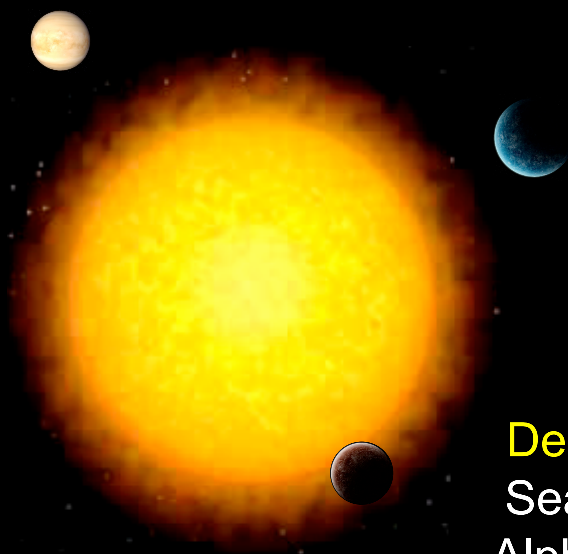
Planets Beyond the Solar System: A New Astronomical Revolution

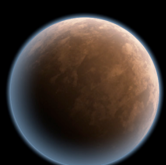
March 27, 2010

Alan Boss
The Crowded Universe: The Search for Living Planets



James Kasting
Finding a Habitable Planet

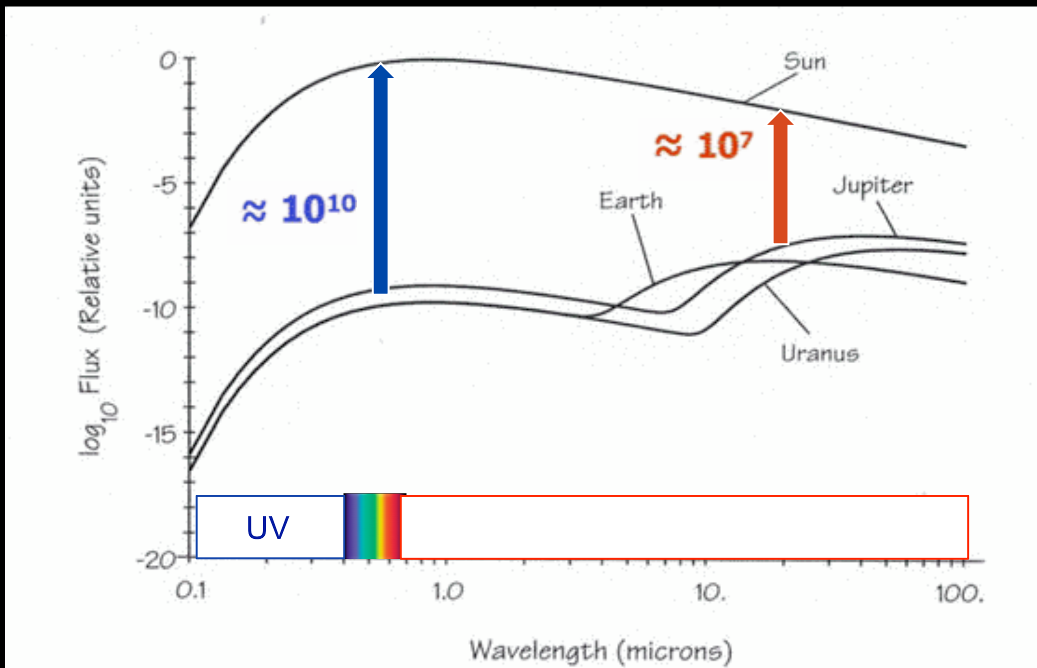
Debra Fischer
Searching for Earths in the Alpha Centauri System



Adam Burgasser
Cold Stars, New Neighbors: Discovering Brown Dwarfs

By Steve Brehmer
The Bakken
Minneapolis, MN

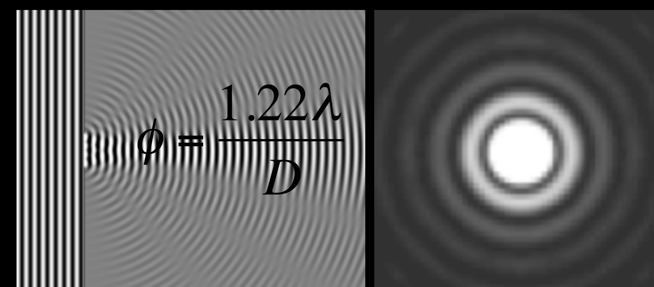
How Do You Search for Exoplanets?



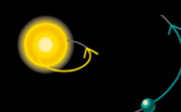
Direct Observation

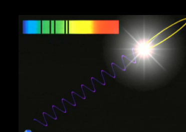
It is hard to see a planet if it is close to a bright star – IR is better than visible.

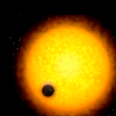
Longer wavelengths mean lower resolution – bigger telescopes are required.

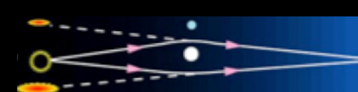


Less Direct

Astrometry 

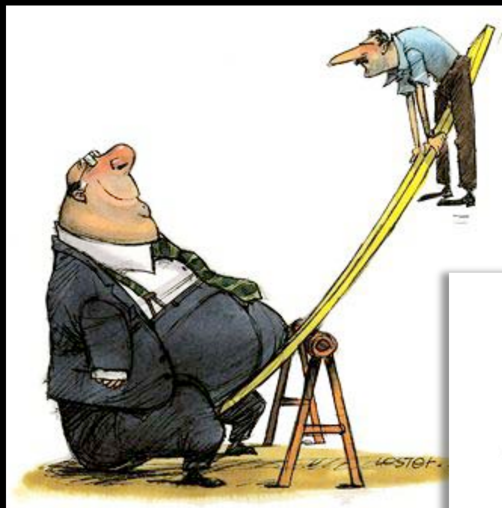
Doppler Shift – Radial Velocity 

Transit 

Gravitational Microlensing 

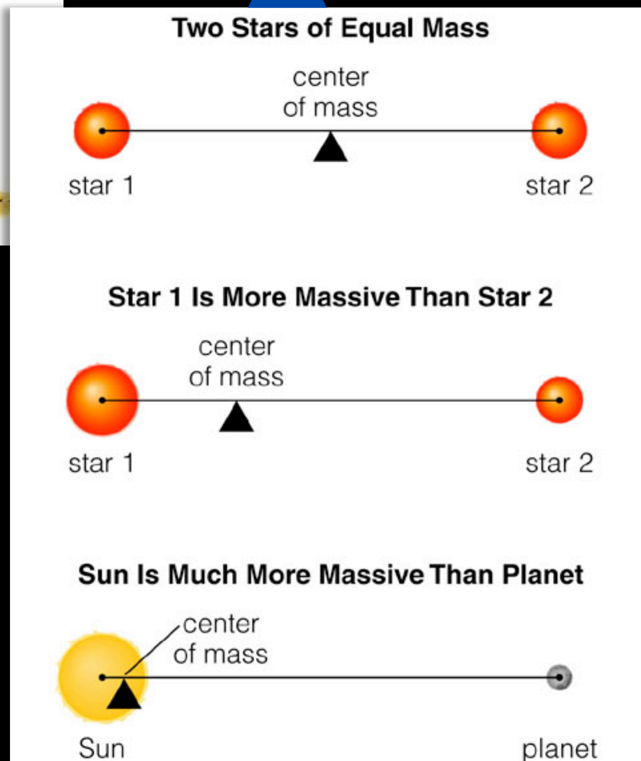
Center of Mass

A planet doesn't rotate around the center of a star. The star and planet both rotate around the center of mass.

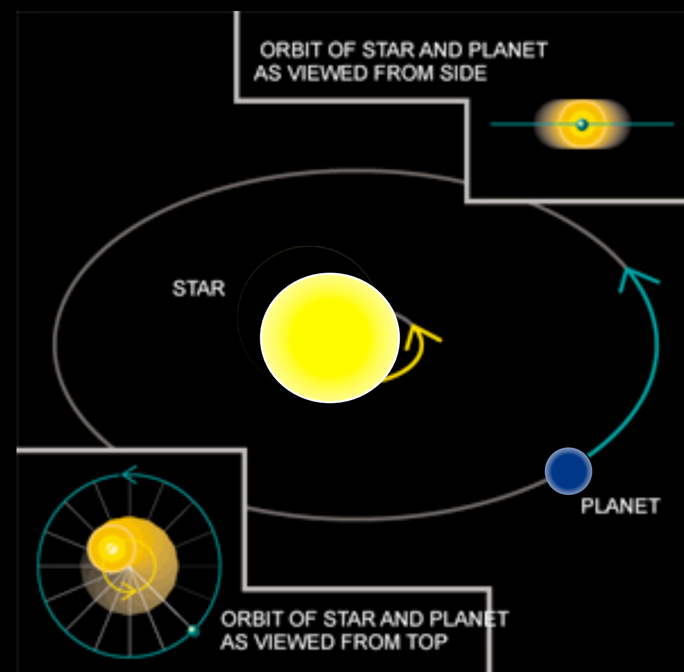


We can calculate the center of mass for a system. If the system starts to rotate, it will rotate around the center of mass.

$$\mathbf{R} = \frac{m_1\mathbf{r}_1 + m_2\mathbf{r}_2}{m_1 + m_2}$$



That means the star will appear to wobble.



Astrometry

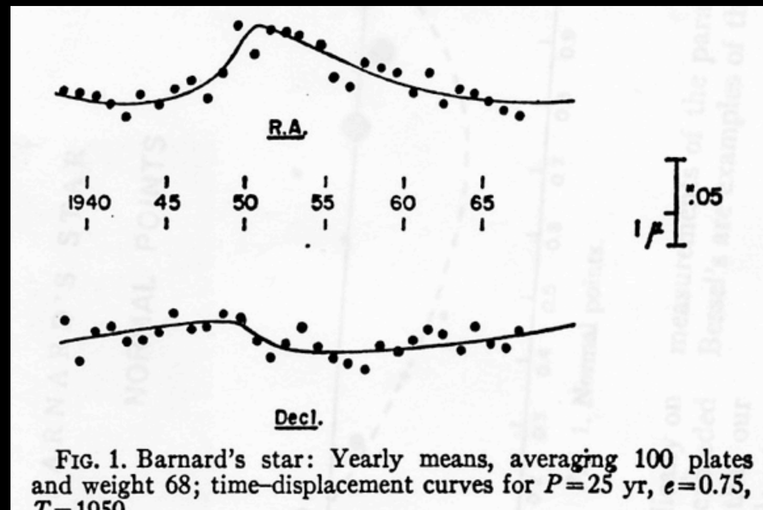


FIG. 1. Barnard's star: Yearly means, averaging 100 plates and weight 68; time–displacement curves for $P=25$ yr, $e=0.75$, $T=1950$

In the 1960's Peter van de Kamp measured the position of Barnard's star in images that had been taken between 1916 and 1962.

His data seemed to show a wobble, indicating a planet.

In 1973 George Gatewood used images from a another telescope to show there was no wobble.

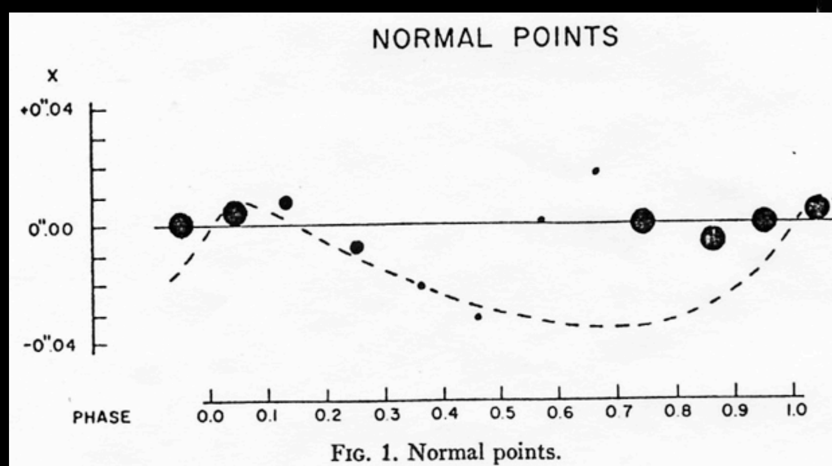


FIG. 1. Normal points.

