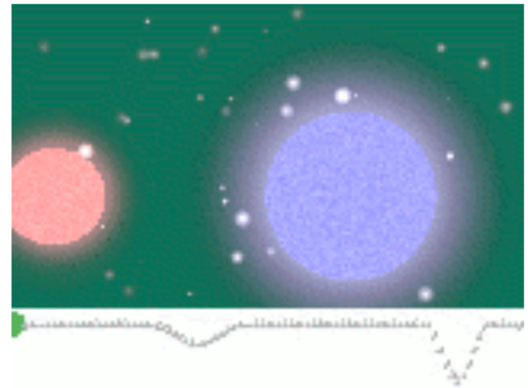
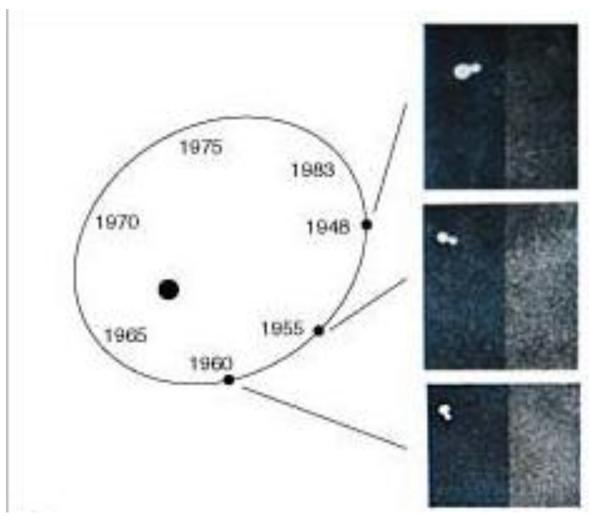
Binary Systems and Stellar Parameters

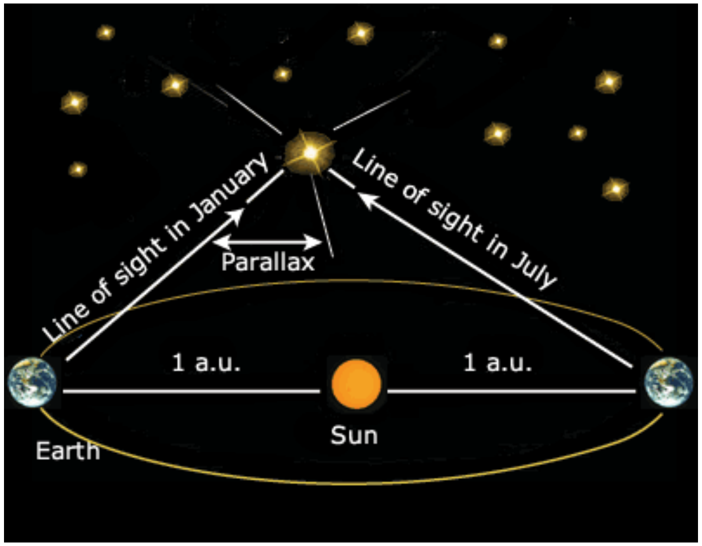
- The Classification of Binary Stars
- Mass Determination using visual Binaries
- Eclipsing,Spectroscopic Binaries
- The Search for Extra-solar Planets



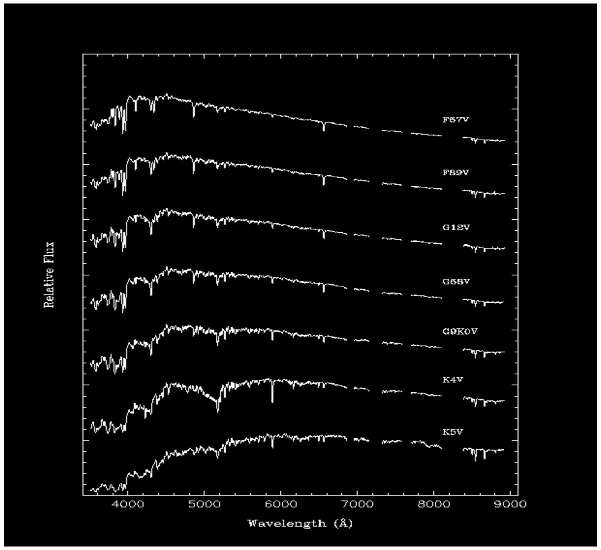


How to Weigh a Star?

- By "looking" at a Star



•Effective surface temperature
•Luminosity
•Radius
•Composition,….

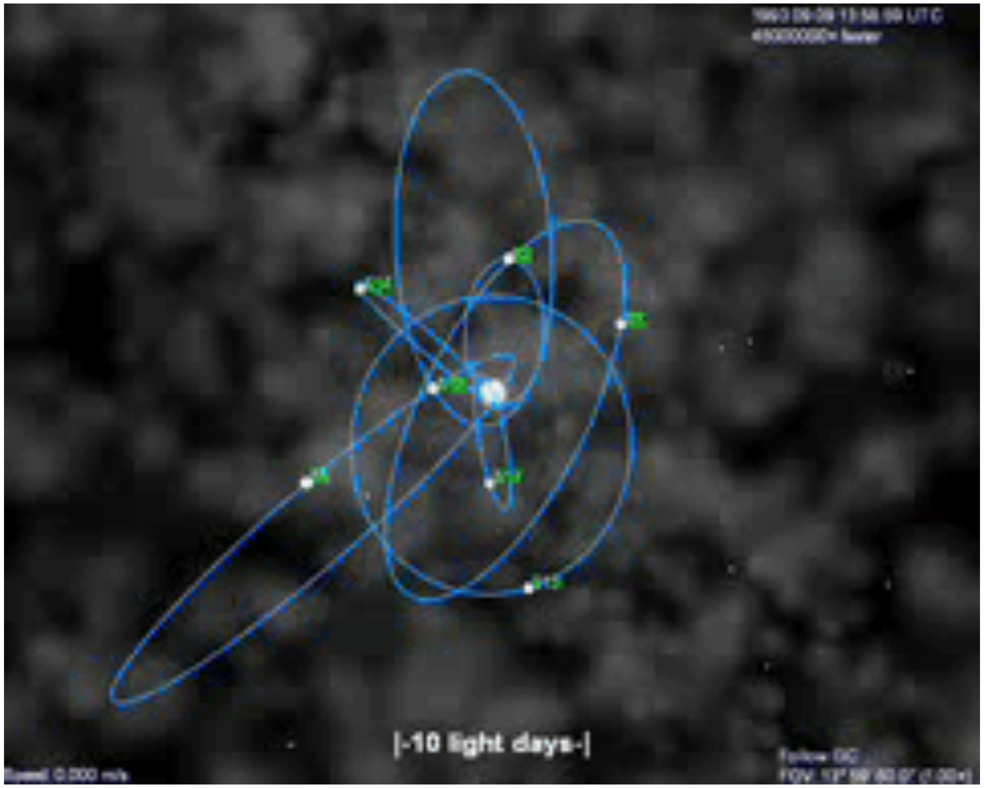


What about its mass?

How to Weigh a Star?

Determine mass of star **only** by observing its gravitational interaction with other objects….

Can even weigh black holes!!!!



From 17 years of astrometric measurements of stars orbiting a radio source called Sagittarius A

Determined that mass of object is $(4.31 \pm 0.38) \times 10^6\ M_\odot$
http://www.astro.ucla.edu/~ghezgroup/gc/

Supermassive black hole at center of our galaxy!!!

http://www2011.mpe.mpg.de/ir/GC/papers/nature2002.pdf

How to Weigh a Star?

Can use Kepler's and Newton's laws if you can "observe" motion of star(s)

At least half of all stars are in multiple-star systems

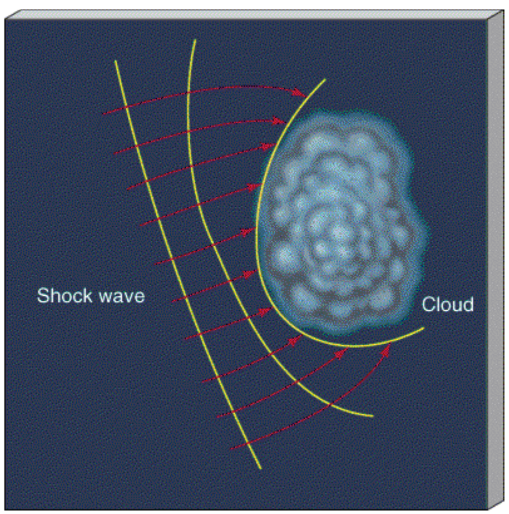
- Can not determine mass of a single lone star!!!
- Mass measurements of many stars are possible…

How?

How to Weigh a Star?

At least half of all stars are in multiple-star systems

Shock wave from supernova explosion triggers star forming region in nebulae…



Classification of Binary Stars

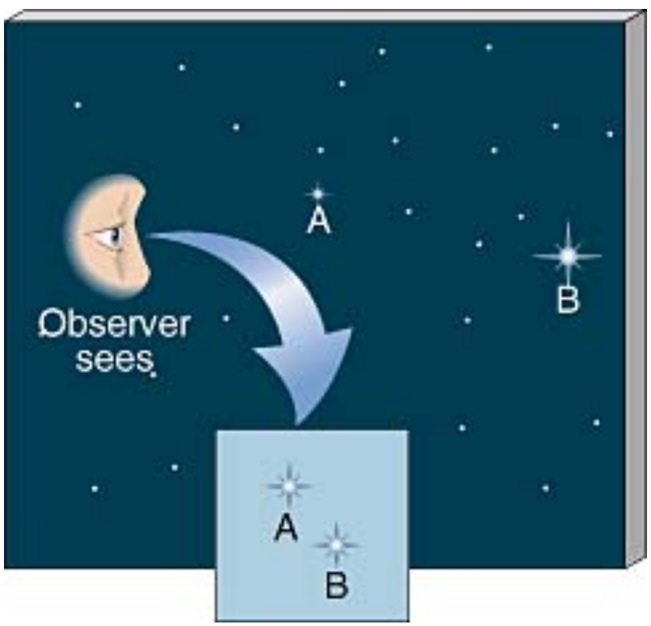
- **Optical Double** Two stars that lie along nearly the same line of sight. Similar RA and DEC. At greatly different distances. Not gravitationally bound.
- **Visual Binary** Both stars in the binary system can be spatially resolved. Possible to monitor the motion of each member (if the orbital period is not too long..). Can observe angular separation. If distance to system is known linear separation can be determined.
- **Astrometric Binary** In some cases only one member of a binary system can be seen. Its oscillatory motion betrays the presence of the other member of the binary system. The center of mass of the binary system moves at a constant velocity.

