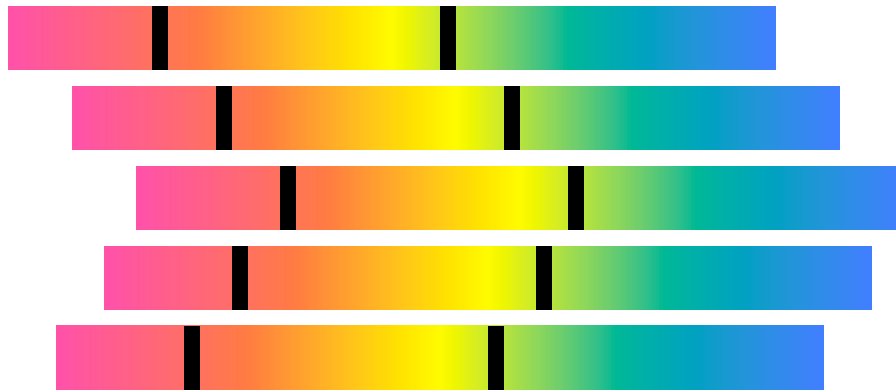
ζ^1 Ursae Majoris



Stellar Mass

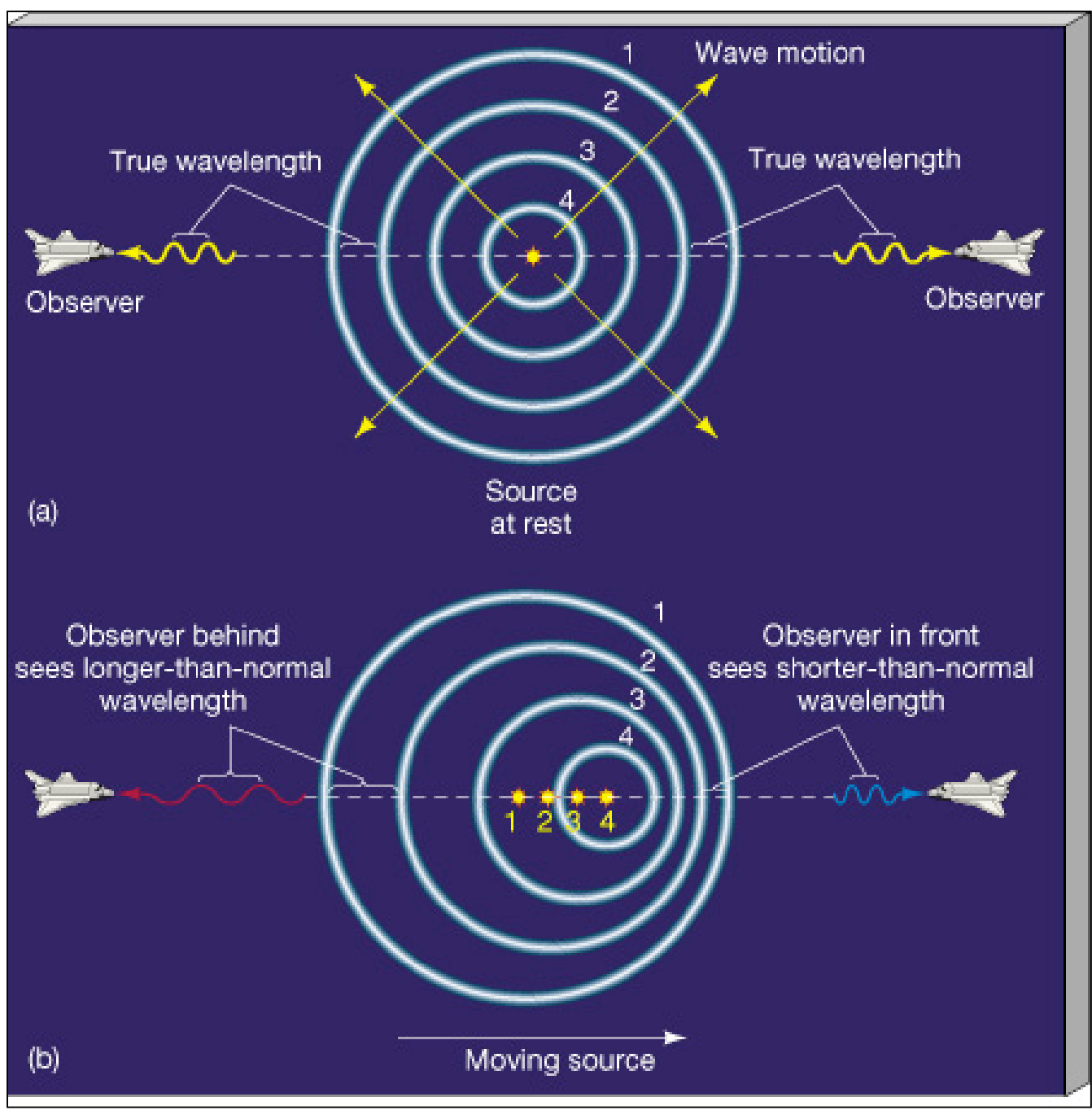
(3) Spectroscopic binary -- now it is getting interesting. There are three subclasses:

(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.



Doppler Shift

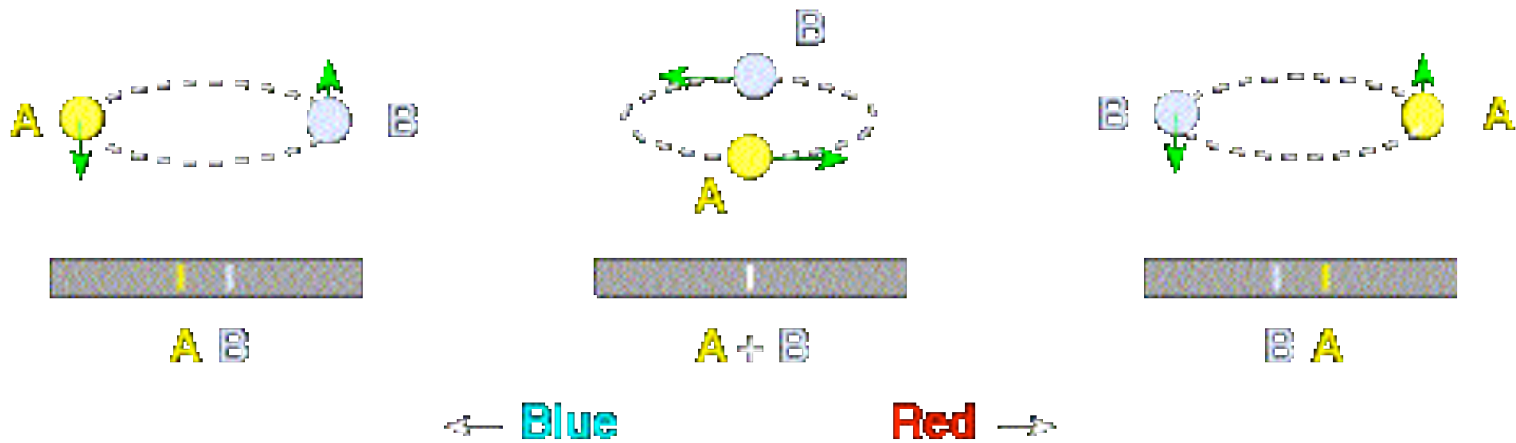
- Note that only the RADIAL component of the relative motion affects the observed frequency. The relationship between speed and frequency shift is:

$$\frac{v}{c} = \frac{\lambda - \lambda_0}{\lambda_0} = \frac{\lambda_0 - \lambda_v}{\lambda_0}$$