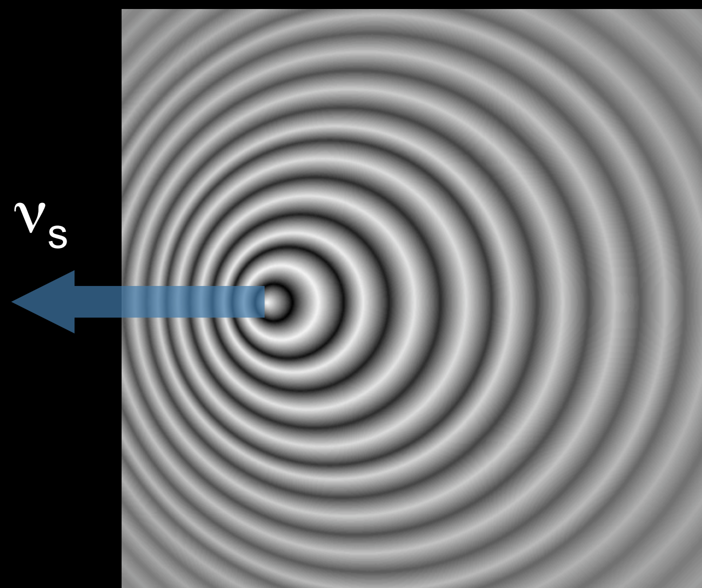
Is there a different way to use the wobble?

Doppler Shift

$$f' = f\frac{v}{v - v_s}$$

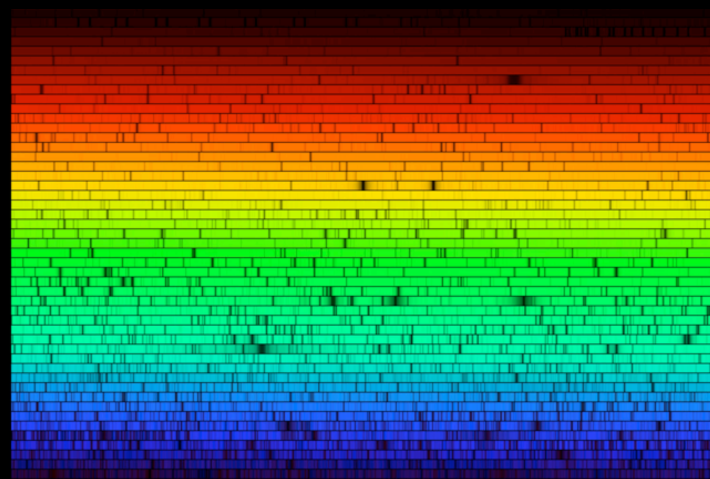
$$\Delta\lambda = \frac{v_r \lambda}{c}$$

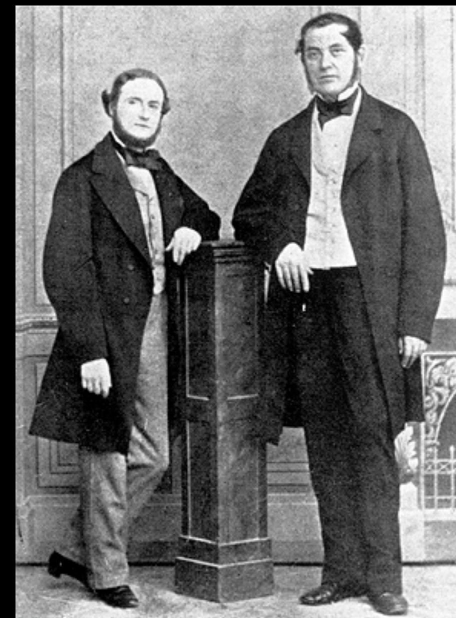
$$f' = f\frac{v}{v + v_s}$$



In 1842 Christian Doppler proposed that the frequency of a moving source of sound would be different depending on the location of the observer. The Doppler effect also applies to light waves.

In 1672 Newton published the results of experiments that showed that white light was composed of a rainbow of color.



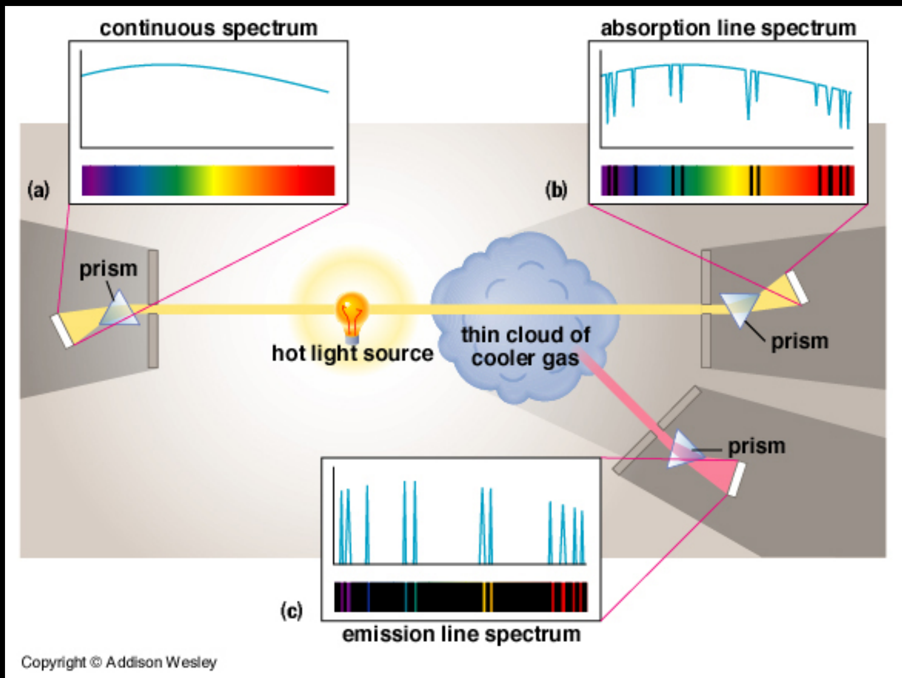


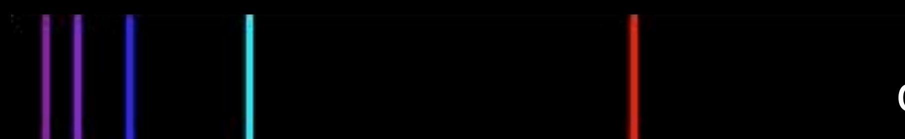
In the 1860's Kirchhoff (left) and Bunsen discovered the connection between those spectral lines and the elements.

Joseph Fraunhofer, in 1814, looked at the solar spectrum and saw the dark lines that now bear his name.

A very hot body will produce a continuous spectrum of light.

A continuous spectrum that passes through a cool gas will produce an absorption spectrum.

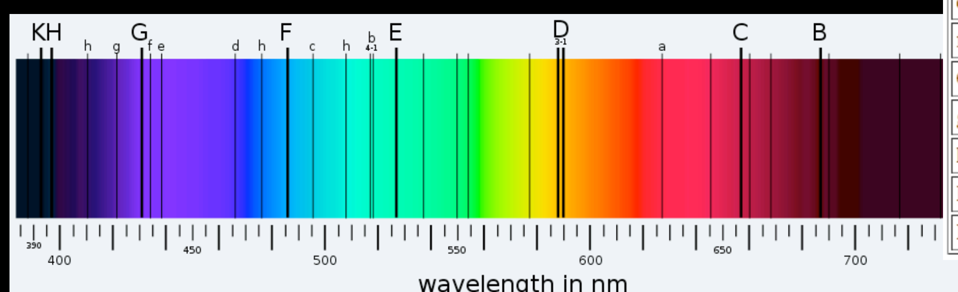




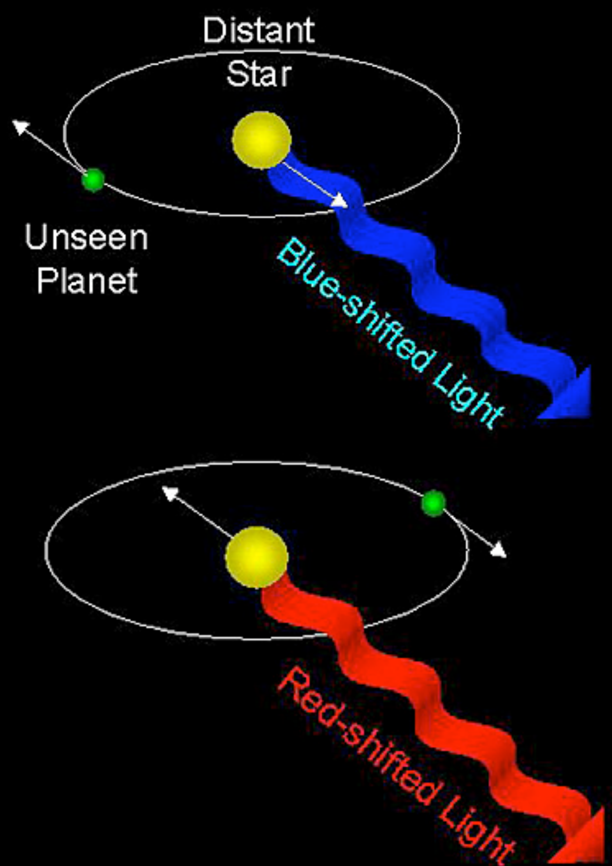
Kirchhoff and Bunsen realized that Fraunhofer's dark lines are a "fingerprint" of the elements and compounds present in the gas

Fraunhofer Line	Element	Wavelength (Å)
A - (band)	O_2	7594 - 7621
B - (band)	O_2	6867 - 6884
C	H	6563
a - (band)	O_2	6276 - 6287
D - 1, 2	Na	5896 & 5890
E	Fe	5270
b - 1, 2	Mg	5184 & 5173
c	Fe	4958
F	H	4861
d	Fe	4668
e	Fe	4384
f	H	4340
G	Fe & Ca	4308
g	Ca	4227
h	H	4102
H	Ca	3968
K	Ca	3934

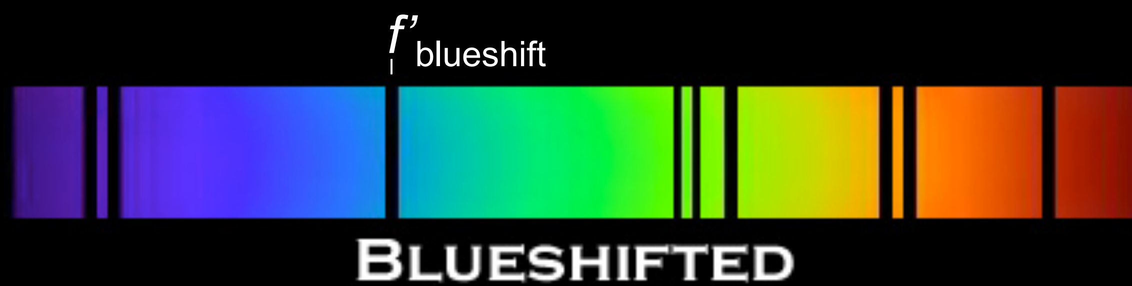
A cooler gas of a particular element will produce a line spectrum.

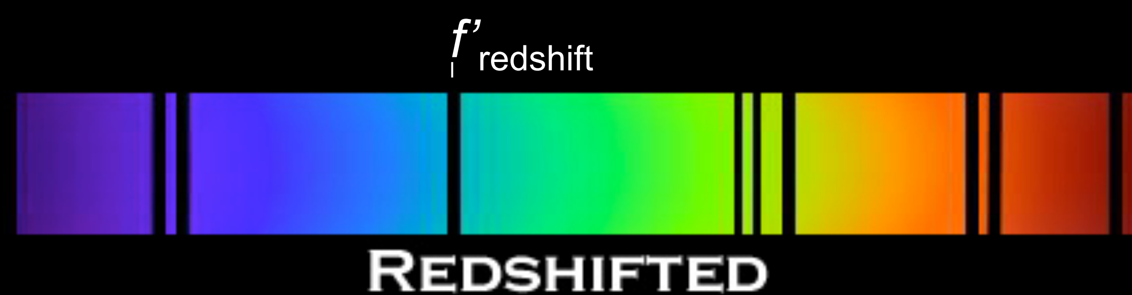


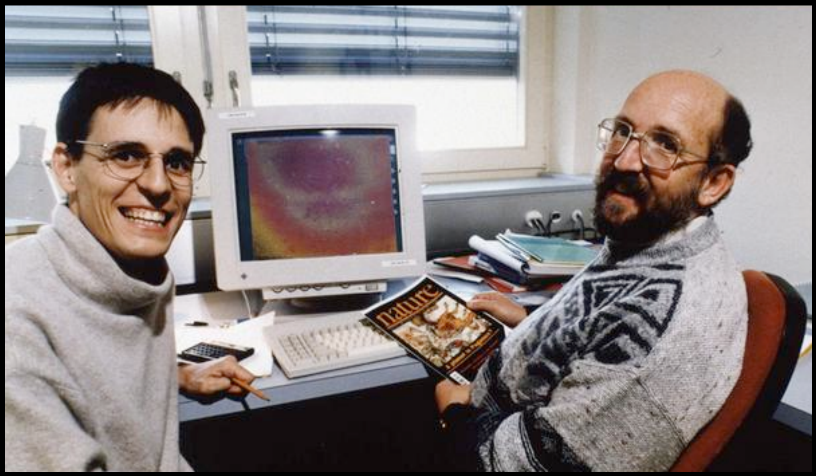
Using the absorption spectrum of a star and the Doppler effect….