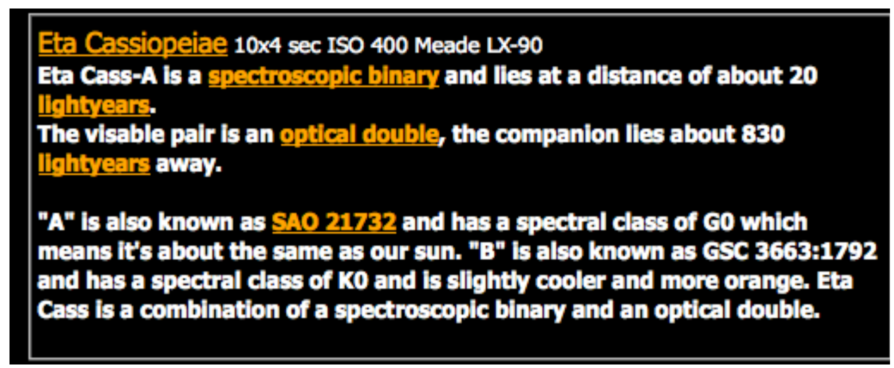
- **Eclipsing Binary** For binary systems that have orbital planes oriented approximately along the line of sight one star may pass in front of the other, blocking the light of the other. This results in a variation of light received from this system. The light curve indicates the presence of two stars and can provide information about the radii and relative temperatures of the stars.
- **Spectrum Binary** A spectrum binary is a system with two superimposed, independent, discernible spectra. Periodic shifts in the wavelengths of spectral lines due to the changing motion of the stars.
- **Spectroscopic Binary** If the orbital period is not too long and the orbital plane has a component along the line of sight, a periodic shift in wavelength will be observable. Both spectra will be available if the luminosities are comparable. In the case of a large difference in luminosity only one set of spectra will be observable. The periodic shift in wavelength in this case still reveals the presence of a binary system.

Optical Double

- **Optical Double** Two stars that lie along nearly the same line of sight. Similar RA and DEC. At greatly different distances. Not gravitationally bound.

- http://en.wikipedia.org/wiki/Double_star



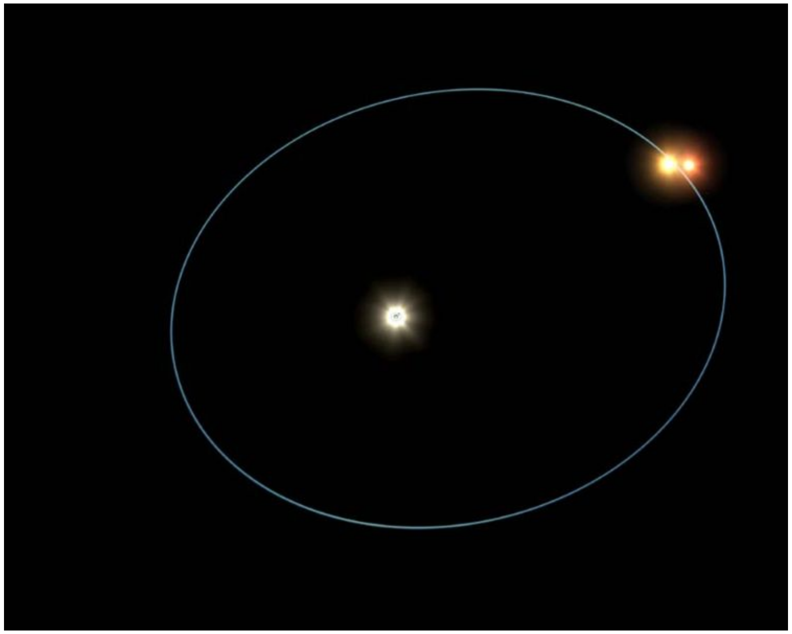


Eta Cassiopeiae 10x4 sec ISO 400 Meade LX-90
Eta Cass-A is a spectroscopic binary and lies at a distance of about 20 lightyears.
The visable pair is an optical double, the companion lies about 830 lightyears away.

"A" is also known as SAO 21732 and has a spectral class of G0 which means it's about the same as our sun. "B" is also known as GSC 3663:1792 and has a spectral class of K0 and is slightly cooler and more orange. Eta Cass is a combination of a spectroscopic binary and an optical double.

Triple Star Systems

- HD 188753
- http://en.wikipedia.org/wiki/HD_188753



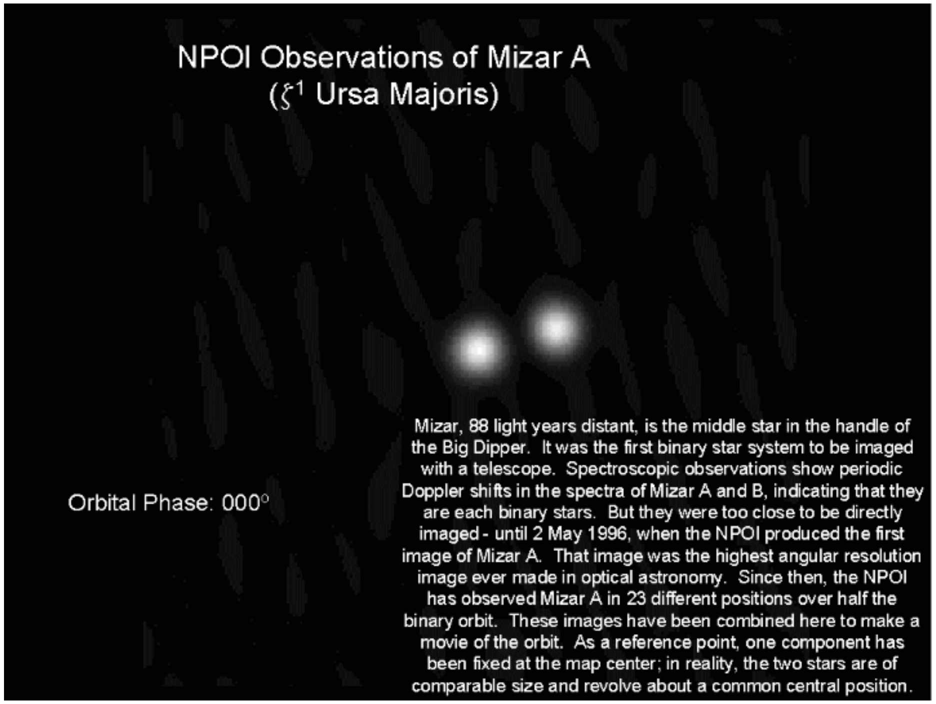
Artist Conceptions are great!!!

Quad Star Systems

- HD 98800
- http://en.wikipedia.org/wiki/HD_98800

Visual Binary

- **Visual Binary** Both stars in the binary system can be spatially resolved. Possible to monitor the motion of each member (if the orbital period is not too long..). Can observe angular separation. If distance to system is known linear separation can be determined



http://en.wikipedia.org/wiki/Mizar_and_Alcor

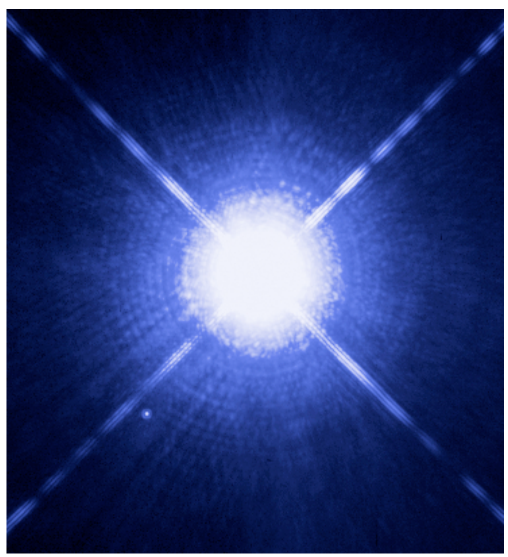
Visual Binary

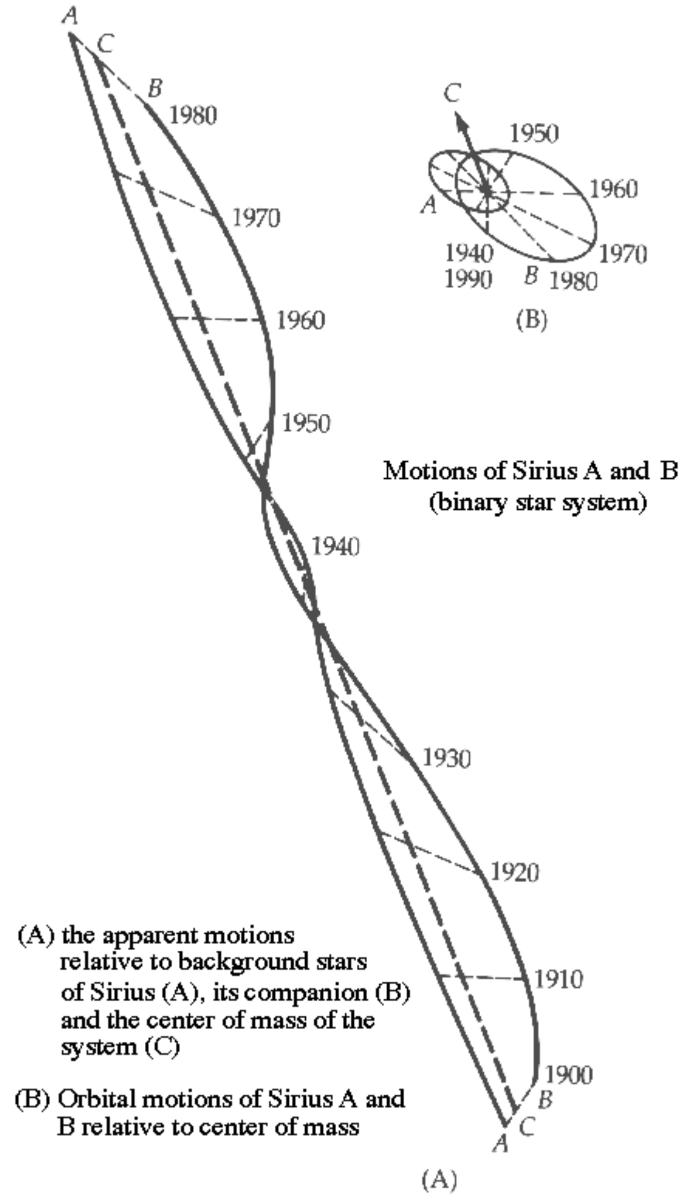
Sirius A and B now a visual binary…

The presence of Sirius B was first detected by observing the wobble in the motion of Sirius A
…an Astrometric Binary