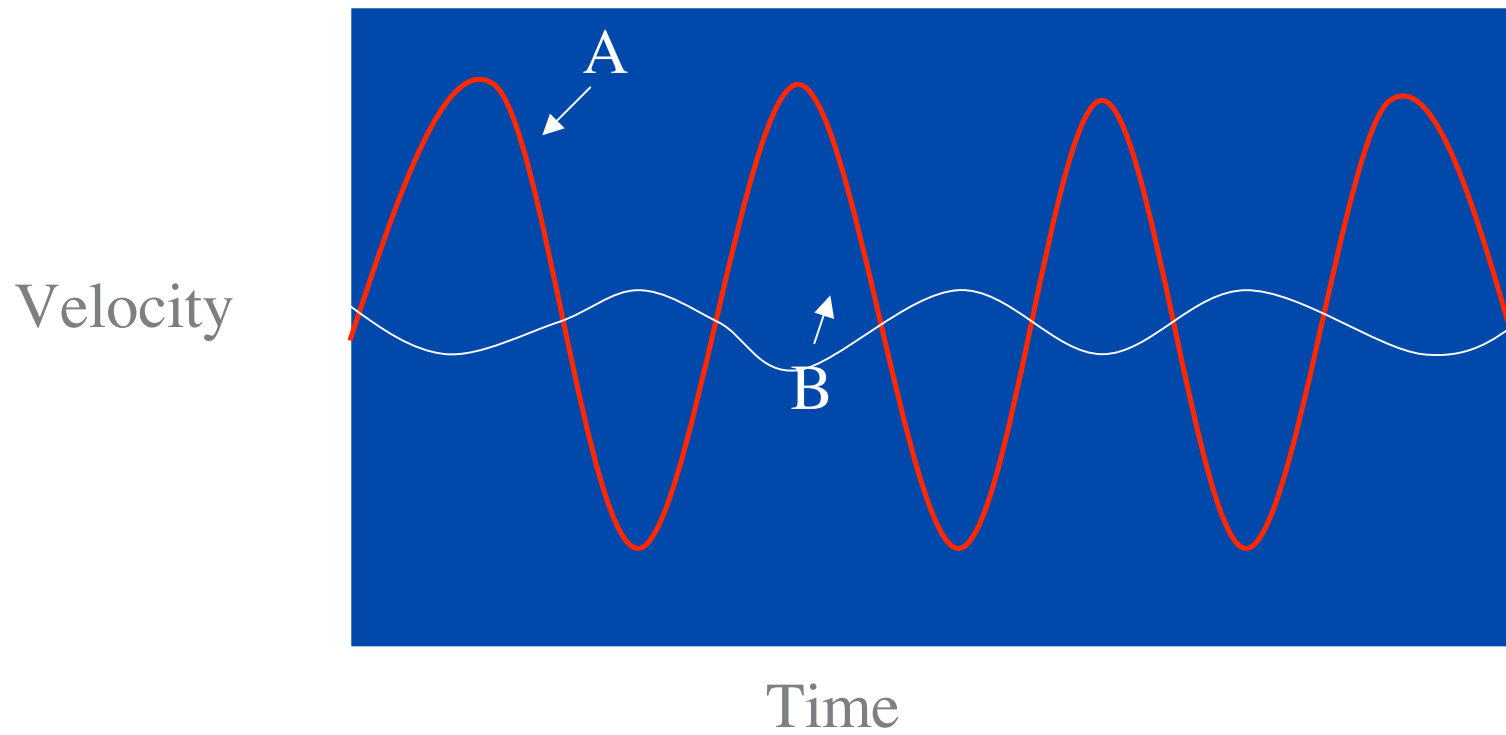
- `blueshift' for approaching, `redshift' for receding sources.

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.