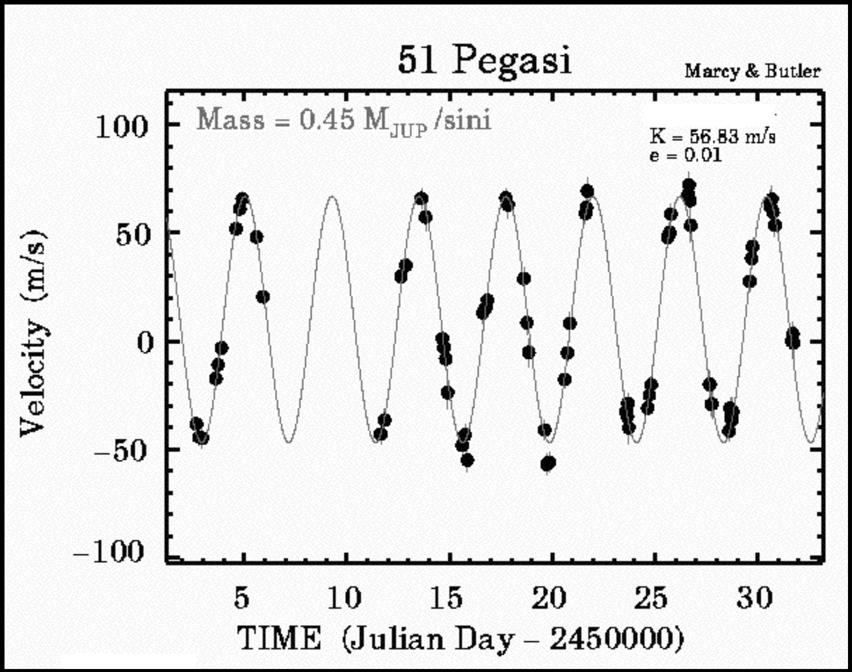
we can calculate the radial velocity of the star as it wobbles because of an orbiting planet.

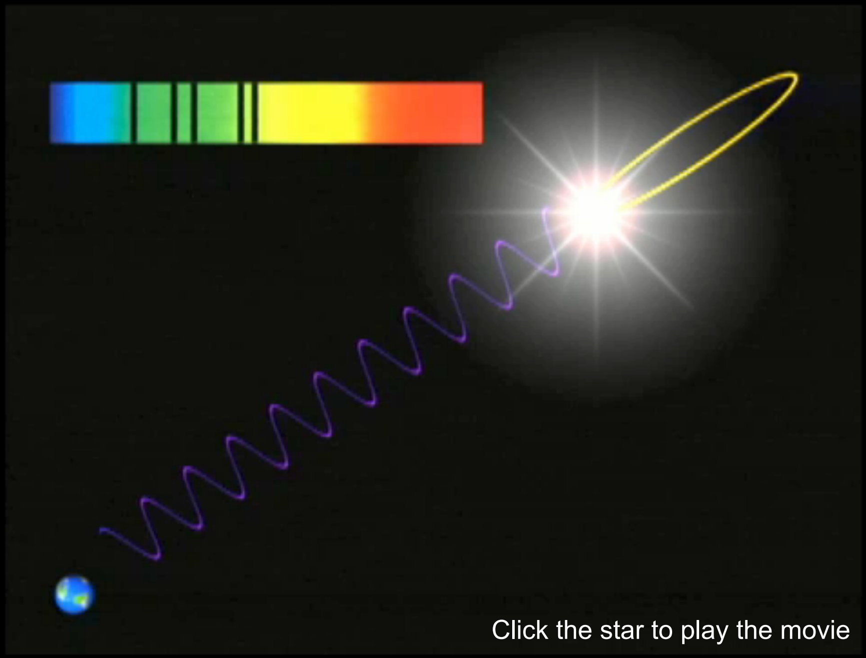






In 1995 Michel Mayor and Didier Queloz using the Doppler shift, or radial velocity method, announced the first definitive discovery of an exoplanet.



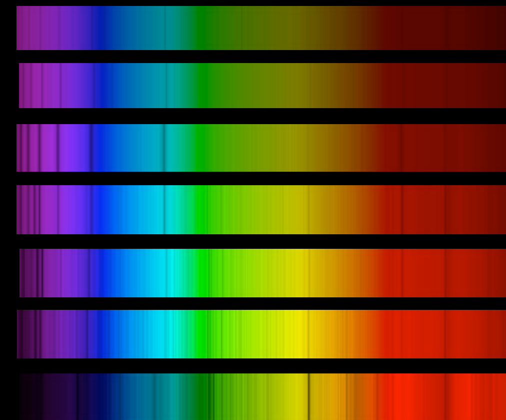


The planet orbits the star 51 Pegasi, has a mass of about 0.5 Jupiters, and an orbital period of about 4.23 days!

Annie Jump Cannon

Spectral Class	Effective Temperature (K)	Colour	H Balmer Features	Other Features	M/M_{Sun}	R/R_{Sun}
O	28,000 - 50,000	Blue	weak	ionised He^+ lines, strong UV continuum	20 - 60	9 - 15
B	10,000 - 28,000	Blue-white	medium	neutral He lines	3 - 18	3.0 - 8.4
A	7,500 - 10,000	White	strong	strong H lines, ionised metal lines	2.0 - 3.0	1.7 - 2.7
F	6,000 - 7,500	White-yellow	medium	weak ionised Ca^+	1.1 - 1.6	1.2 - 1.6
G	4,900 - 6,000	Yellow	weak	ionised Ca^+, metal lines	0.85 - 1.1	0.85 - 1.1
K	3,500 - 4,900	Orange	very weak	Ca^+, Fe, strong molecules, CH, CN	0.65 - 0.85	0.65 - 0.85
M	2,000 - 3,500	Red	very weak	molecular lines, eg TiO, neutral metals	0.08 - 0.05	0.17 - 0.63

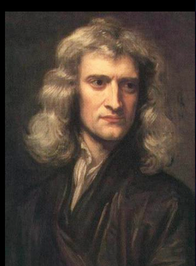
How do we know it’s mass and velocity?



Estimate the mass of the star using it’s spectral class.

Use the mass of the star to find the average radius of the planet’s orbit.

Use the radius and mass of the star to find the planet’s velocity in orbit.



$$F_g = \frac{Gm_p m_s}{R^2}$$

$$F_c = \frac{4\pi^2 m_p R}{T^2}$$

$$F_g = F_c$$

$$\frac{Gm_p m_s}{R^2} = \frac{4\pi^2 m_p R}{T^2}$$

$$R^3 = \frac{Gm_s T^2}{4\pi^2}$$

$$F_g = \frac{Gm_p m_s}{R^2}$$

$$F_c = \frac{v^2 m_p}{R}$$

$$F_g = F_c$$

$$\frac{Gm_p m_s}{R^2} = \frac{v^2 m_p}{R}$$

$$v_p = \sqrt{Gm_s / R}$$

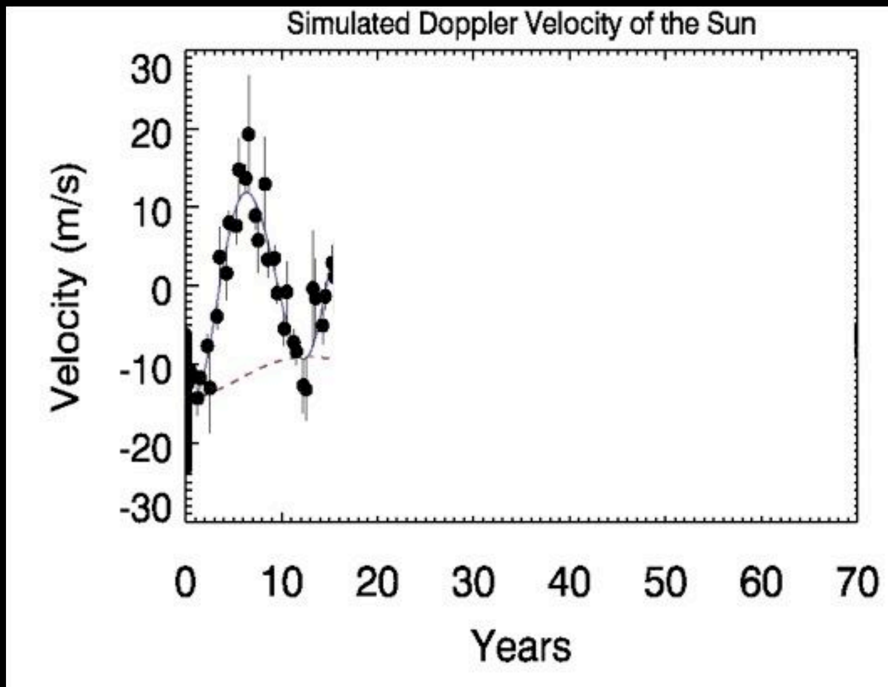
$$m_p v_p = m_s v_s$$

$$m_p = \frac{m_s v_s}{v_p}$$

$$Amplitude = v_s \sin i$$

$$m_p \sin i = \frac{m_s v_s \sin i}{v_p}$$

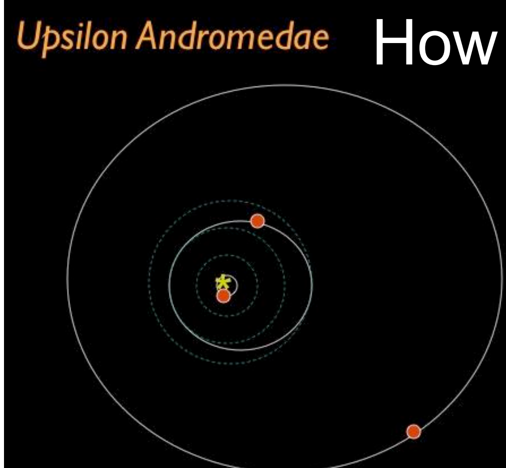
Use the mass of the star and the velocity of the star, from Doppler data, to find the mass of the planet.



We can simulate a graph that represents the sun's wobble caused by the two largest planets in our solar system, Jupiter and Saturn.

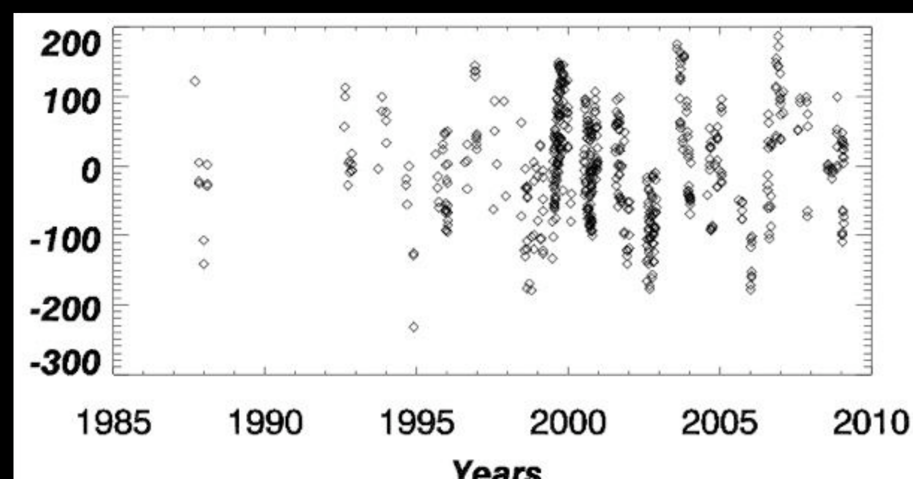
If we add real data to the graph we can see that it might be difficult to pick out the orbit of Saturn.