Sirius A is much brighter that Sirius B

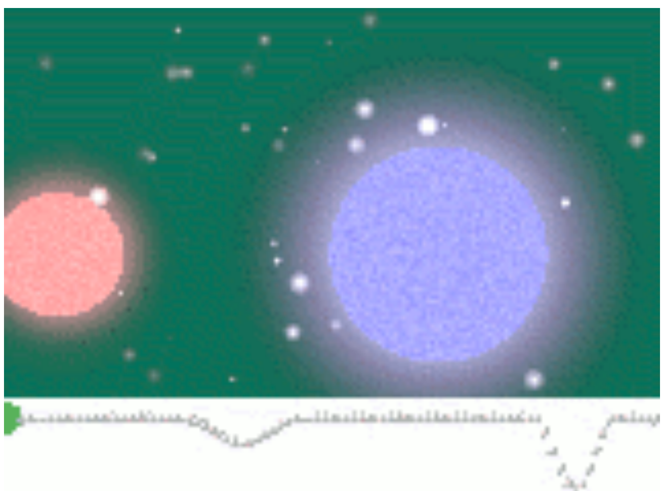
http://en.wikipedia.org/wiki/Sirius

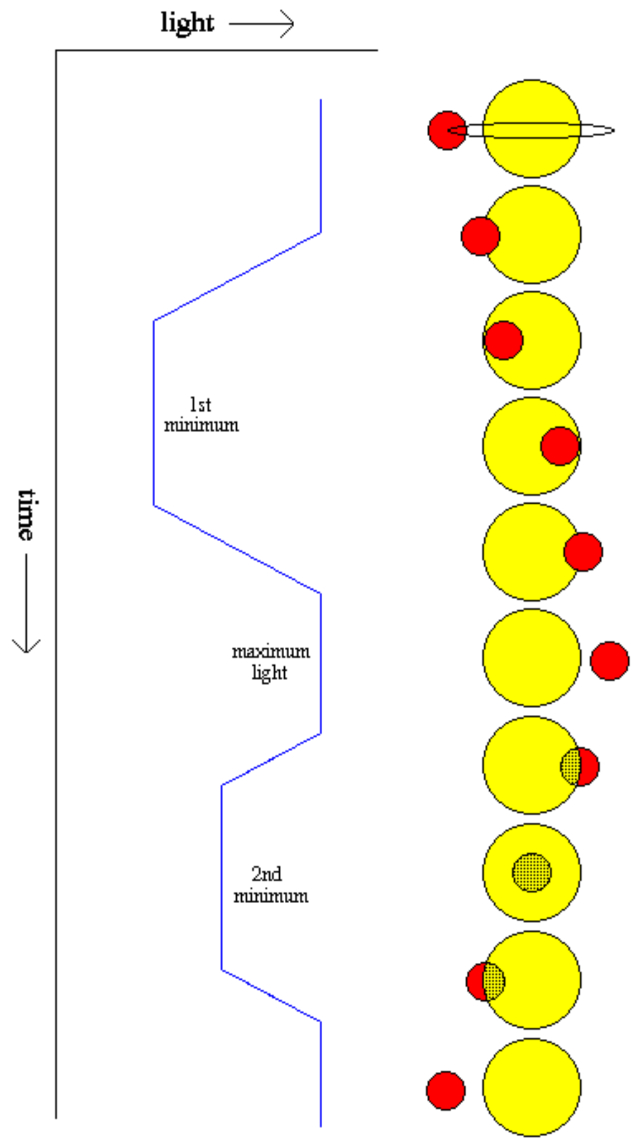




Eclipsing Binary

- **Eclipsing Binary** For binary systems that have orbital planes oriented approximately along the line of sight one star may pass in front of the other, blocking the light of the other. This results in a variation of light received from this system. The light curve indicates the presence of two stars and can provide information about the radii and relative temperatures of the stars.





Eclipsing Binary

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- http://abyss.uoregon.edu/~js/applets/eclipse/eclipse.htm

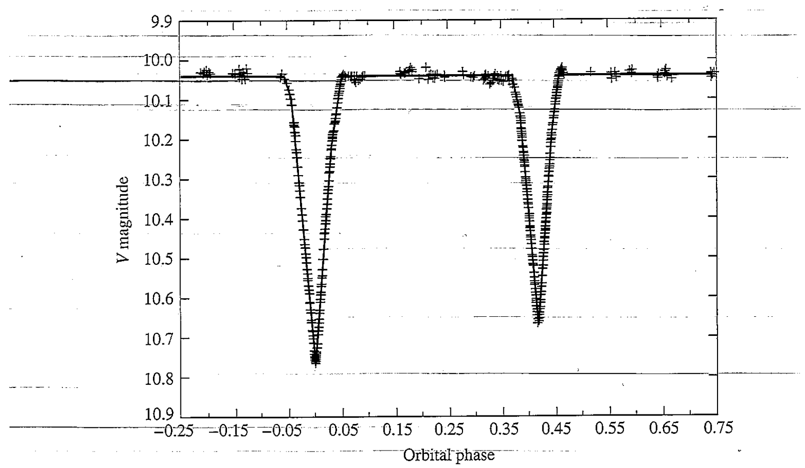
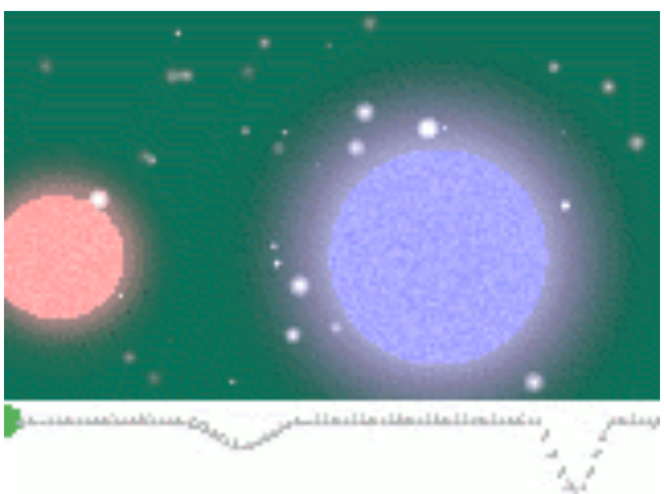
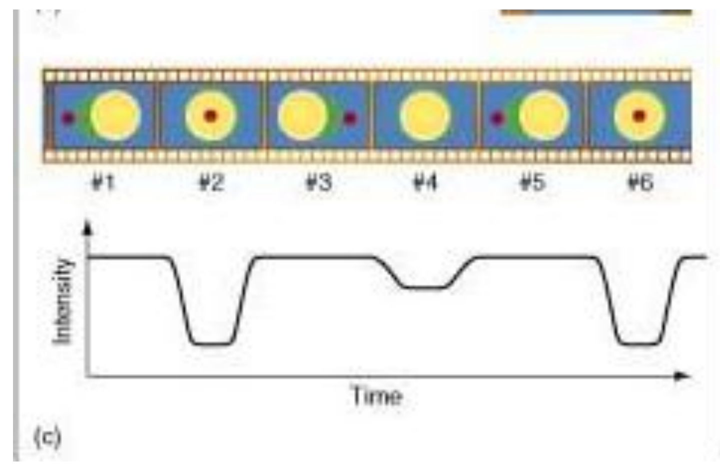


FIGURE 7.2 The V magnitude light curve of YY Sagittarii, an eclipsing binary star. The data from many orbital periods have been plotted on this light curve as a function of phase, where the phase is defined to be 0.0 at the primary minimum. This system has an orbital period $P = 2.6284734$ d, an eccentricity $e = 0.1573$, and orbital inclination $i = 88.89°$ (see Section 7.2). (Figure adopted from Lacy, C. H. S., *Astron. J.*, *105*, 637, 1993.)





Astrometric Binary

- **Astrometric Binary** In some cases only one member of a binary system can be seen. Its oscillatory motion betrays the presence of the other member of the binary system. The center of mass of the binary system moves at a constant velocity.

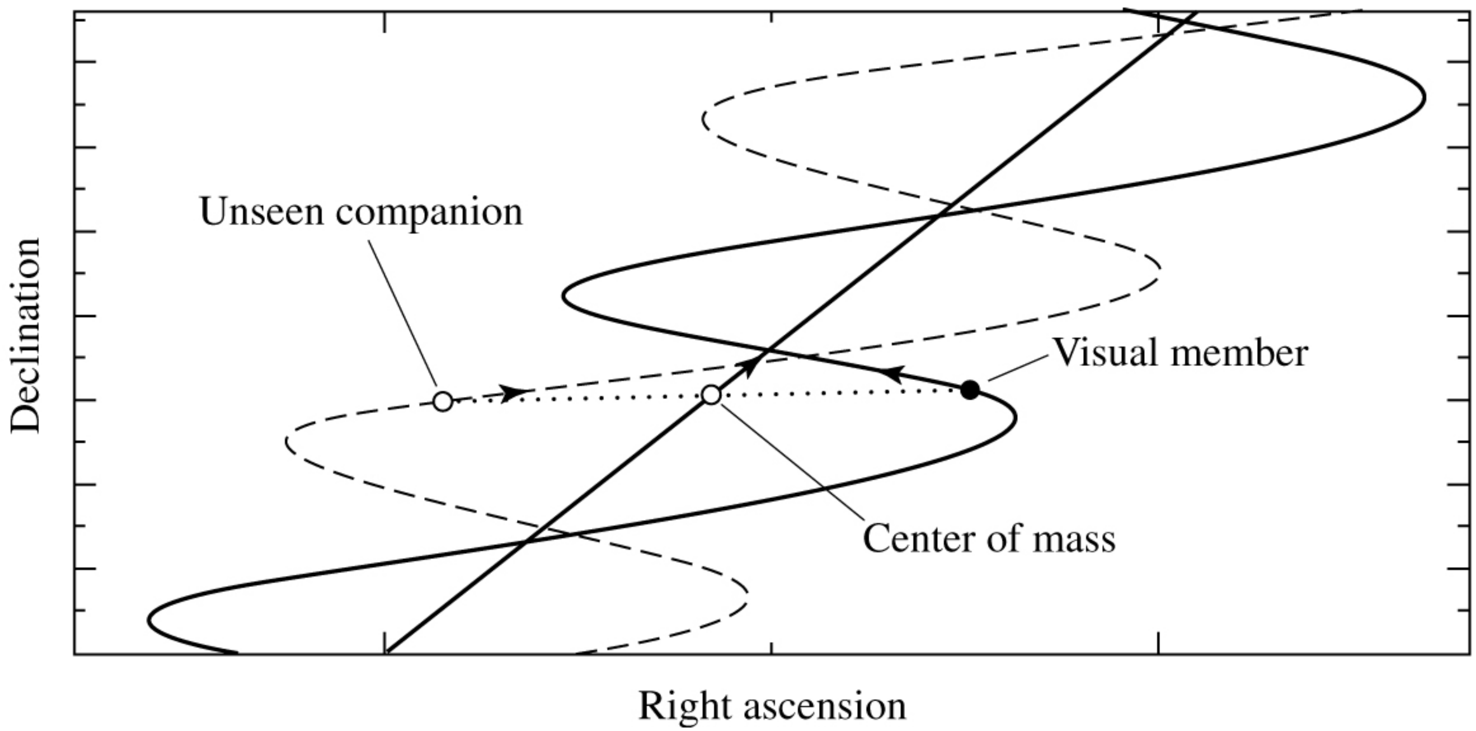


FIGURE 7.1 An astrometric binary, which contains one visible member. The unseen component is implied by the oscillatory motion of the observable star in the system. The proper motion of the entire system is reflected in the straight-line motion of the center of mass.

Spectrum Binary

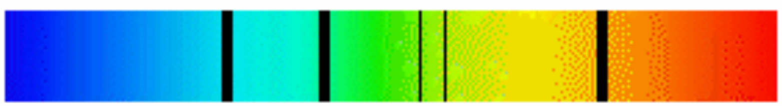
- **Spectrum Binary** A spectrum binary is a system with two superimposed, independent, discernible spectra. Periodic shifts in the wavelengths of spectral lines due to the changing motion of the stars.