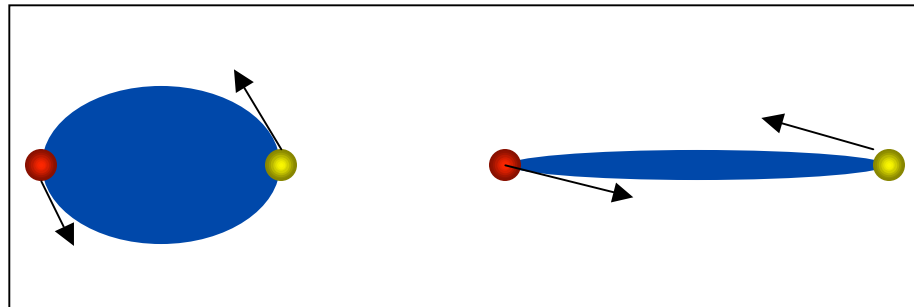
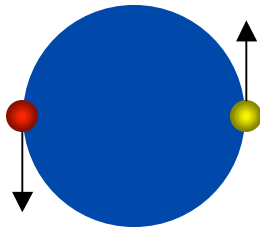


DLSB



Stellar Masses

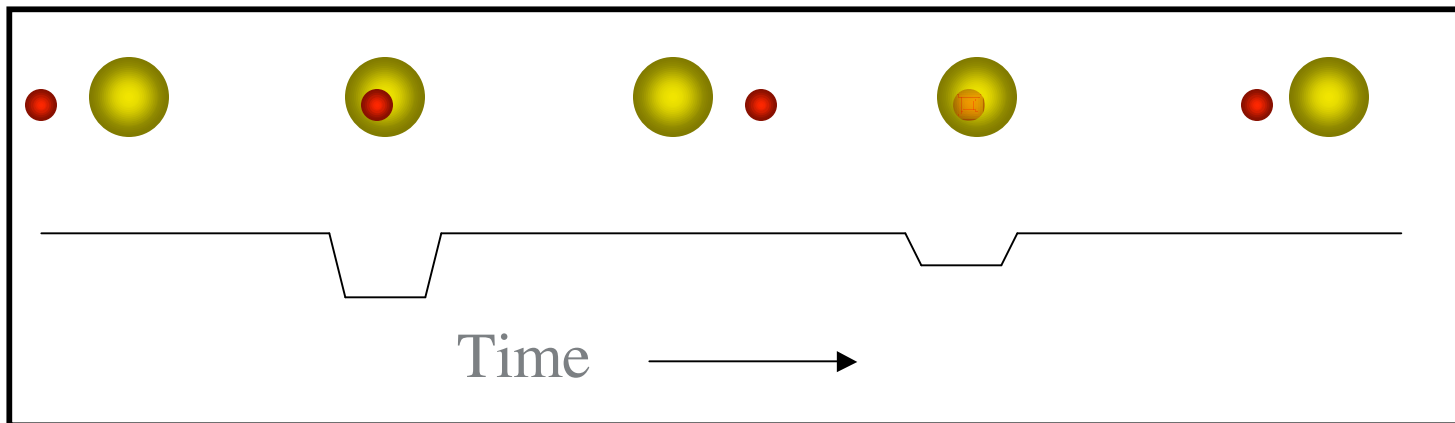
- With Double-lined Spectroscopic Binary stars you can determine the mass of each member of the binary to within a factor of the **inclination of the orbit**.



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

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.