If you only use about 15 years of data the process becomes even more difficult.



How many planets?

Probably three…



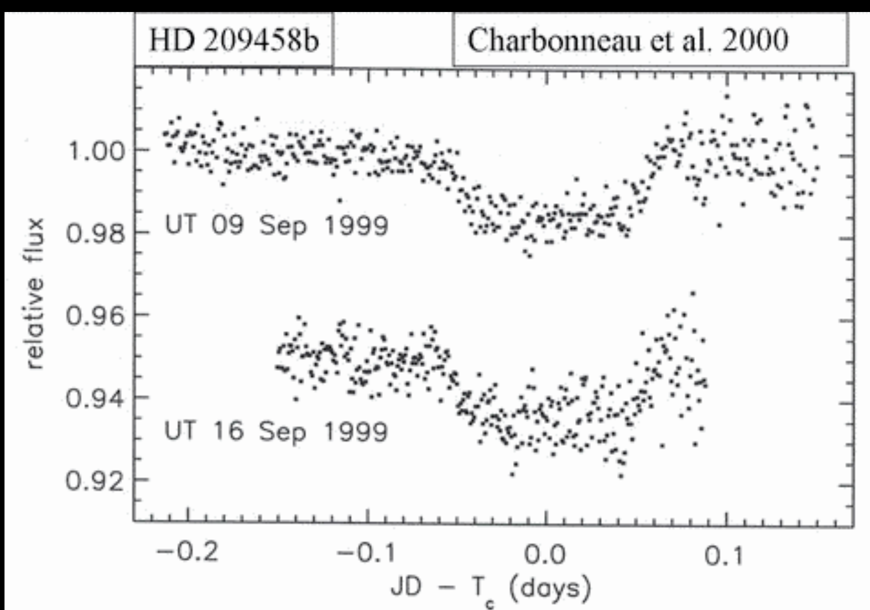
Transits

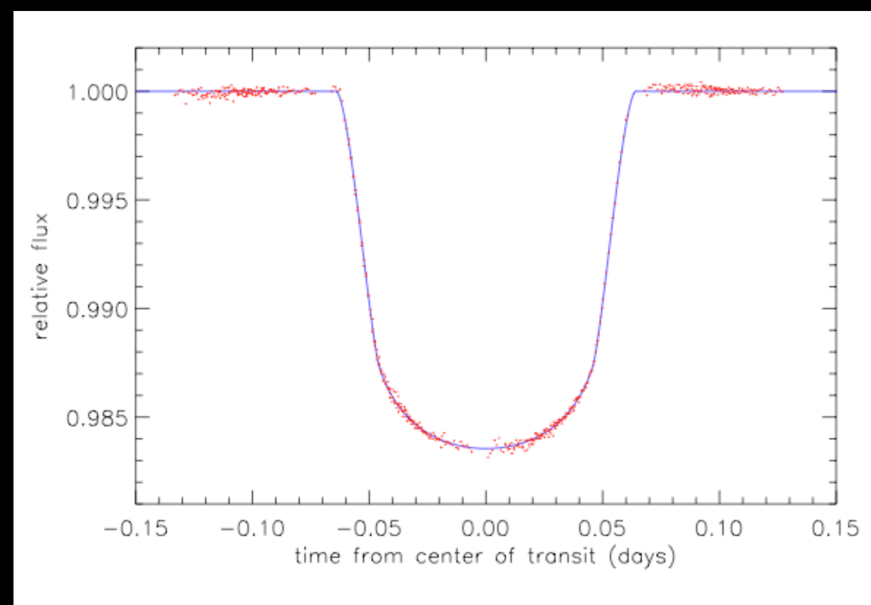
Click the star to play the movie

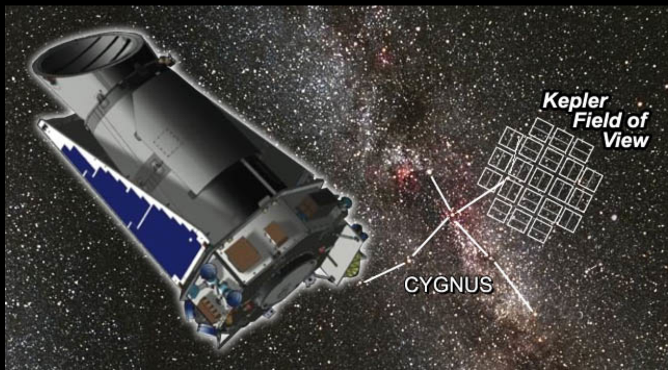
If the orbit of a planet takes it between us and it's star the brightness of the star will vary with time.

David Charbonneau used a 4" telescope in a parking lot to see the transit of HD 2009458b.

The HST also recorded the transit.



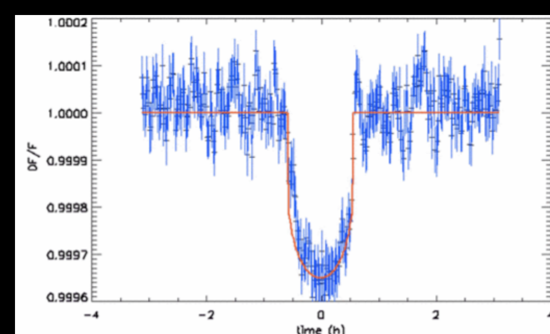




Name	Planetary Characteristics						Planetary Orbit			
	Mass		Radius		Density	Temperature	Period	Semi-Major axis	Eccentricity	Inclination
	Jupiter masses	*Earth masses*	*Jupiter radii*	*Earth radii*	*grams/cc*	*Kelvin*	*days*	*AU*		*degrees*
***Kepler* discoveries:**										
Kepler 4b	0.077		0.357		1.91	1650	3.2135	0.04558	(0)	89.76
Kepler 5b	2.114		1.431		0.894	1868	3.5485	0.05064	(0)	86.3
Kepler 6b	0.669		1.323		0.352	1500	3.2347	0.04567	(0)	86.8
Kepler 7b	0.433		1.478		0.166	1540	4.8855	0.06224	(0)	86.5
Kepler 8b	0.603		1.419		0.261	1764	3.5225	0.0483	(0)	84.07

Kepler - launched in March 2009

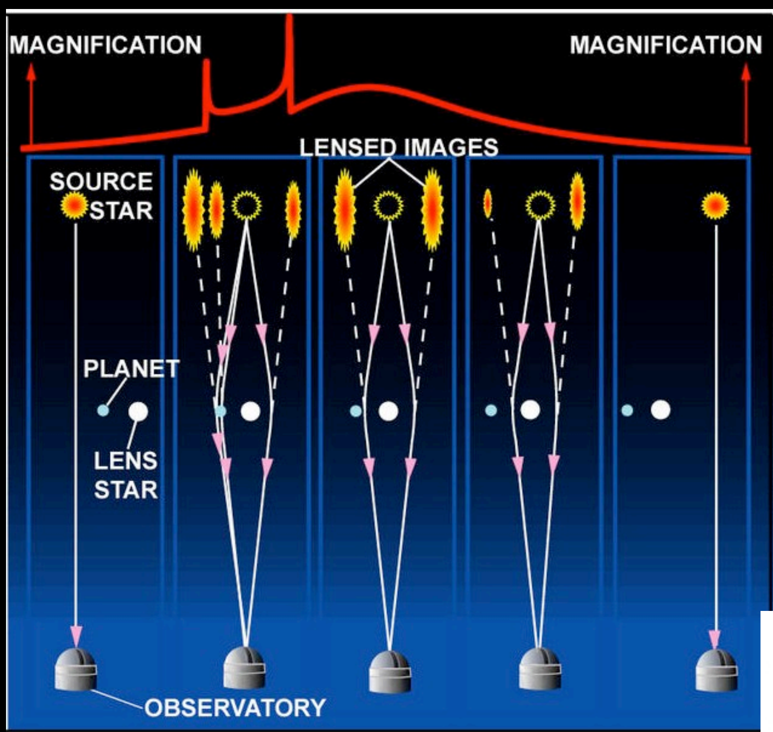
Star	Constellation	Right ascension	Declination	App. mag.	Distance (ly)	Spectral type	Planet	Mass (M_J)	Radius (R_J)	Orbital period (d)	Semimajor axis (AU)	Orbital eccentricity	Inclination (°)	Discovery year
COROT-1	Monoceros	$06^h 48^m 19^s$	−03° 06′ 08″	13.6	1560	G0V	b	1.03	1.49	1.5089557	0.0254	0	85.1	2007
COROT-2	Serpens	$19^h 27^m 07^s$	+01° 23′ 02″	12.57	930	G7V	b	3.31	1.465	1.7429964	0.0281	0	87.84	2007
COROT-3	Aquila	$19^h 28^m 13.265^s$	+00° 07′ 18.62″	13.3	2200	F3V	b	21.66	1.01	4.25680	0.057	0	85.9	2008
COROT-4	Monoceros	$06^h 48^m 47^s$	−00° 40′ 22″	13.7		F0V	b	0.72	1.19	9.20205	0.090	0	90	2008
COROT-5	Monoceros	$06^h 45m^m 07s^s$	+00° 48′ 55″	14		F9V	b	0.459	1.28	4.0384	0.04947	0.09	85.83	2008
COROT-6	Aquila	$18^h 44^m 17.42^s$	+6° 39′ 47.95″	13.9		F5V	b	3.3	1.16	8.89	0.0855	< 0.1		2009
COROT-7	Monoceros	$06^h 43^m 49.0^s$	−01° 03′ 46.0″	11.668	489	G9V	b	0.0151	0.150	0.853585	0.0172	0	80.1	2009
COROT-8							b							
COROT-9	Serpens	$18^h 43^m 09^s$	+06° 12′ 15″	13.7	1500	G3V	b	0.84	1.05	95.2738	0.407	0.11		2010

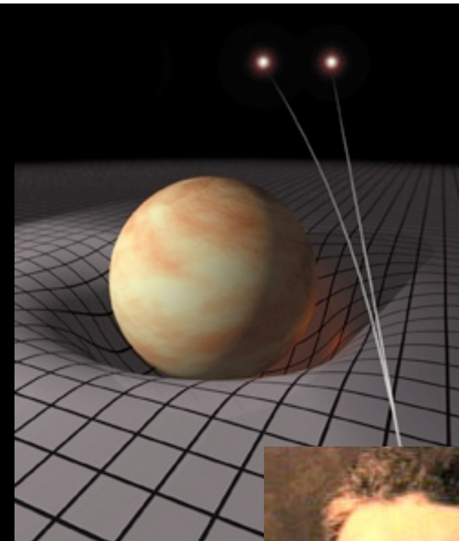


CoRoT – launched in May, 2007

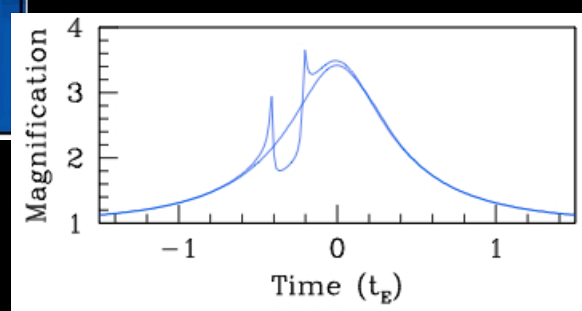
Gravitational Microlensing

Einstein's theory of general relativity predicts that light will be bent as it passes near a mass.



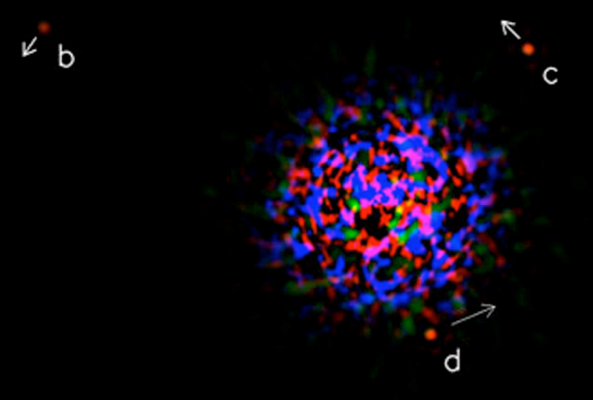


Because of gravitational lensing, an unseen star passing in front a source star causes the image of the source star to brighten.