Spectrum Binary

Normally, each star as a unique spectrum (spectral class). For example, a hot star has a spectrum rich in hydrogen lines

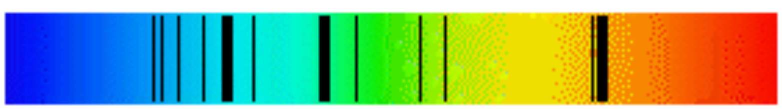
hot star

A cool star has thicker lines from metals, such as below



cool star

So, a spectrum binary is when you can not see two stars on the sky, but a spectrum of the object show two difference stellar classes, as below.

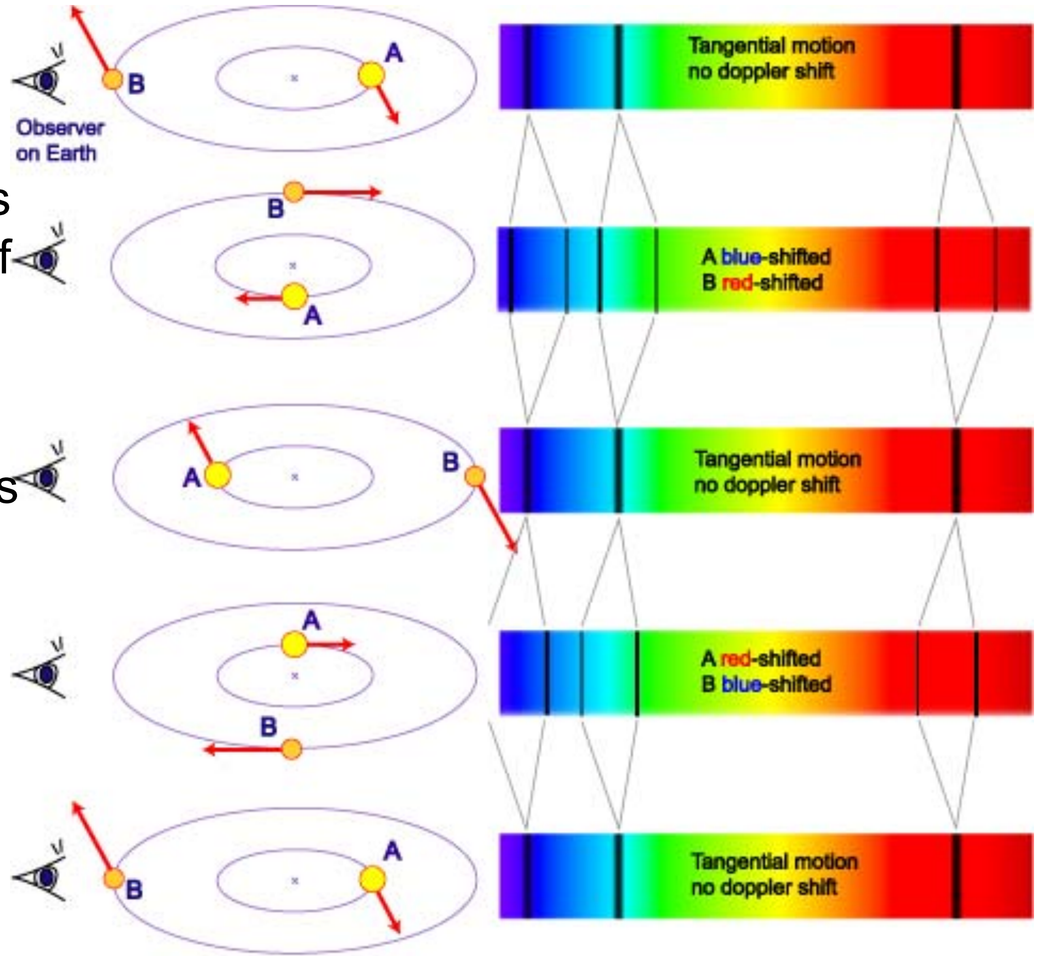


spectrum binary

Spectroscopic Binaries

Spectroscopic Binary

If the orbital period is not too long and the orbital plane has a component along the line of sight, a periodic shift in wavelength will be observable. Both spectra will be available if the luminosities are comparable. In the case of a large difference in luminosity only one set of spectra will be observable. The periodic shift in wavelength in this case still reveals the presence of a binary system.

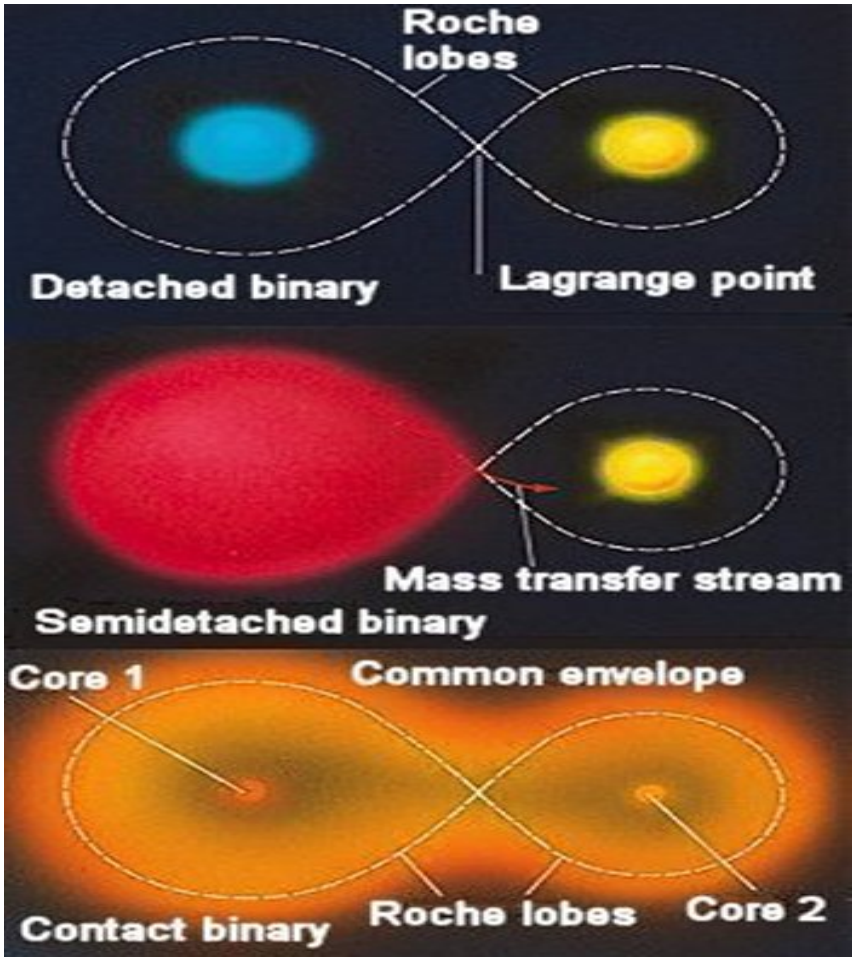


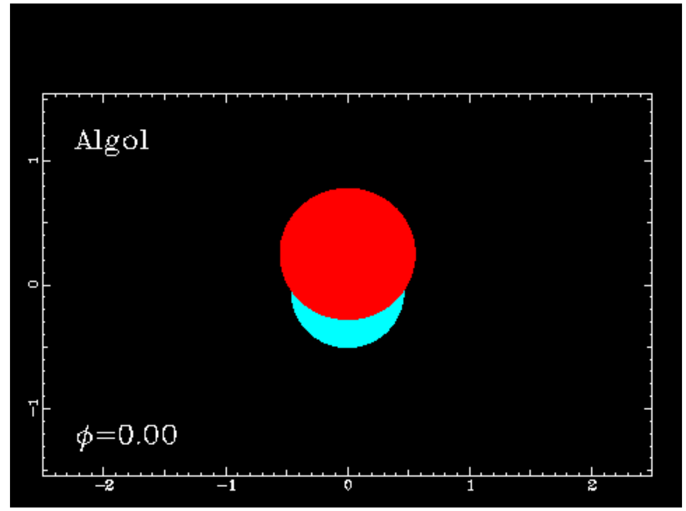
A Spectroscopic Binary System
High-mass star A and lower-mass B orbit around a common centre of mass. The observed combined spectrum shows periodic splitting and shifting of spectral lines. The amount of shift is a function of the alignment of the system relative to us and the orbital speed of the stars.

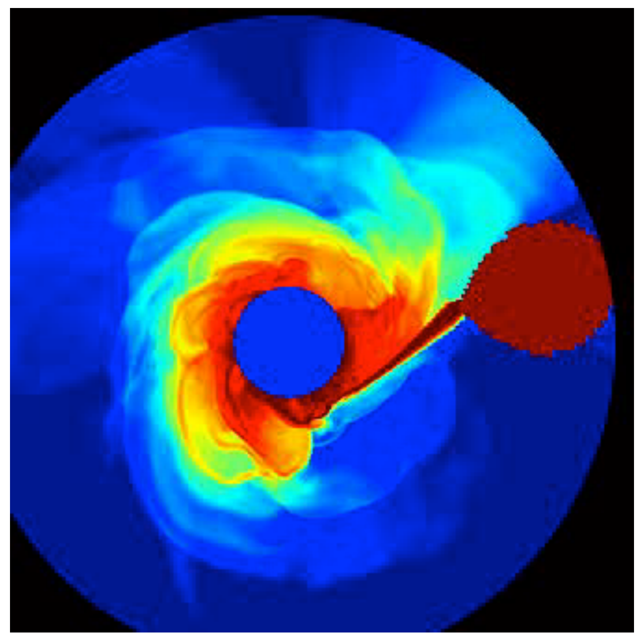
http://www.astro.cornell.edu/academics/courses/astro1101/java/binary/binary.htm

Contact Binaries

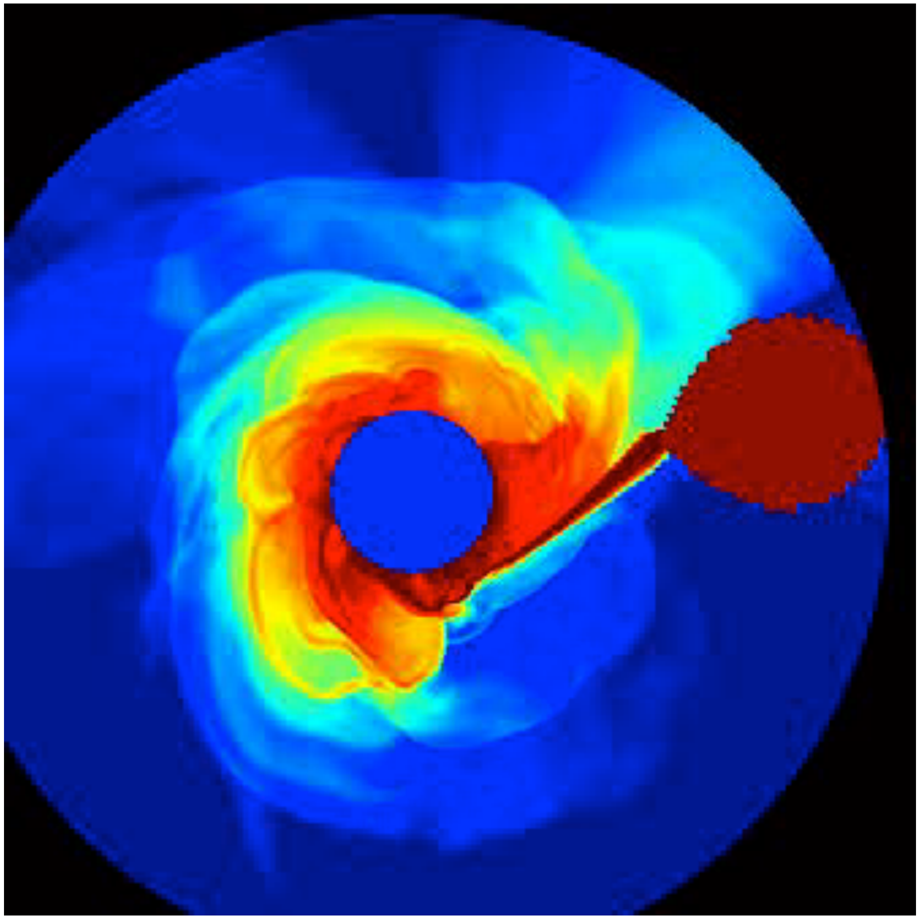
Roche Lobe: Envelope beyond which accretion to partner occurs