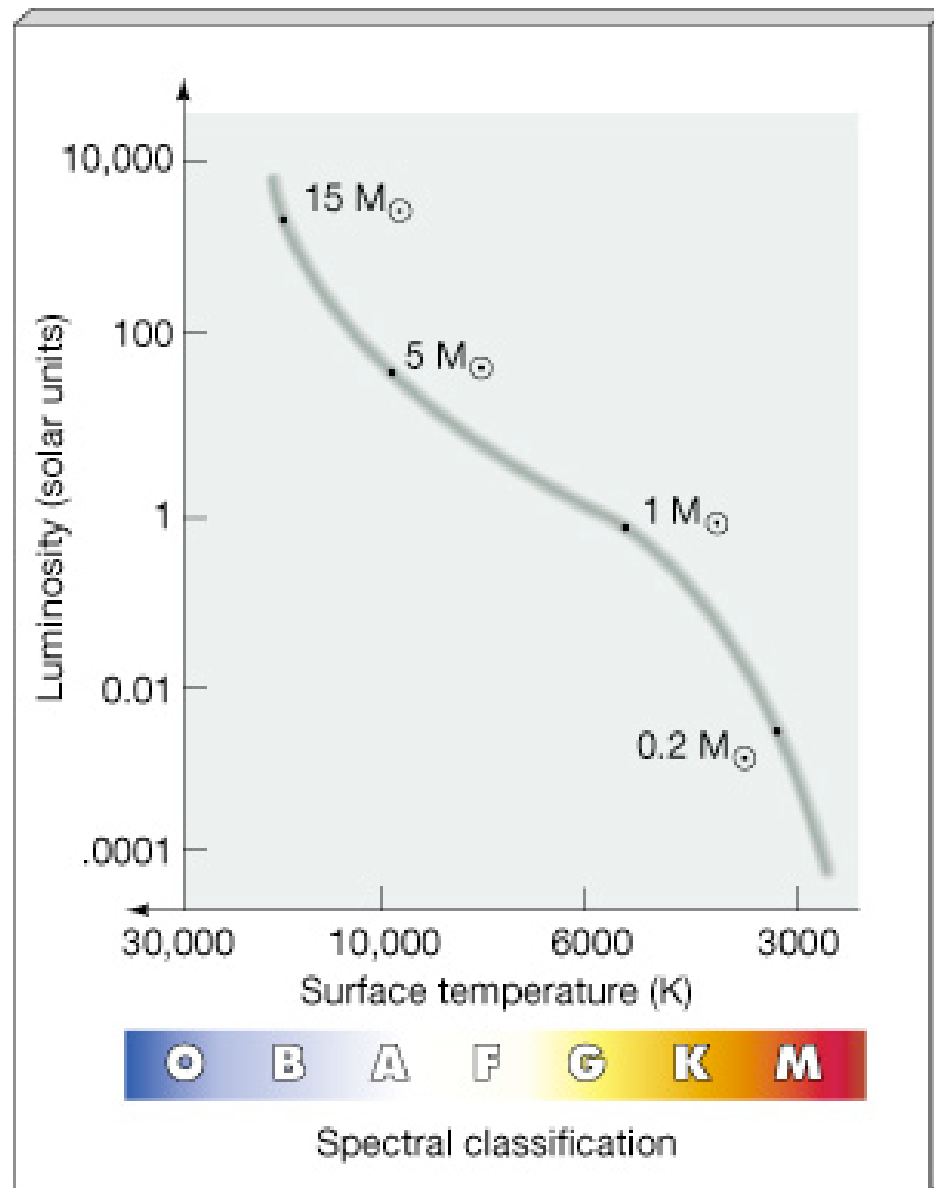


Mass-Luminosity Relation

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

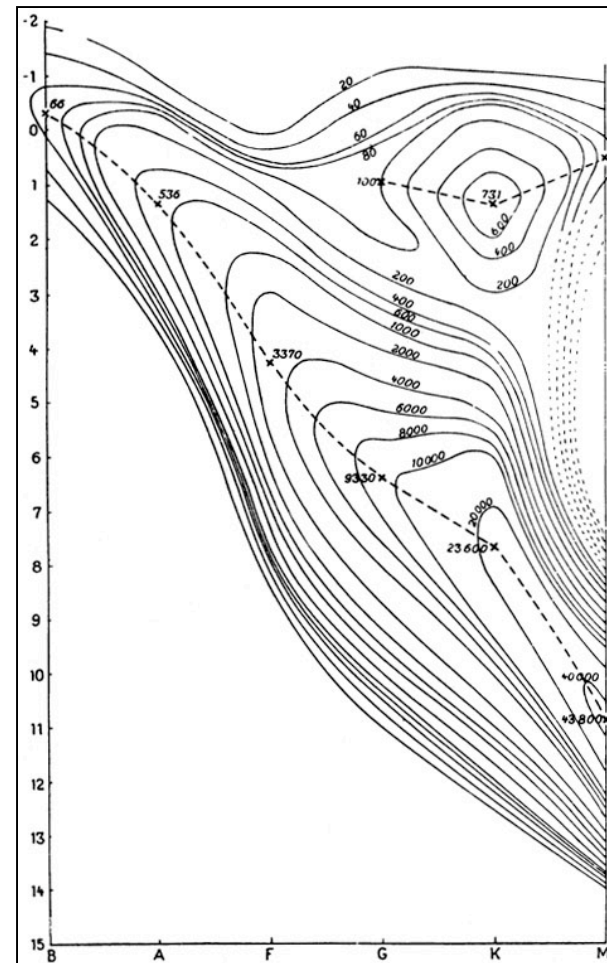
$$L \propto M^{3.5}$$