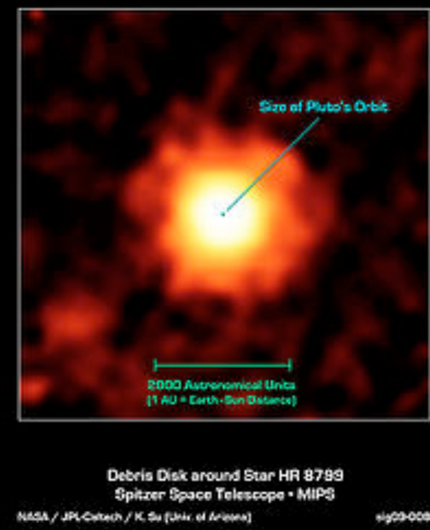


The profile of the brightening will be different if the unseen star is accompanied by a planet

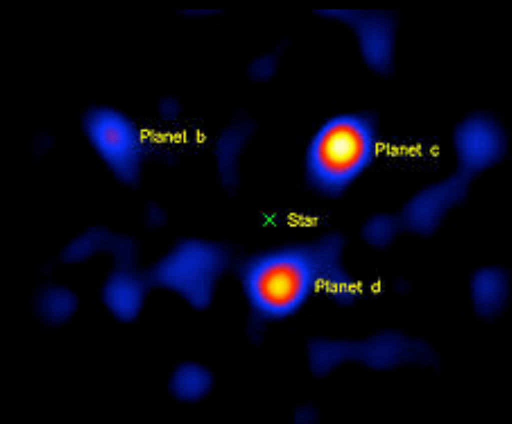
Direct Observation



The Spitzer Space Telescope produced this image of the HR 8799's debris disk in January, 2009.

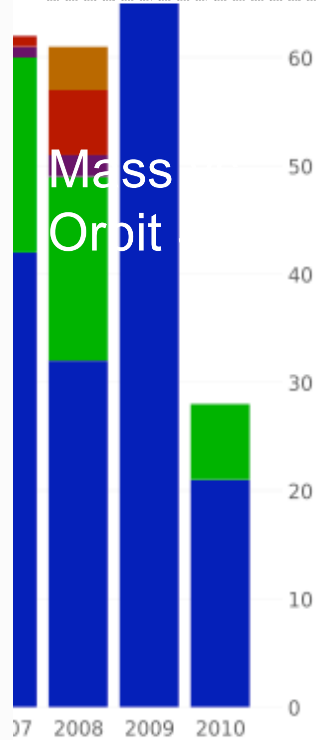


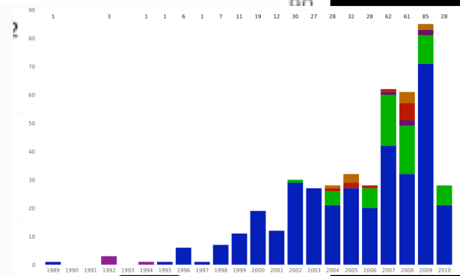
In November of 2008, Christian Marois announced the discovery of three planets around HR 8799. His group used the Keck and Gemini telescopes in Hawaii to obtain this infrared image.

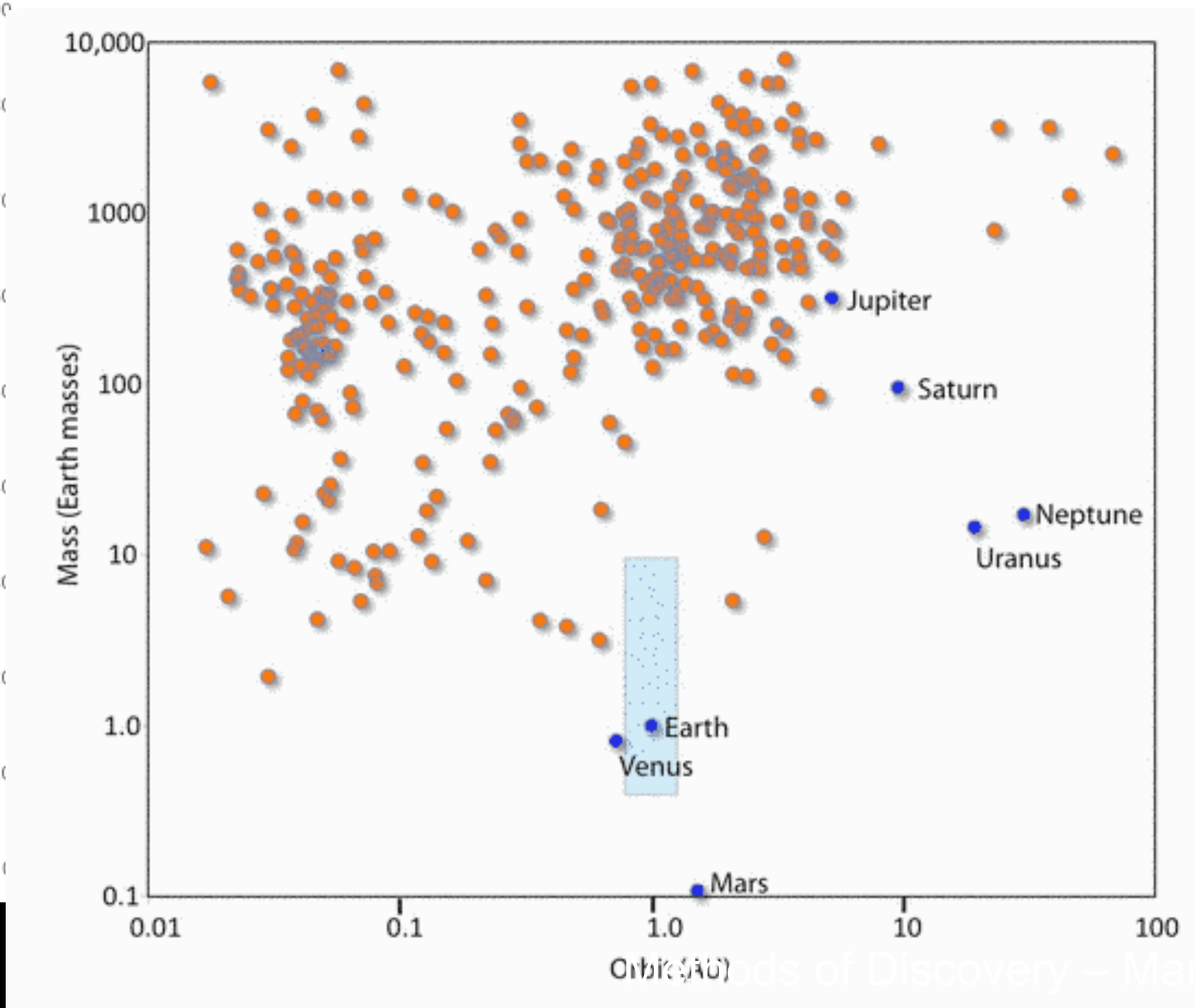


Companion (in order from star)	Mass	Semimajor axis (AU)	Orbital period (years)	Eccentricity
d	10±3 M_J	~ 24	~ 100	>0.04[16][note 2]
c	10±3 M_J	~ 38	~ 190	?
b	7^{+4}_{-2} M_J	~ 68	~ 460	?
Dust disk	75 AU			

This image was produced by the vortex coronagraph on the Hale telescope in 2010







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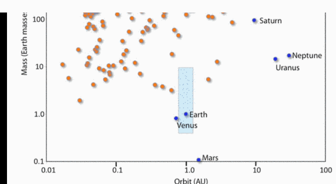
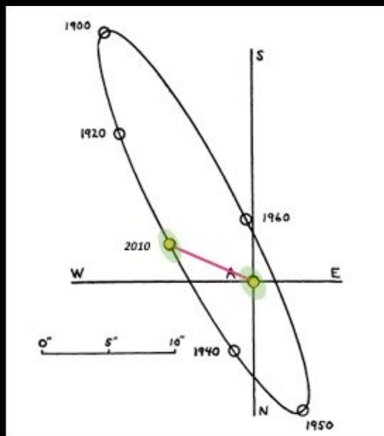


…but, how do we find habitable planets?

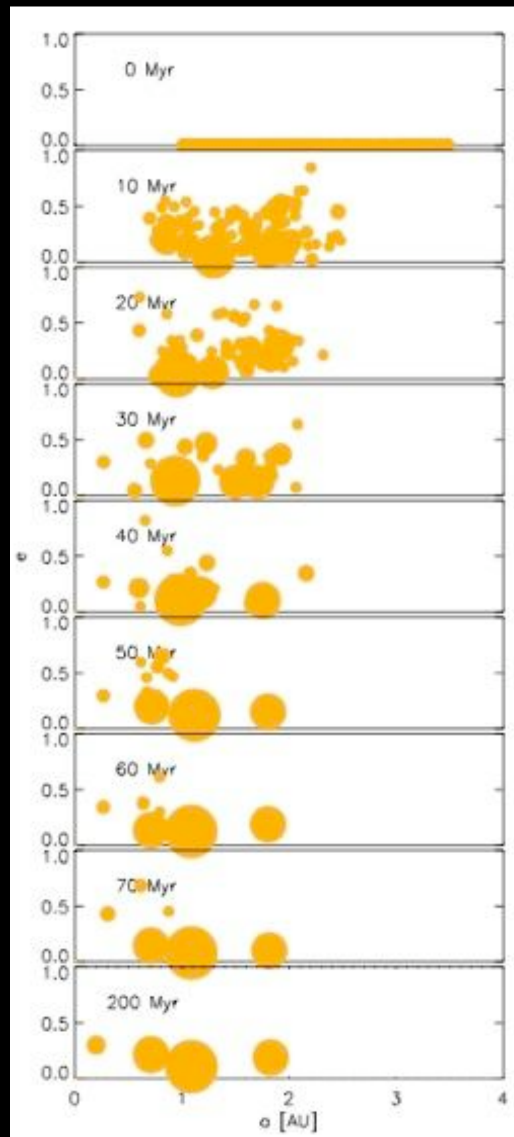
Push the Limits – Look in the Neighborhood