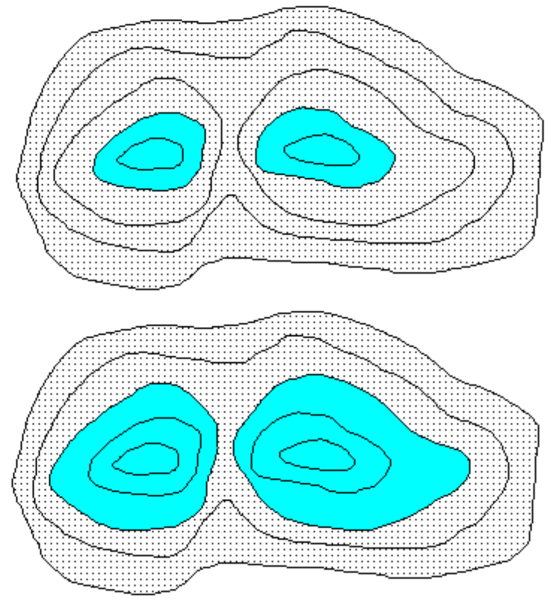


Equipotential and Roche Lobe

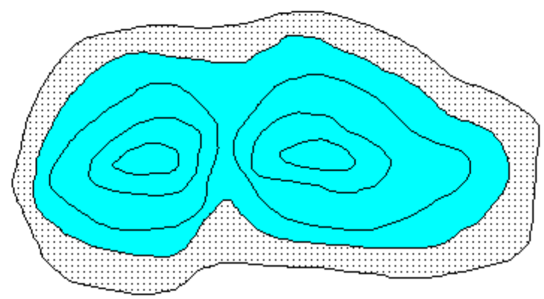


Equipotential

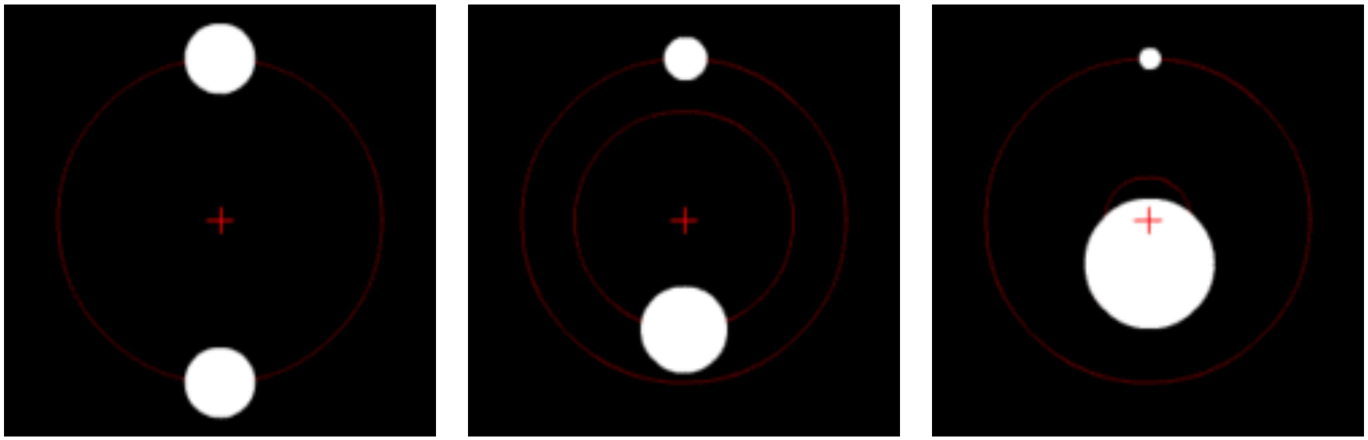
Lines of equipotential are like contour lines on a map. As two lakes fill with water, the level increases following lines of equipotential

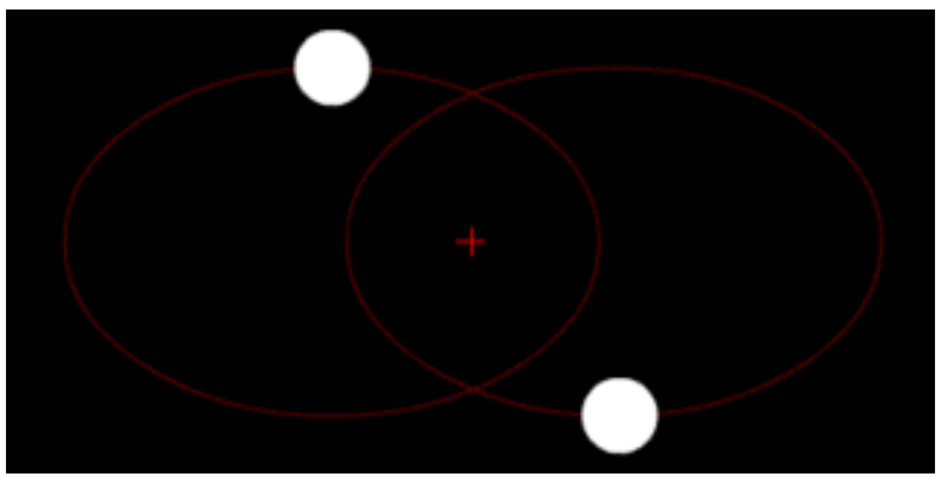


At some point the contours meet, and the lakes are joined



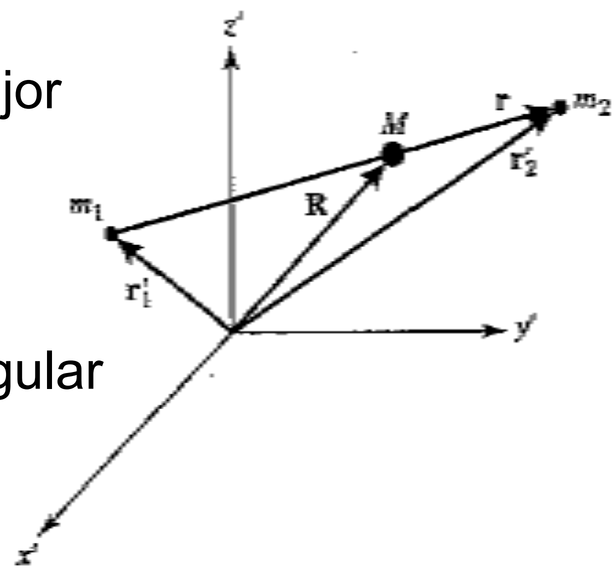
Mass Determination using visual binaries





Mass Determination using visual binaries

- Measure Period
- Measure orbital semi-major axis
- Apply Kepler's 3rd law
- Even when distance to system is not known, angular measurements allow determination of mass ratio…!!!
- If distance and inclination known can determine individual masses
- Derivation from pp 183-185



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

C.M frame ==> R=0

$$\frac{m_1\mathbf{r}_1 + m_2\mathbf{r}_2}{m_1 + m_2} = 0,$$

$$\frac{m_1}{m_2} = \frac{r_2}{r_1} = \frac{a_2}{a_1},$$

Angles subtended by semi-major axes can be observed directly. Even if distance d is unknown mass ratio can be determined

$$\alpha_1 = \frac{a_1}{d} \quad \text{and} \quad \alpha_2 = \frac{a_2}{d},$$

$$\boxed{\frac{m_1}{m_2} = \frac{\alpha_2}{\alpha_1}.}$$

Mass Determination using visual binaries

$$a = a_1 + a_2$$

$$P^2 = \frac{4\pi^2}{G\,(m_1 + m_2)} a^3,$$

Need to know distance

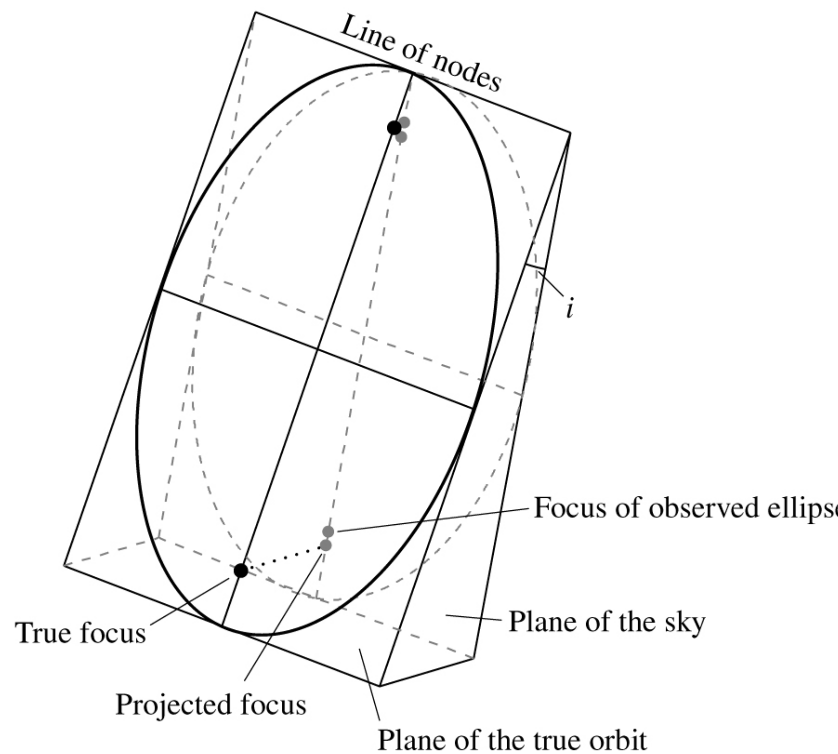
Total mass from Kepler's law

Individual masses from ratio

Need to account for inclination…

$$\frac{m_1}{m_2} = \frac{\alpha_2}{\alpha_1} = \frac{\alpha_2 \cos i}{\alpha_1 \cos i} = \frac{\tilde{\alpha}_2}{\tilde{\alpha}_1}.$$

$$m_1 + m_2 = \frac{4\pi^2}{G} \frac{(\alpha d)^3}{P^2} = \frac{4\pi^2}{G} \left(\frac{d}{\cos i}\right)^3 \frac{\tilde{\alpha}^3}{P^2},$$