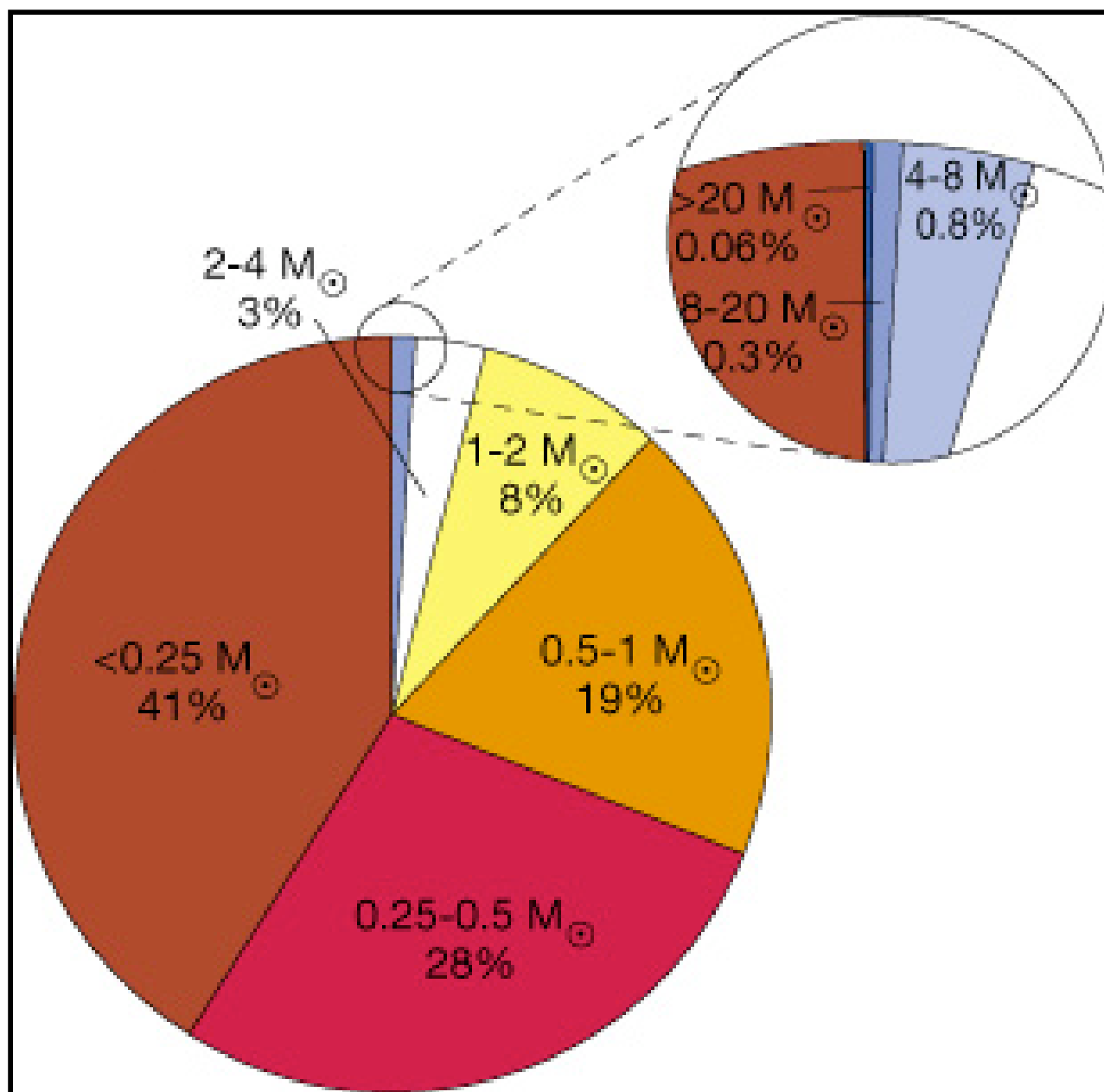
- *The main-sequence in the H-R Diagram is a mass sequence.*
- Temp, Luminosity and Mass all increase and decrease together.