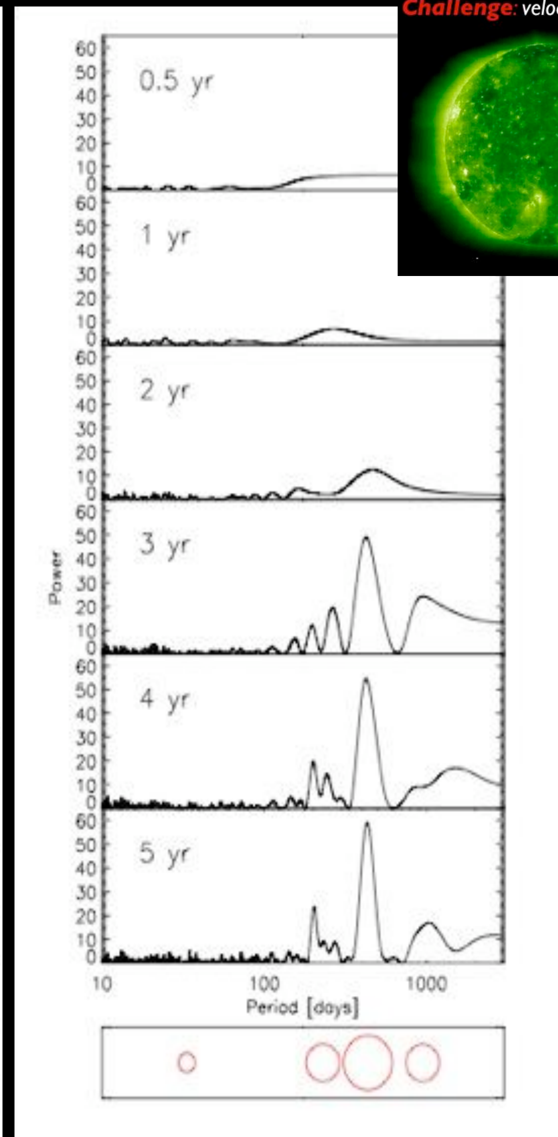


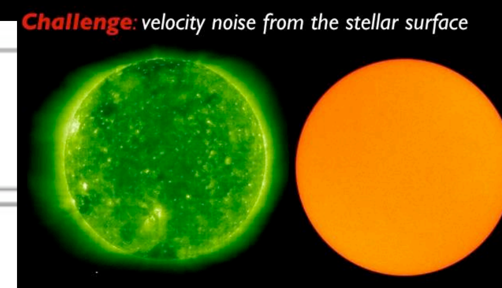
α-Centuri A & B

Simulations suggest that earth-like planets could evolve in this system,

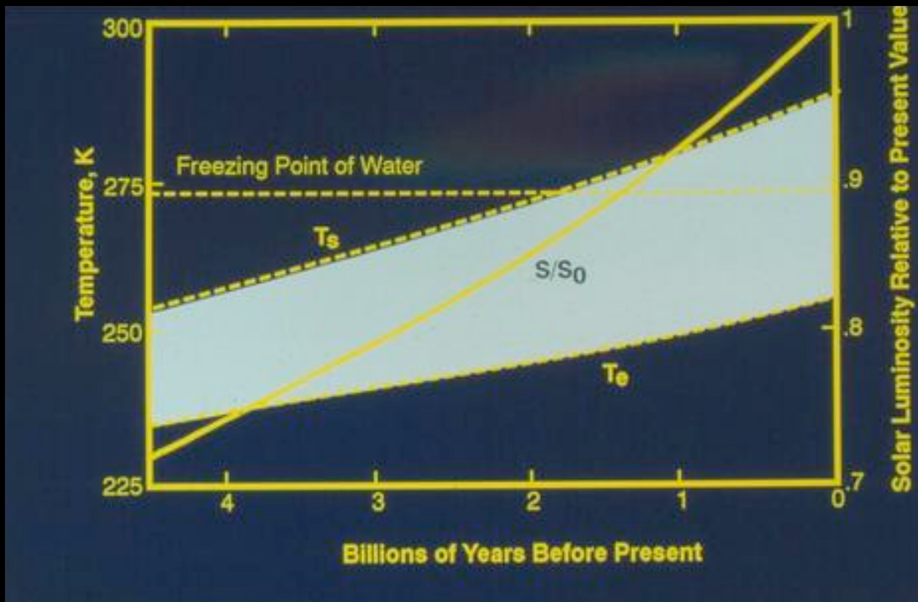
and be found after 90000 Doppler measurements over 5 years





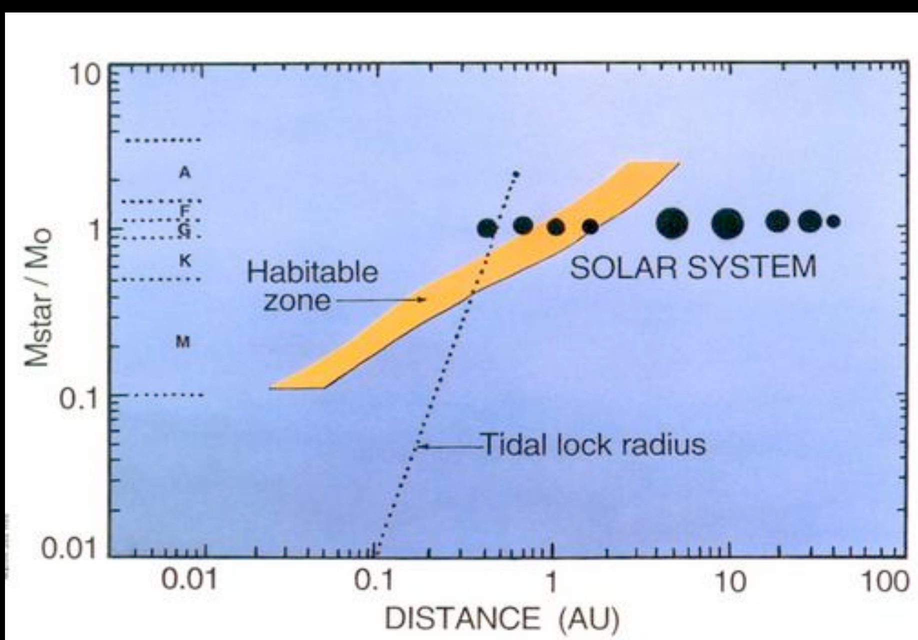


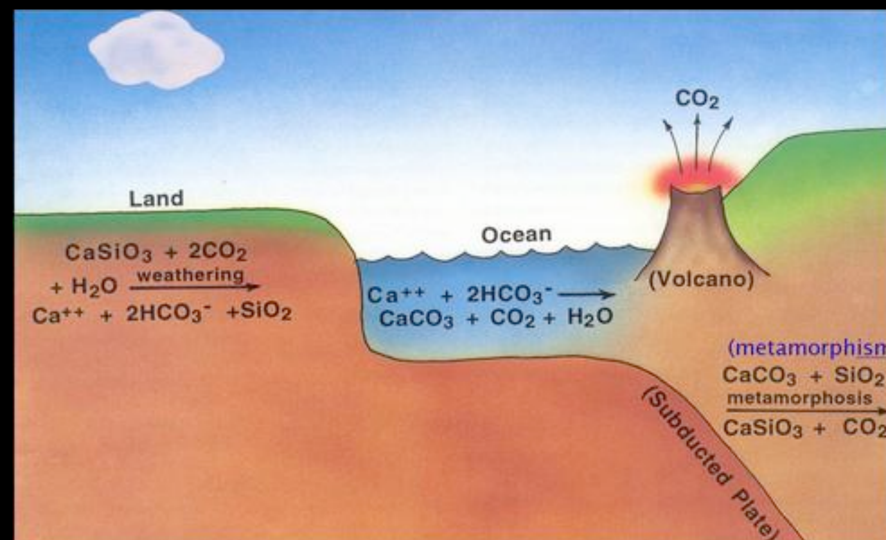
if you can look in longer wavelengths with a precision of 3 m/s or better.



Look for Liquid Water

Our knowledge of stellar evolution indicates that water on earth should have been frozen until 2 billion years ago - if the atmosphere was the same composition as today.

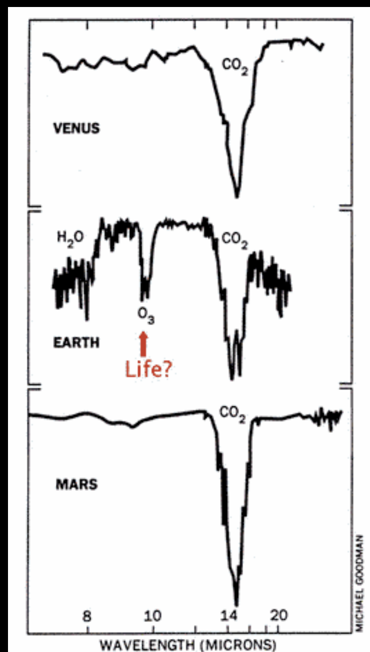


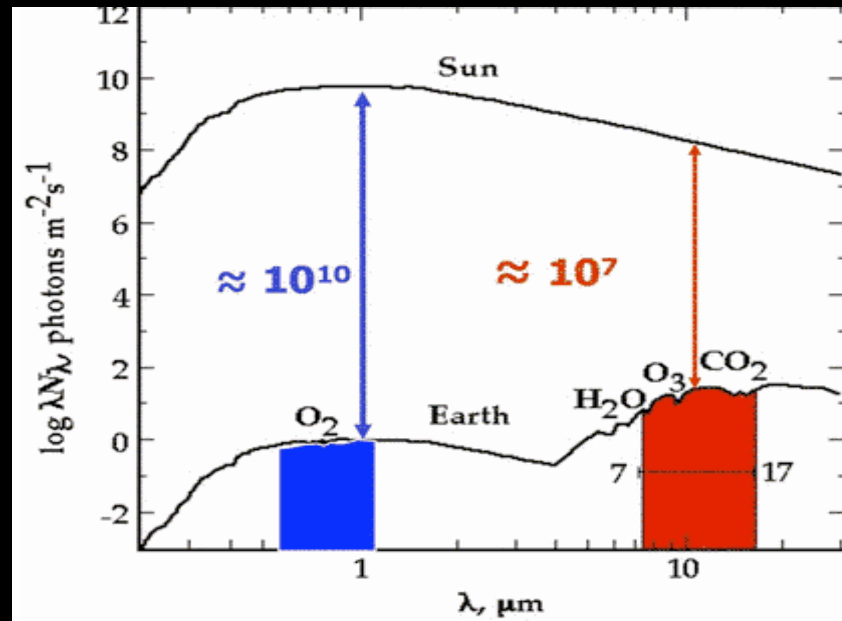


The carbon-silicate cycle my have helped by pumping more CO_2 , a green house gas, into the atmosphere when water froze.

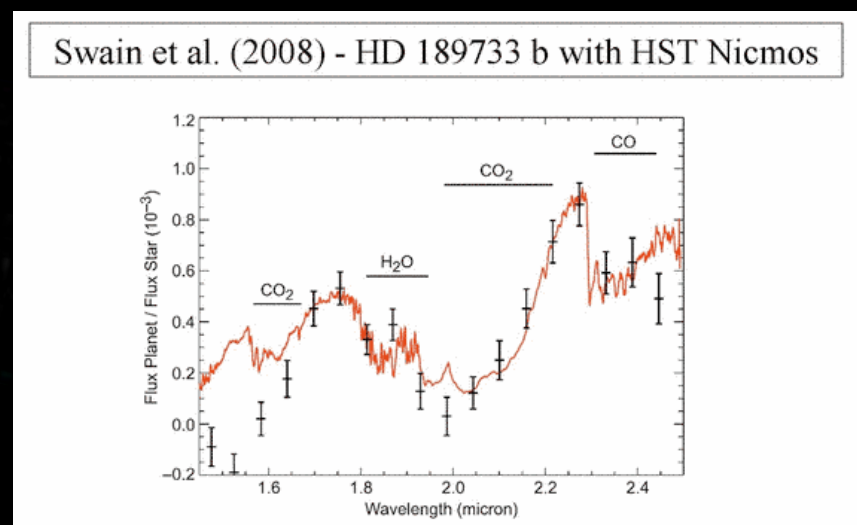
Look for Molecules Associated with Life

Promising!



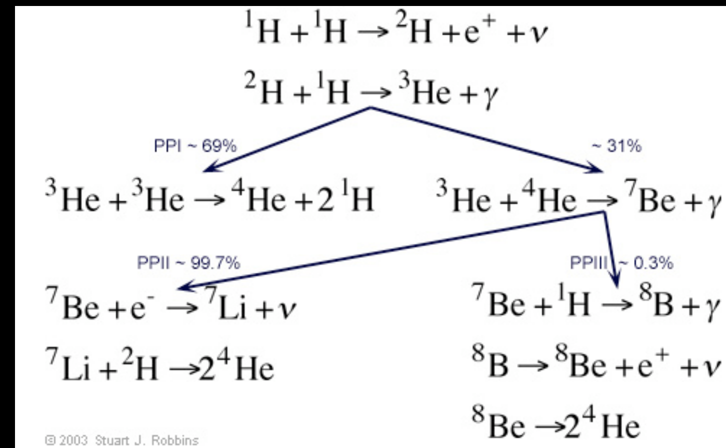


HTS took a spectrum of HD 18973 when the planet was visible and again when the the planet was behind the star. The difference of the two is the spectrum of the planet's atmosphere.

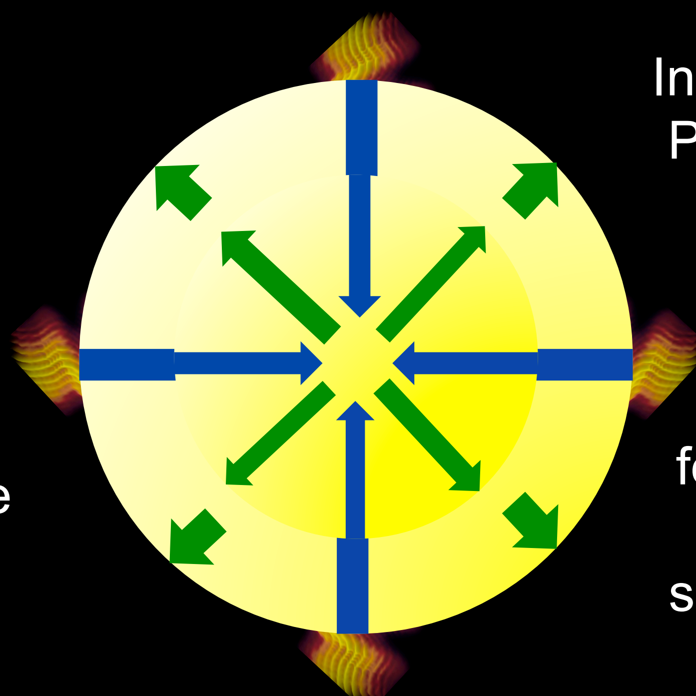


Between Planets and Stars

In 1939 Han Bethe worked many out many of the details for the fusion reactions that happen in stars. He won the Nobel Prize for his work in 1967.