Spectroscopic Binaries

- Individual stars not spatially resolved.
- Both spectra seen

- Inclination angle affects observed radial velocities
- For circular orbits with I=90° velocity curves are sinusoidal. Inclination will reduce amplitude

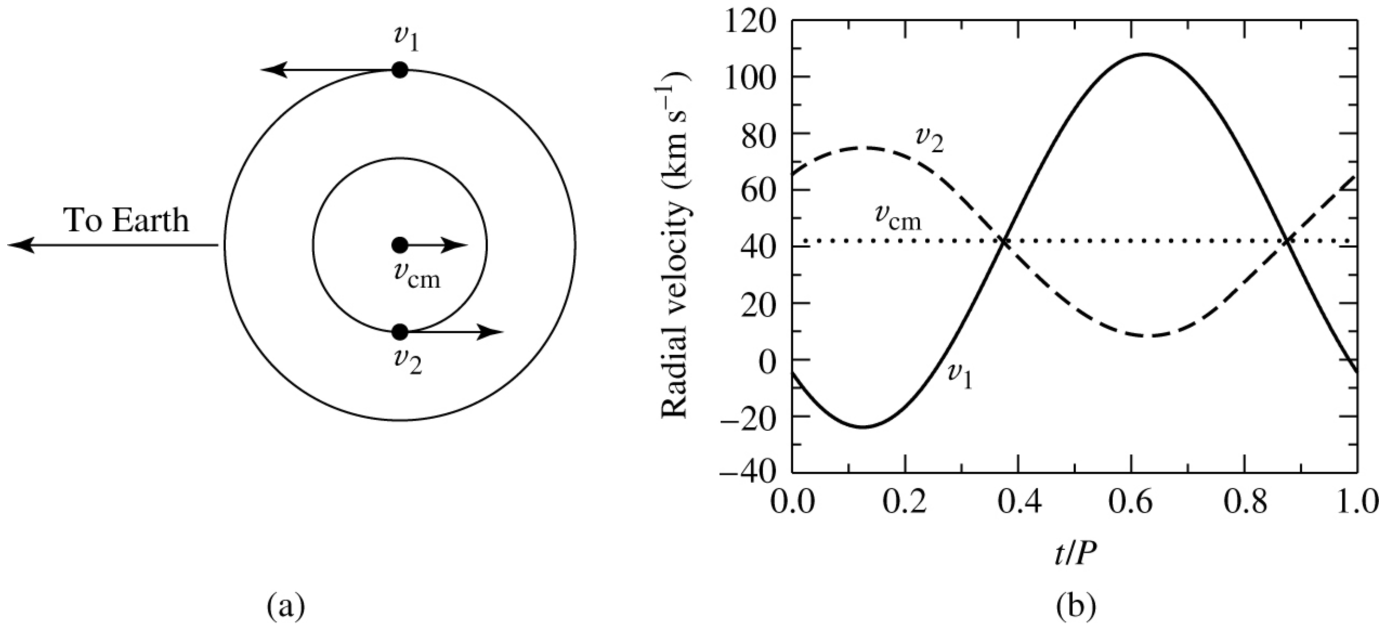


FIGURE 7.5 The orbital paths and radial velocities of two stars in circular orbits ($e = 0$). In this example, $M_1 = 1\ M_\odot$, $M_2 = 2\ M_\odot$, the orbital period is $P = 30$ d, and the radial velocity of the center of mass is $v_{cm} = 42$ km s^{-1}. v_1, v_2, and v_{cm} are the velocities of Star 1, Star 2, and the center of mass, respectively. (a) The plane of the circular orbits lies along the line of sight of the observer. (b) The observed radial velocity curves.

Spectroscopic Binaries

- Eccentricity will change velocity curve to be non-sinusoidal. Can estimate eccentricity from deviation from sinusoidal shape

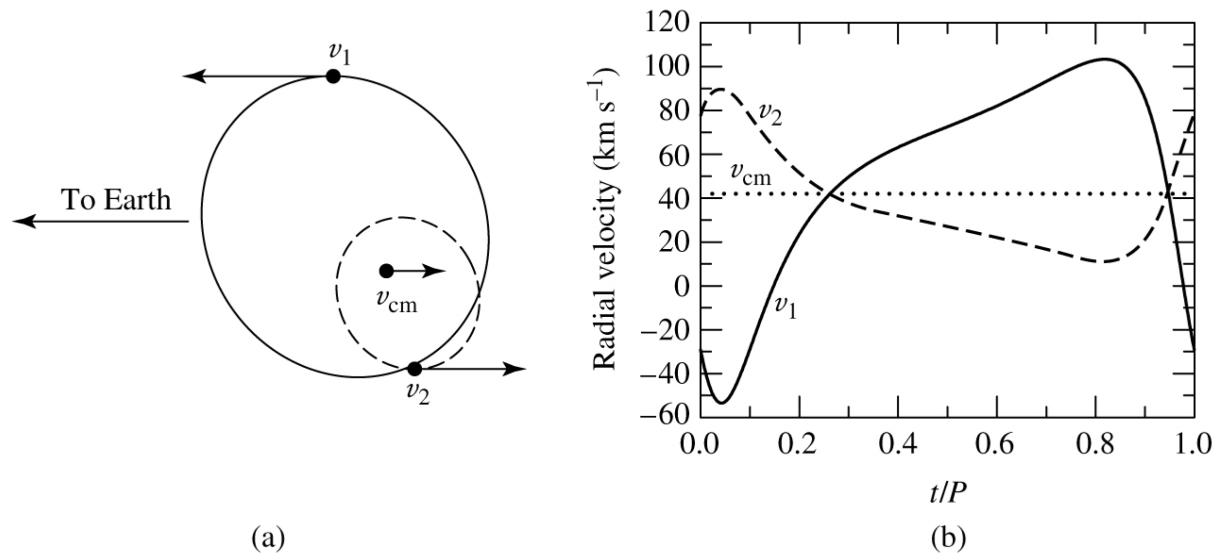


FIGURE 7.6 The orbital paths and radial velocities of two stars in elliptical orbits ($e = 0.4$). As in Fig. 7.5, $M_1 = 1\ M_\odot$, $M_2 = 2\ M_\odot$, the orbital period is $P = 30$ d, and the radial velocity of the center of mass is $v_{cm} = 42$ km s^{-1}. In addition, the orientation of periastron is 45°. v_1, v_2, and v_{cm} are the velocities of Star 1, Star 2, and the center of mass, respectively. (a) The plane of the orbits lies along the line of sight of the observer. (b) The observed radial velocity curves.

The Mass Function

- For small eccentricity
- Do not need to know inclination angle to determine mass ratio
- To obtain sum of masses do need to know inclination angle
- Derivation pp187-188

$$v_1 = 2\pi a_1 / P$$
$$v_2 = 2\pi a_2 / P$$

$\Rightarrow$

$$a_1 = P v_1 / 2\pi$$
$$a_2 = P v_2 / 2\pi$$

$$\frac{m_1}{m_2} = \frac{v_2}{v_1}.$$

$$\frac{m_1}{m_2} = \frac{v_{2r}/\sin i}{v_{1r}/\sin i} = \frac{v_{2r}}{v_{1r}}.$$

$$a = a_1 + a_2 = \frac{P}{2\pi}(v_1 + v_2)$$

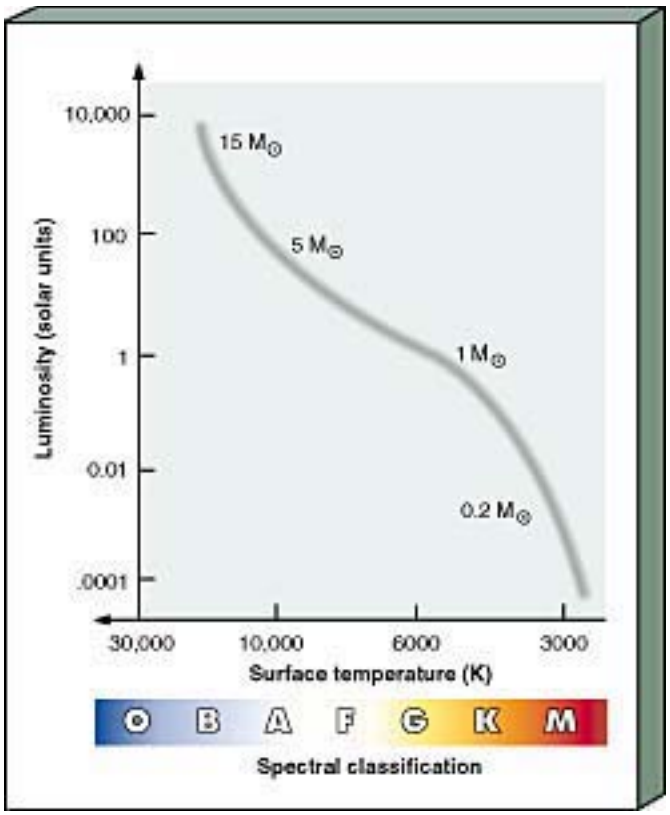
$$m_1 + m_2 = \frac{P}{2\pi G}(v_1 + v_2)^3.$$

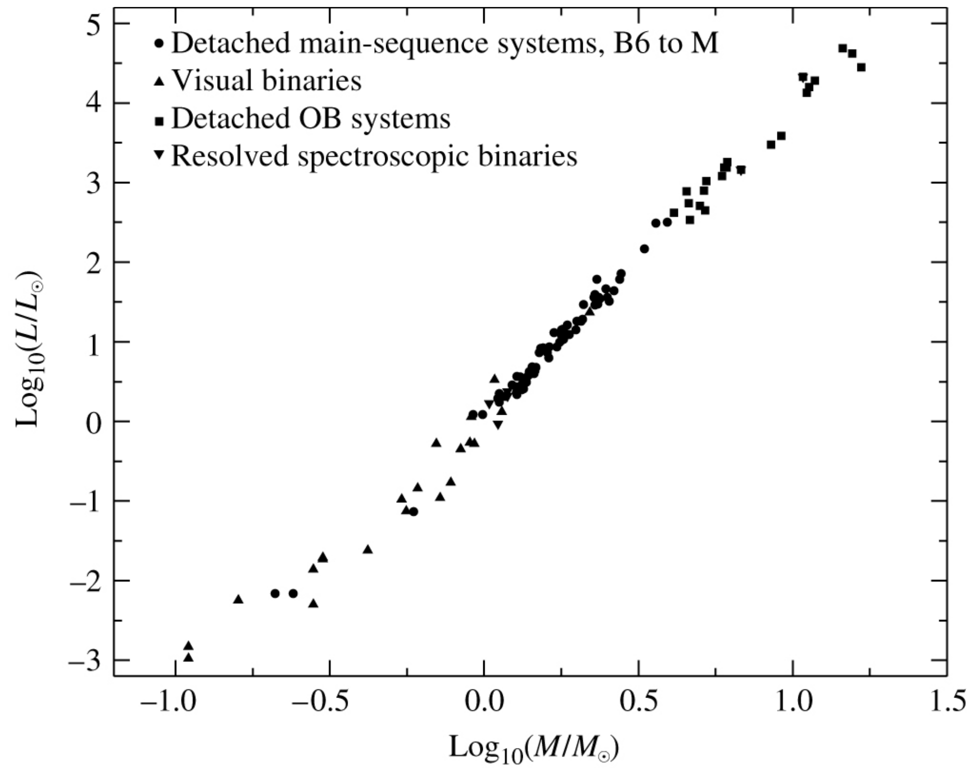
$$m_1 + m_2 = \frac{P}{2\pi G}\frac{v_{1r}^3}{\sin^3 i}\left(1 + \frac{m_1}{m_2}\right)^3.$$

$$\frac{m_2^3}{(m_1 + m_2)^2}\sin^3 i = \frac{P}{2\pi G} v_{1r}^3.$$

Mass-Luminosity Relation

- Luminosity is highly correlated to stellar mass !!!! Why???