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.



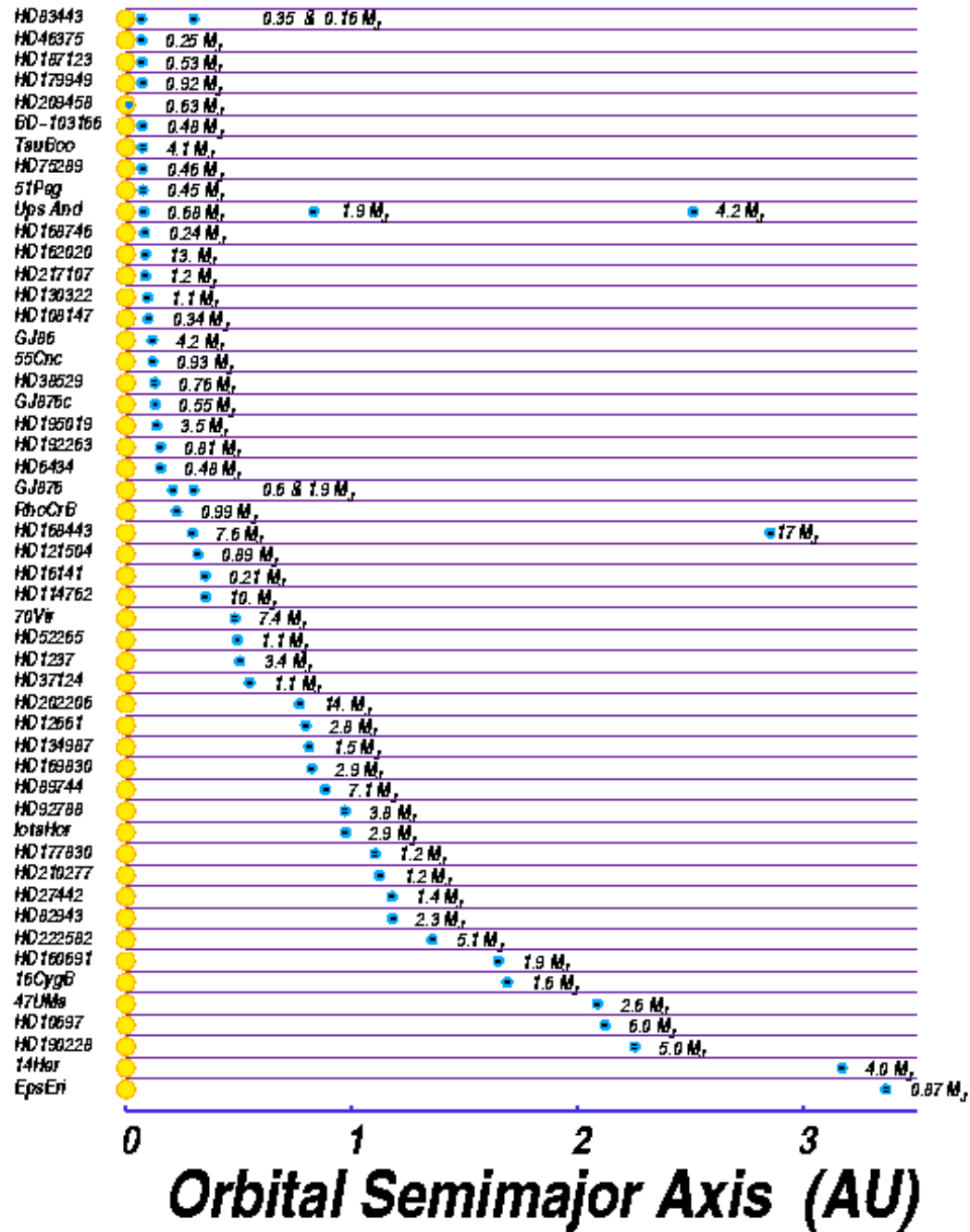


Stellar Mass

- 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.



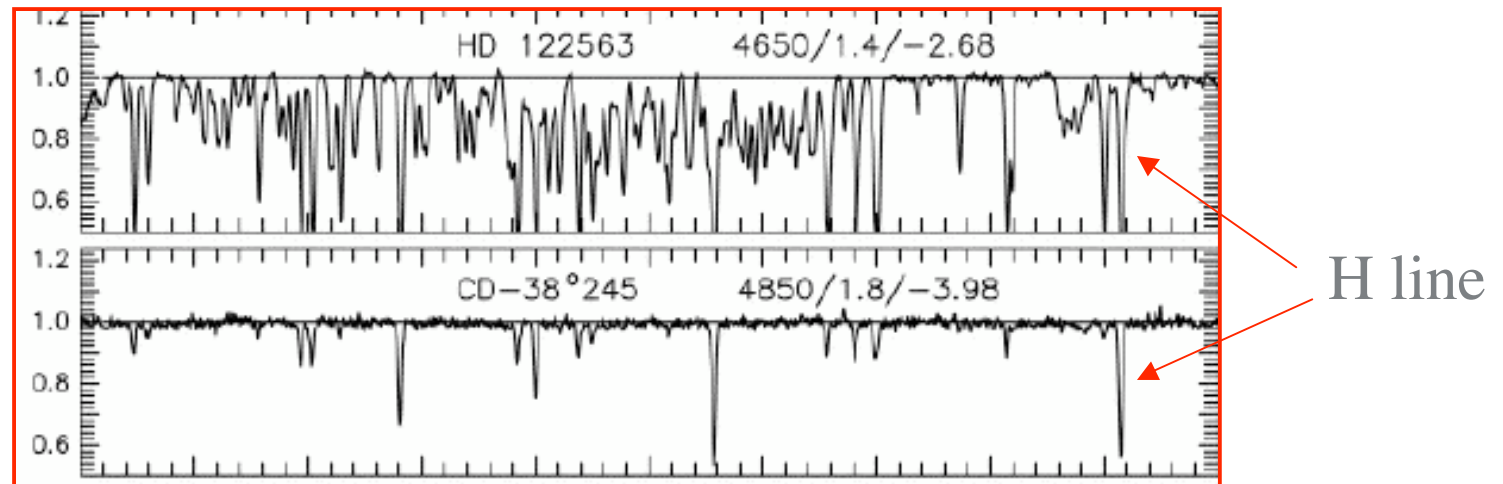
Chemical Composition

- 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 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+bright ness	$10^{-5}L_{\odot}$ - 10^6L_{\odot}
Radius	Stephan's Law	$0.01R_{\odot}$ - $800R_{\odot}$
Mass	Binary orbits	$0.08M_{\odot}$ - $80M_{\odot}$