As a gas cloud starts to collapse due to the force of gravity, pressure from the hot gas increases.
As the gas cools due to radiation the cloud shrinks even more.

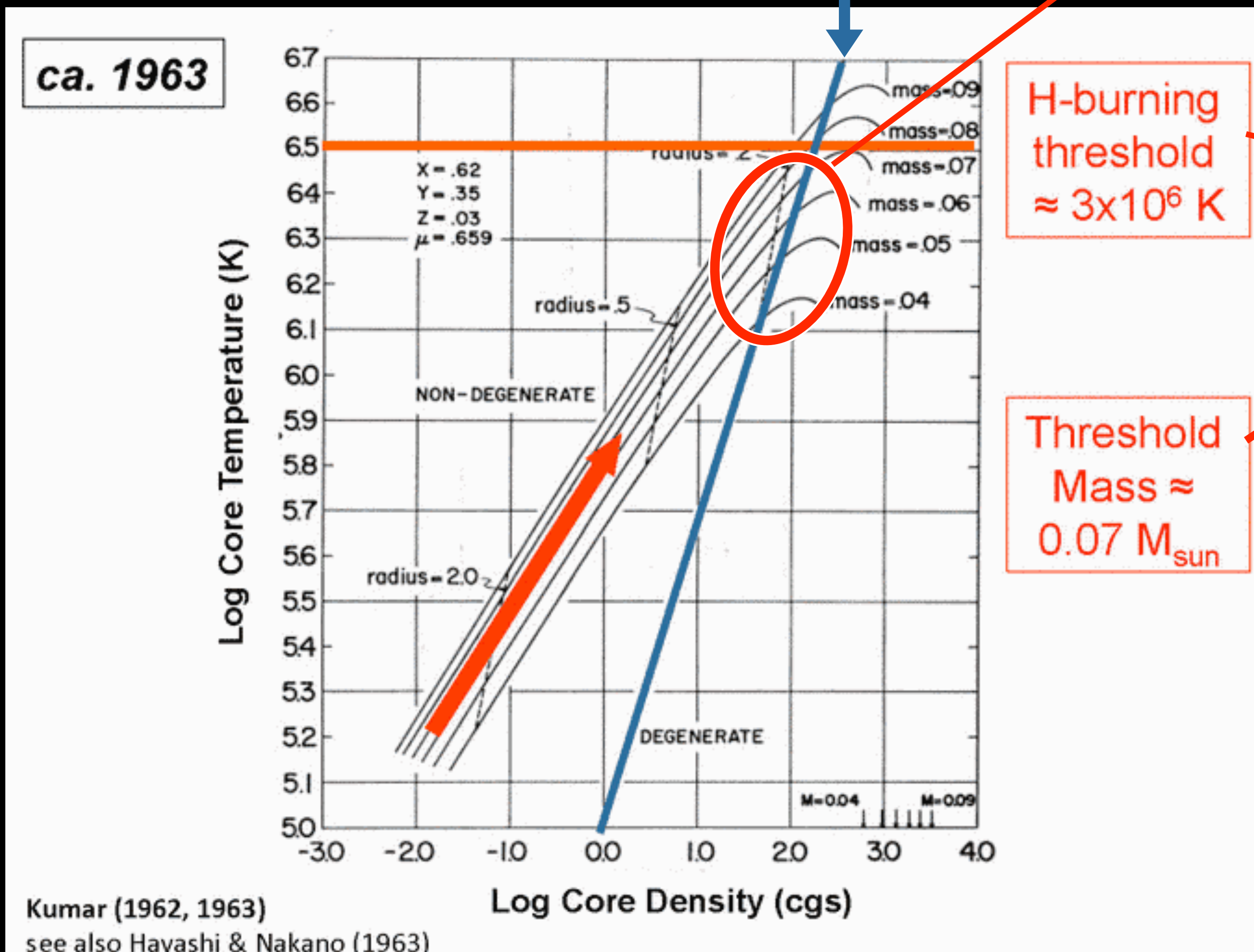


In 1925 Wolfgang Pauli developed the exclusion principle.

It tells us that no two fermions (protons, neutrons, or electrons) can be in the same place at the same time – they can not be degenerate.

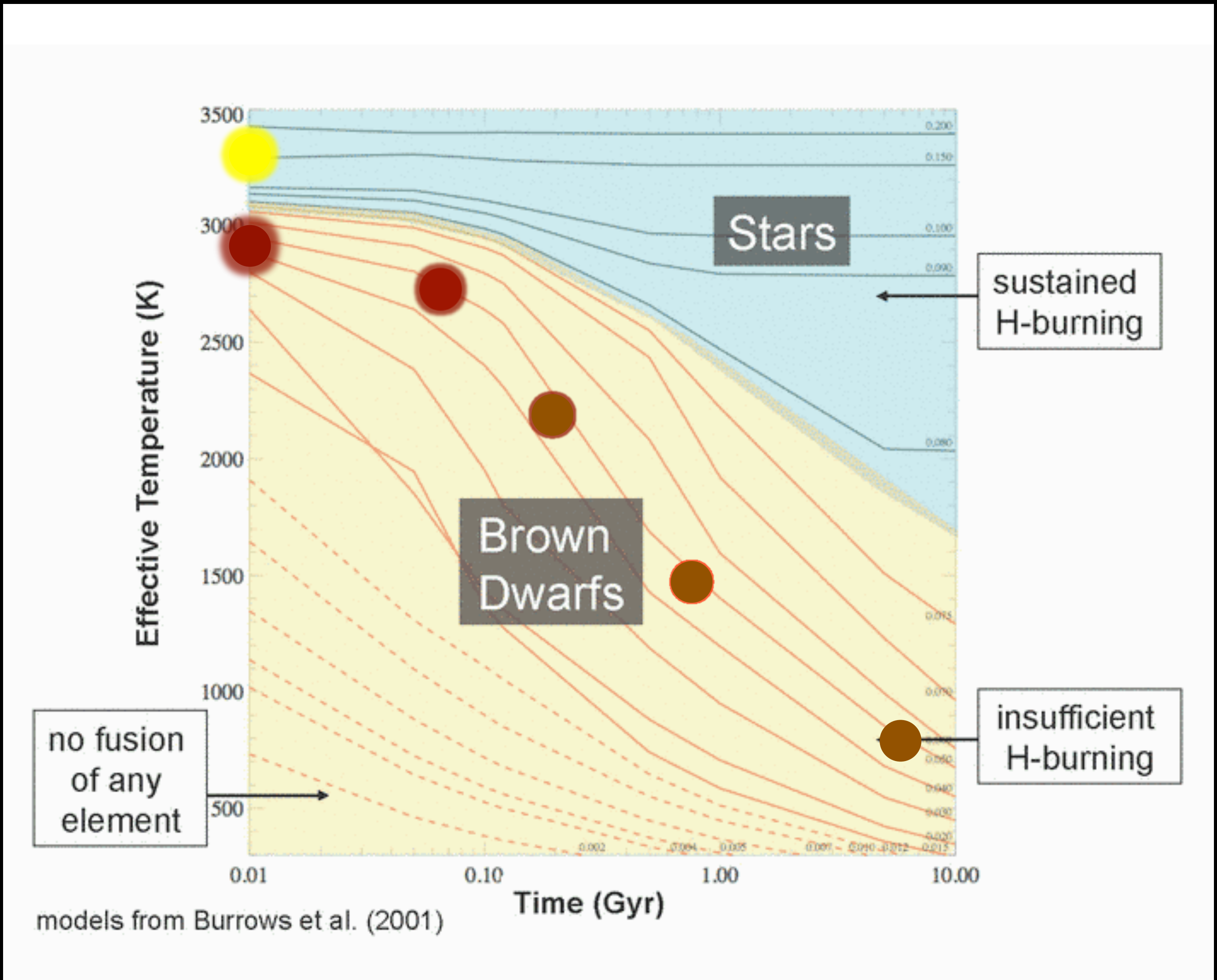
A cloud of gas can not shrink past the point where the particles in it's core would be degenerate.

If the core reaches this point before fusion starts it will become a brown dwarf.



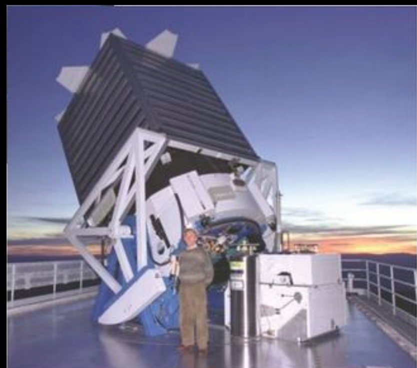
If the cloud has enough mass it can reach the H-burning threshold and start fusion before it reaches the degenerate limit.

If energy is produced at the same rate that it radiates away, the forces of gravity and pressure will be in equilibrium.

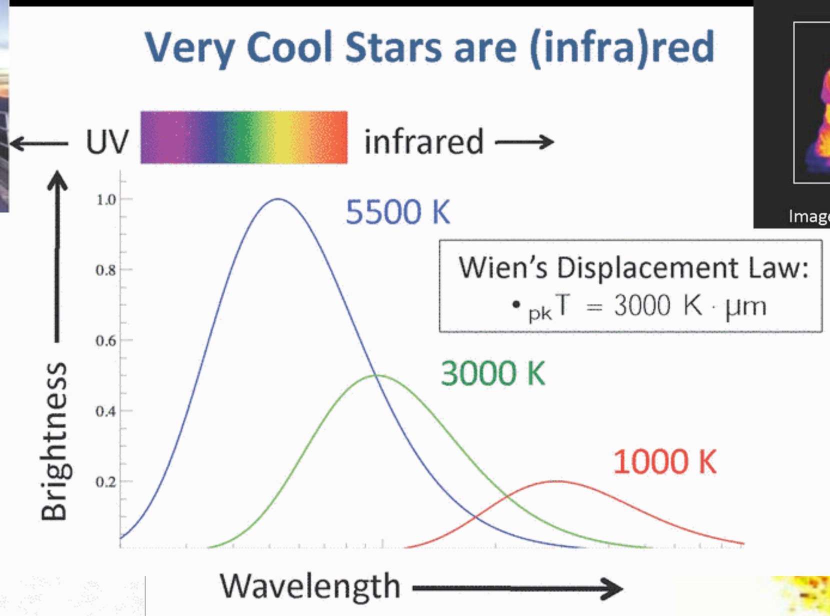


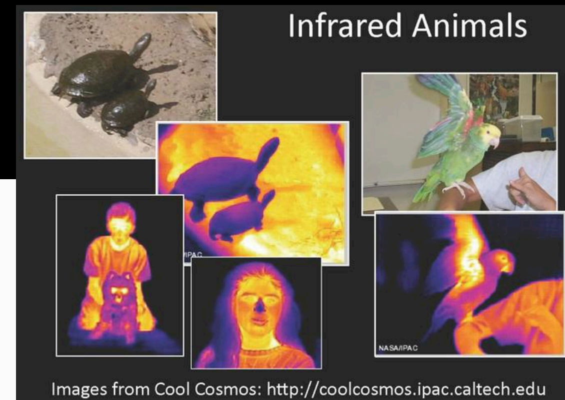
In a star like our sun, once the inward gravitational force is balanced by the outward pressure the star burns steadily for most of its life.

A brown dwarf, because in can't produce enough heat, will continue to cool throughout it's life.