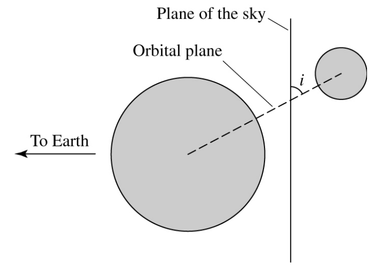


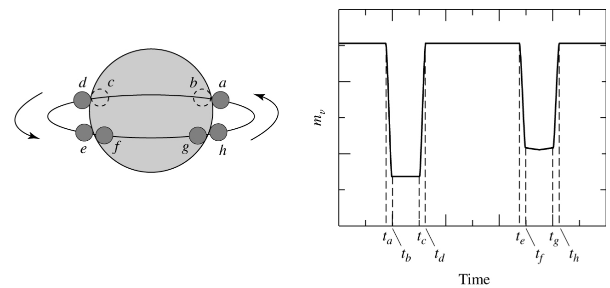


L/L(Sun) ~ [M/M(Sun)]**3.9

Eclipsing Binaries

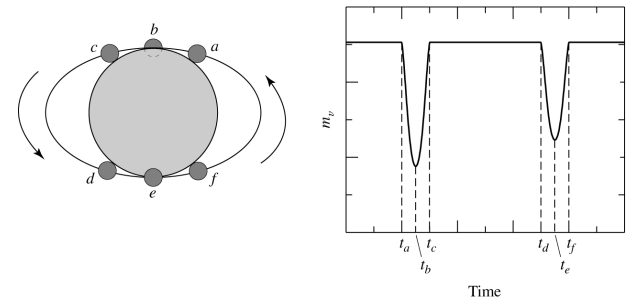
- Can use eclipses to determine radii and ratio of temperatures from eclipsing binaries!!!
- Radii from First contact time, minimum light time,…





$$r_s = \frac{v}{2}\left(t_b - t_a\right),$$

$$r_\ell = \frac{v}{2}\left(t_c - t_a\right) = r_s + \frac{v}{2}\left(t_c - t_b\right).$$



- Derivation pp190-191
- Example 7.3.1

Eclipsing Binaries

Example 7.3.1. An analysis of the spectrum of an eclipsing, double-line, spectroscopic binary having a period of $P = 8.6$ yr shows that the maximum Doppler shift of the hydrogen Balmer Hα (656.281 nm) line is $\Delta\lambda_s = 0.072$ nm for the smaller member and only $\Delta\lambda_\ell = 0.0068$ nm for its companion. From the sinusoidal shapes of the velocity curves, it is also apparent that the orbits are nearly circular. Using Eqs. (4.39) and (7.5), we find that the mass ratio of the two stars must be

$$\frac{m_\ell}{m_s} = \frac{v_{rs}}{v_{r\ell}} = \frac{\Delta\lambda_s}{\Delta\lambda_\ell} = 10.6.$$

Assuming that the orbital inclination is $i = 90°$, the Doppler shift of the smaller star implies that the maximum measured radial velocity is

$$v_{rs} = \frac{\Delta\lambda_s}{\lambda} c = 33 \text{ km s}^{-1}$$

and the radius of its orbit must be

$$a_s = \frac{v_{rs} P}{2\pi} = 1.42 \times 10^{12} \text{ m} = 9.5 \text{ AU}.$$

In the same manner, the orbital velocity and radius of the other star are $v_{r\ell} = 3.1$ km s^{-1} and $a_\ell = 0.90$ AU, respectively. Therefore, the semimajor axis of the reduced mass becomes $a = a_s + a_\ell = 10.4$ AU.

continued

Eclipsing Binaries

The sum of the masses can now be determined from Kepler's third law. If Eq. (2.37) is written in units of solar masses, astronomical units, and years, we have

$$m_s + m_\ell = a^3/P^2 = 15.2\ \mathrm{M}_\odot.$$

Solving for the masses independently yields $m_s = 1.3\ \mathrm{M}_\odot$ and $m_\ell = 13.9\ \mathrm{M}_\odot$.

Furthermore, from the light curve for this system, it is found that $t_b - t_a = 11.7$ hours and $t_c - t_b = 164$ days. Using Eq. (7.8) reveals that the radius of the smaller star is

$$r_s = \frac{(v_{rs} + v_{r\ell})}{2}(t_b - t_a) = 7.6 \times 10^8\ \mathrm{m} = 1.1\ \mathrm{R}_\odot,$$

where one solar radius is $1\ \mathrm{R}_\odot = 6.96 \times 10^8$ m. Equation (7.9) now gives the radius of the larger star, which is found to be $r_\ell = 369\ \mathrm{R}_\odot$.

In this particular system, the masses and radii of the stars are found to differ significantly.

Ratio of Effective Temperatures

Referring once more to the sample binary system depicted in Fig. 7.9, it can be seen that the dip in the light curve is deeper when the smaller, hotter star is passing behind its companion. To understand this effect, recall that the radiative surface flux is given by Eq. (3.18),

$$F_r = F_{\text{surf}} = \sigma T_e^4.$$

Regardless of whether the smaller star passes behind or in front of the larger one, the same total cross-sectional area is eclipsed. Assuming for simplicity that the observed flux is constant across the disks,[3] the amount of light detected from the binary when both stars are fully visible is given by

$$B_0 = k\left(\pi r_\ell^2 F_{r\ell} + \pi r_s^2 F_{rs}\right),$$

where k is a constant that depends on the distance to the system, the amount of intervening material between the system and the detector, and the nature of the detector. The deeper, or *primary*, minimum occurs when the hotter star passes behind the cooler one. If, as in the last example, the smaller star is hotter and therefore has the larger surface flux, and the smaller star is entirely eclipsed, the amount of light detected during the primary minimum may be expressed as

$$B_p = k\pi r_\ell^2 F_{r\ell}$$

while the brightness of the *secondary* minimum is

$$B_s = k\left(\pi r_\ell^2 - \pi r_s^2\right) F_{r\ell} + k\pi r_s^2 F_{rs}.$$

Ratio of Effective Temperatures

Since it is generally not possible to determine k exactly, ratios are employed. Consider the ratio of the depth of the primary to the depth of the secondary. Using the expressions for B_0, B_p, and B_s, we find immediately that

$$\frac{B_0 - B_p}{B_0 - B_s} = \frac{F_{rs}}{F_{r\ell}} \tag{7.10}$$

or, from Eq. (3.18),

$$\boxed{\frac{B_0 - B_p}{B_0 - B_s} = \left(\frac{T_s}{T_\ell}\right)^4 .} \tag{7.11}$$

Ratio of Effective Temperatures

Example 7.3.2. Further examination of the light curve of the binary system discussed in Example 7.3.1 provides information on the relative temperatures of the two stars. Photometric observations show that at maximum light the bolometric magnitude is $m_{\text{bol},0} = 6.3$, at the primary minimum $m_{\text{bol},p} = 9.6$, and at the secondary minimum $m_{\text{bol},s} = 6.6$. From Eq. (3.3), the ratio of brightnesses between the primary minimum and maximum light is

$$\frac{B_p}{B_0} = 100^{(m_{\text{bol},0} - m_{\text{bol},p})/5} = 0.048.$$

Similarly, the ratio of brightnesses between the secondary minimum and maximum light is

$$\frac{B_s}{B_0} = 100^{(m_{\text{bol},0} - m_{\text{bol},s})/5} = 0.76.$$

Now, by rewriting Eq. (7.10), we find that the ratio of the radiative fluxes is

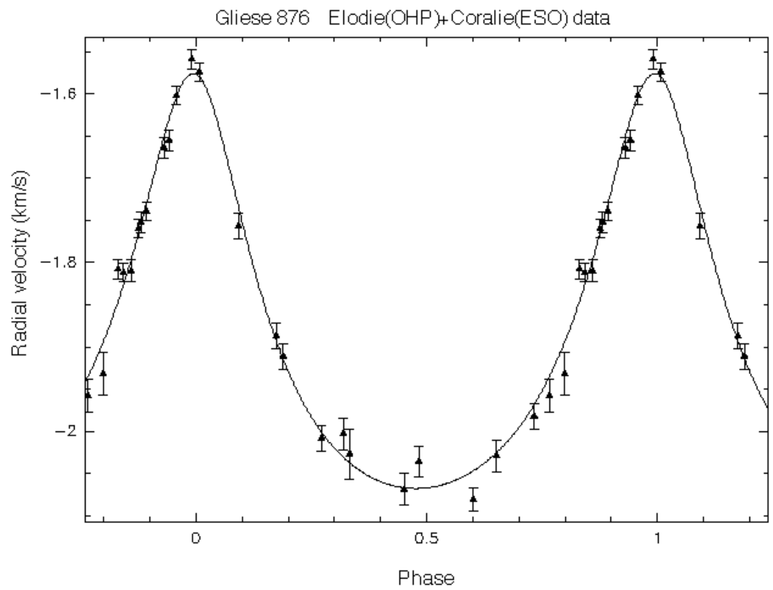
$$\frac{F_{rs}}{F_{r\ell}} = \frac{1 - B_p/B_0}{1 - B_s/B_0} = 3.97.$$