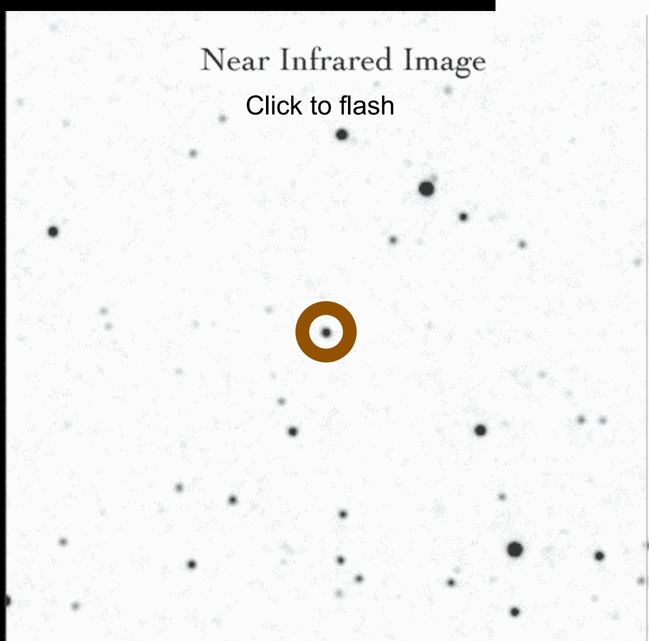
Special detectors are required to see infrared.



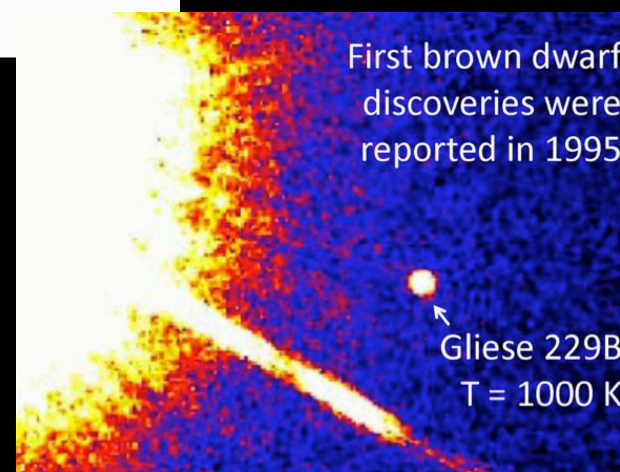


It is some times easier to find a brown dwarf if you compare visible and infrared images.

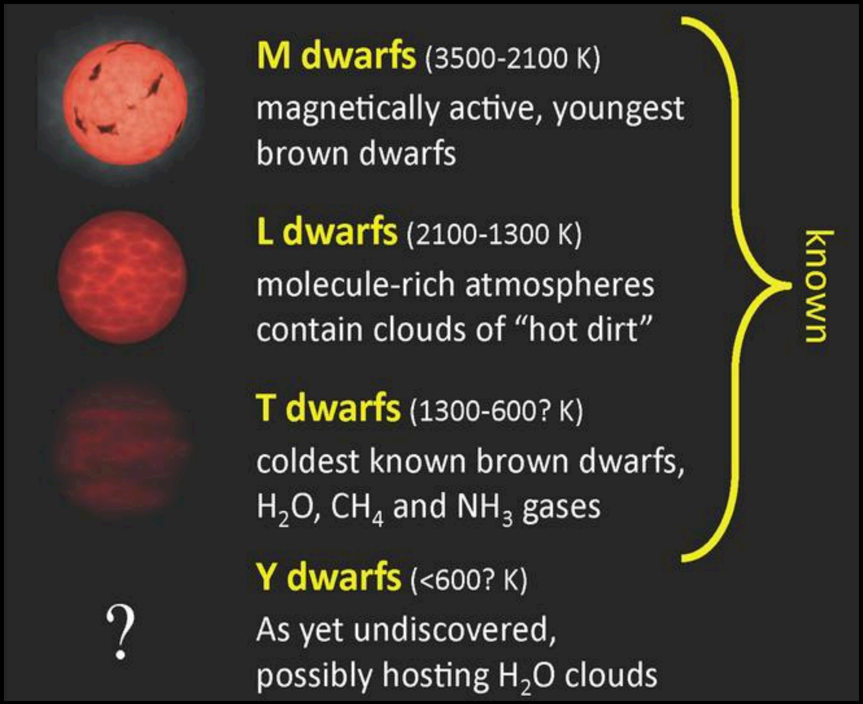
Because of their temperature brown dwarfs give off most of their light in the infrared



The first brown dwarf was reported the same year as the first exoplanet.



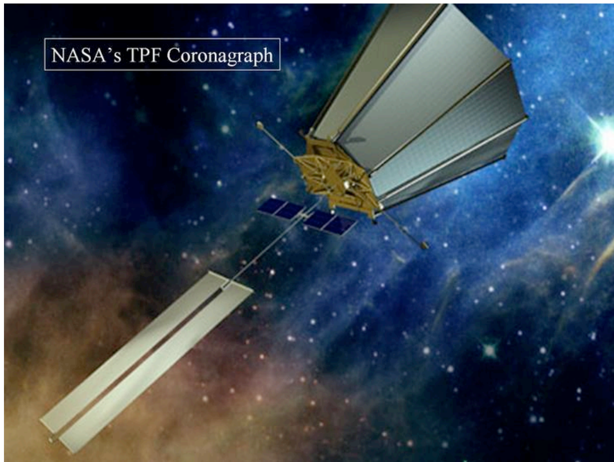
We now know of more then 700 brown dwarfs

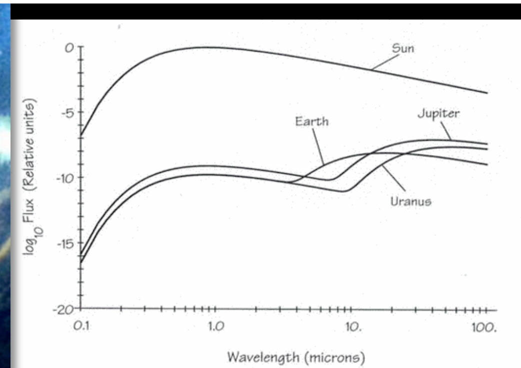


Just like stars, brown dwarfs fall into categories.

Cooler brown dwarf have more complex molecules in their atmospheres.

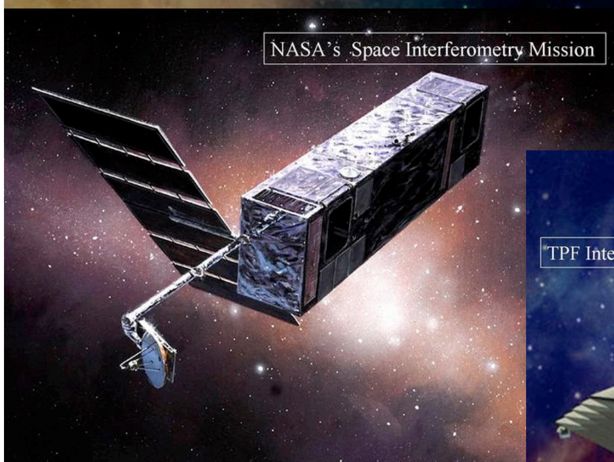
Brown dwarfs share many properties of stars.

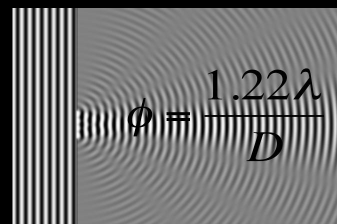


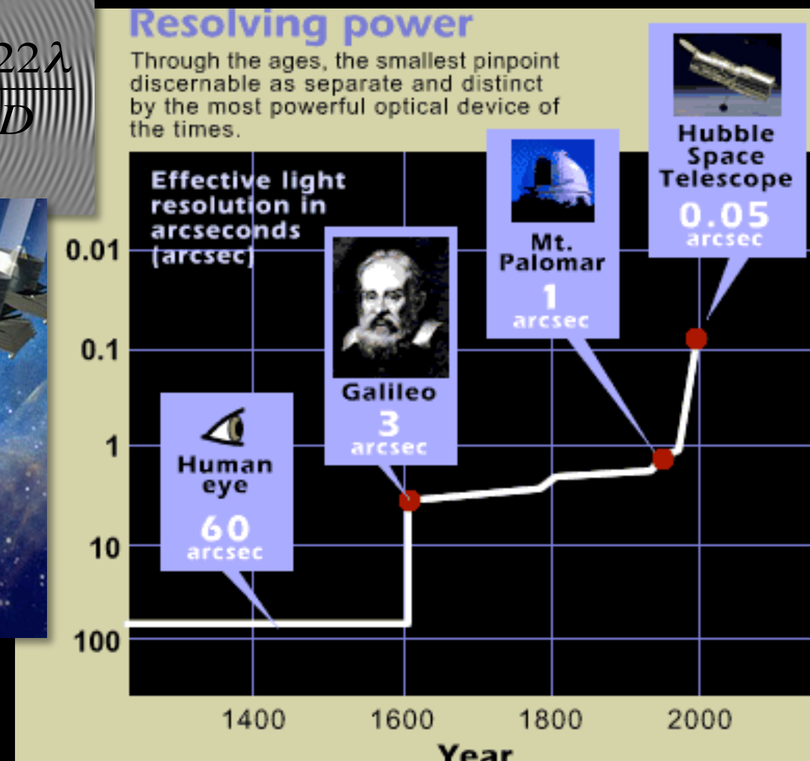


What Next?

Better coronagraphs to block the light from the star.





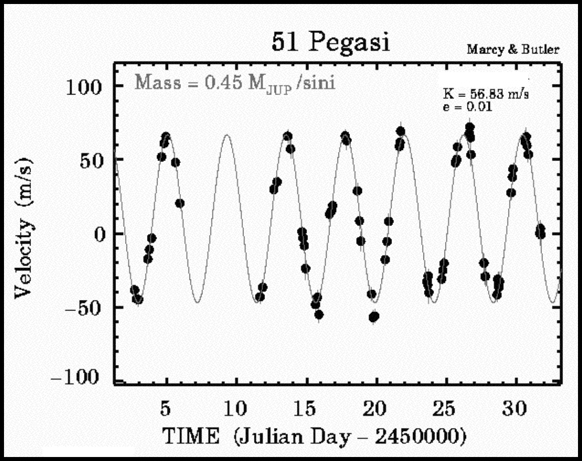


Bigger telescopes for better resolution at longer wavelengths.

Keep track of the count at http://planetquest.jpl.nasa.gov/

Problems

1. Using the graph at the right, and knowing that 51 Pegasi has a mass of about 1.06 the mass of the sun (spectral class G), answer the following questions.
   A. What is the period of the star's wobble? 4.2 days
   B. What is the magnitude of the star's radial velocity? 57 m/s – estimated average of ± peaks
   C. Calculate the radius of the planet's orbit. 7.8×10^9 m or .053 AU
   D. Calculate the radial velocity of the planet. 1.3×10^5 m/s
   E. Calculate the mass of the planet. 9.2×10^{26} kg or 0.49 mass of Jupiter



2. Locate the center of mass of the Sun and Jupiter in relation to the center of the sun. 7.4×10^8 m or just above the Sun's surface at about 1.07 the diameter of the Sun

3. What is the radial speed of the Earth around the Sun? About 3×10^4 m/s

4. What would be the probability of seeing Jupiter orbit the Sun using the transit method? radius of Sun/radius of orbit or about 0.09%

5. Hubble has a 2.5 m diameter mirror.

   A. What would be the resolving power of a telescope with a mirror this size for 470 nm visible light and for 10 μm infrared light? 2.3×10^{-7} radians, 4.8×10^{-6} radians

   B. How many arcseconds does this represent? .047 arcsec, .99 arcsec

   C. If 51 Pegasi is 50.9 light years from earth, what is the closest a planet could be to the star and still be resolved with this telescope? 1.2×10^{-5} lyr or 0.74 A.U., 2.4×10^{-4} lyr or 16 A.U.

   D. What is the advantage of looking in the infrared? The star is less bright and the planet is brighter in the infrared (see slide 2)

   E. If this telescope orbits about 550 km above the earth what is the smallest object it could resolve on the earth's surface in 470 nm light? 13 cm

6. If 656.3 nm light (red line of the hydrogen spectrum) strikes a diffraction grating with 4000 lines /cm,

   A. What will be the angle to the first order maximum? 15.22°

   B. If the planet orbiting 51 Pegasi has a radial velocity of about 50 m/s what will be the Doppler wavelength shift for 656.3 nm light? 1.1×10^{-4} nm

   C. If this is a red shift what will be the new angle to the first order max? 15.22° (You would have to measure in the 10^{-6} degree range to see a change)

7. Go to www.exoplanets.org, select "Exoplanet Data Explorer – Potter" , then select two variables to plot. Talk about what you discovered from your graph.