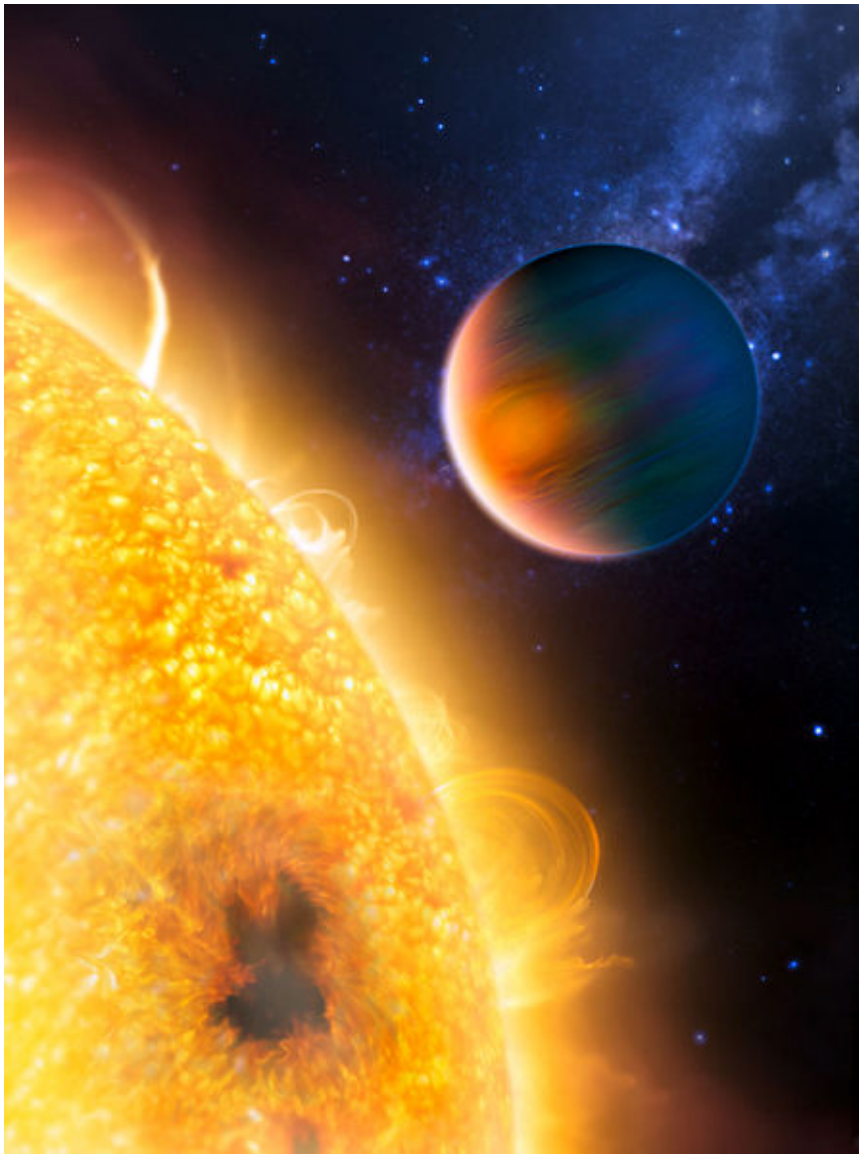
Finally, from Eq. (3.18),

$$\frac{T_s}{T_\ell} = \left(\frac{F_{rs}}{F_{r\ell}}\right)^{1/4} = 1.41.$$

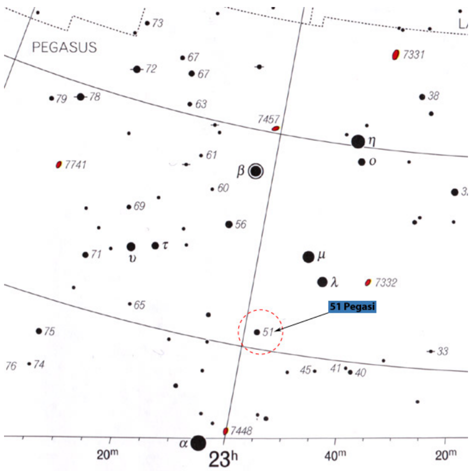
Extrasolar planets

- http://www.obs-hp.fr/www/exotab.shtml
- http://www.obs-hp.fr/www/preprints/pp94/pp94.html
- http://en.wikipedia.org/wiki/Methods_of_detecting_extrasolar_planets
- Example 7.4.1

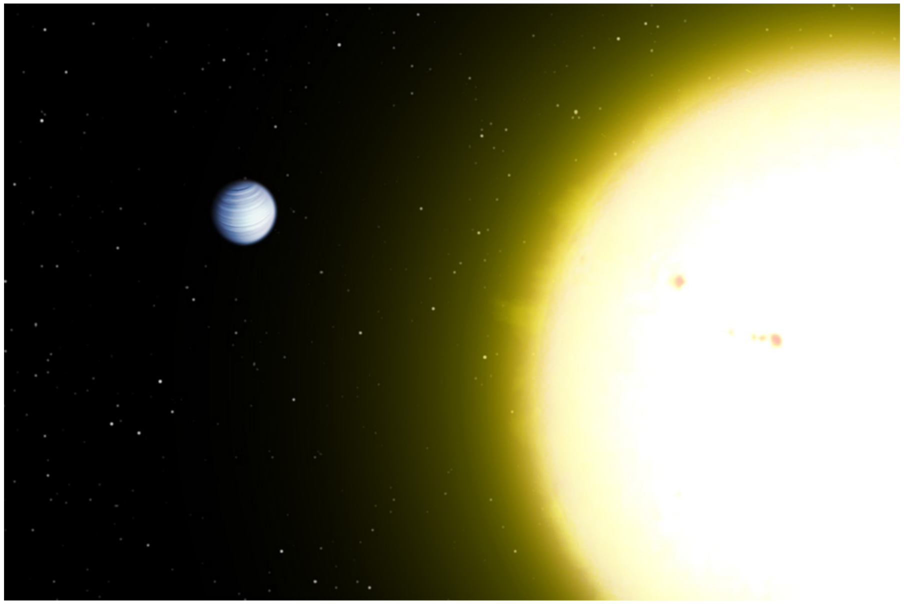


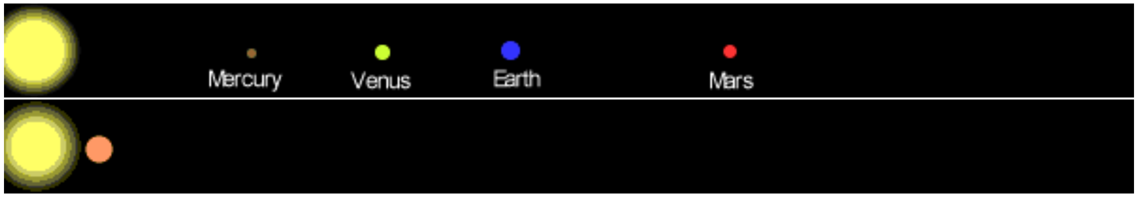


51 pegasi



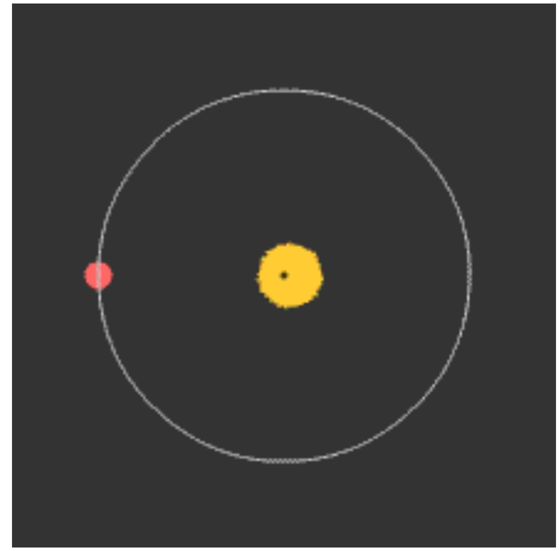
- First Extrasolar planet to be discovered…Oct 6,1995
- Planet mass about 1/2 Mass of jupiter
- P=37 days
- a=0.05 AU
- http://en.wikipedia.org/wiki/51_Pegasi



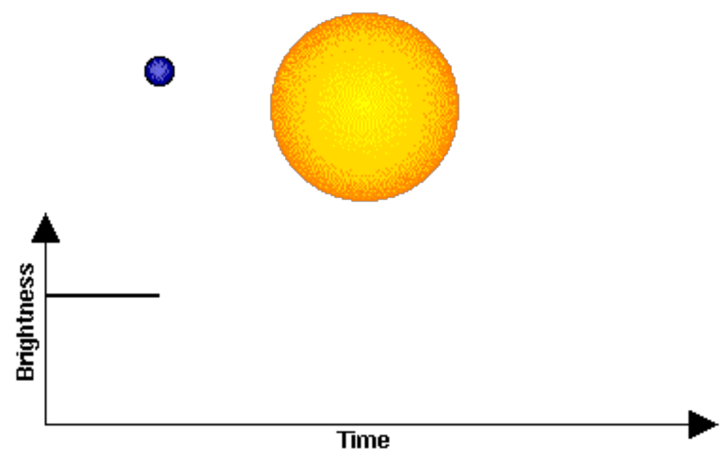


ExoPlanet detection

- Radial Velocity (Wobble)



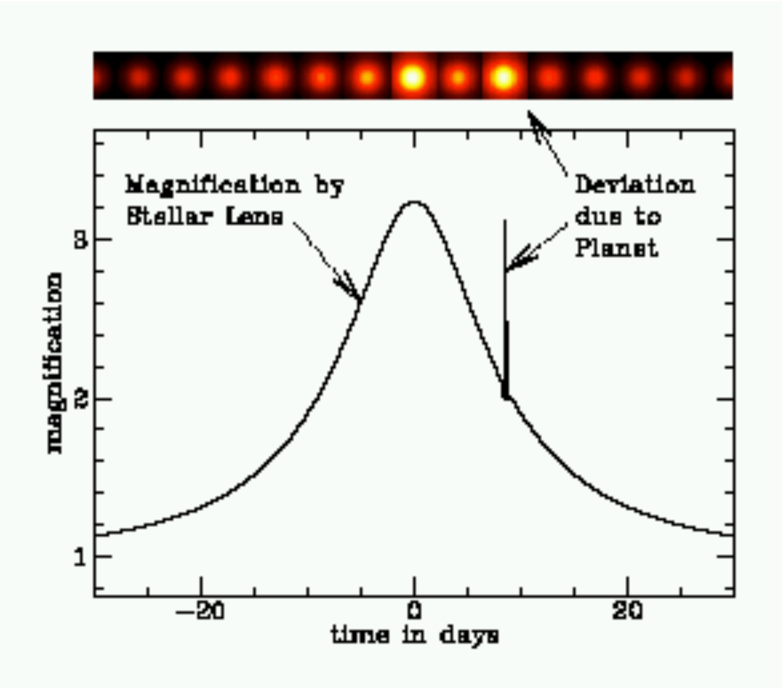
- Transit



ExoPlanet detection

- Gravitational Microlensing

- Other techniques
  http://en.wikipedia.org/wiki/Extrasolar_planet

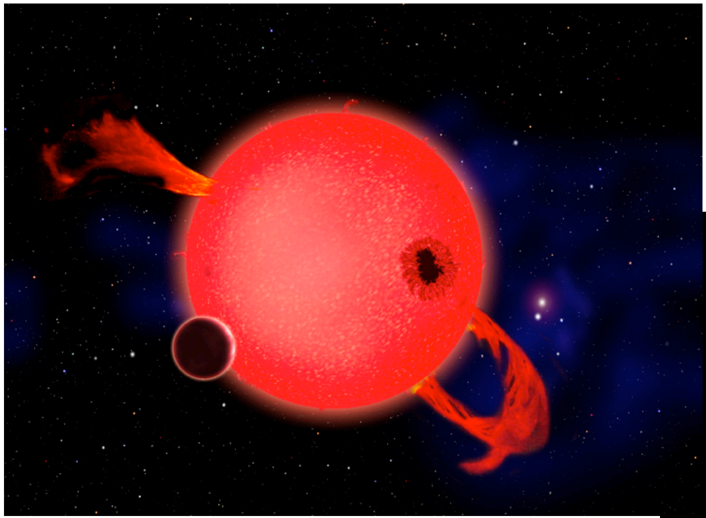


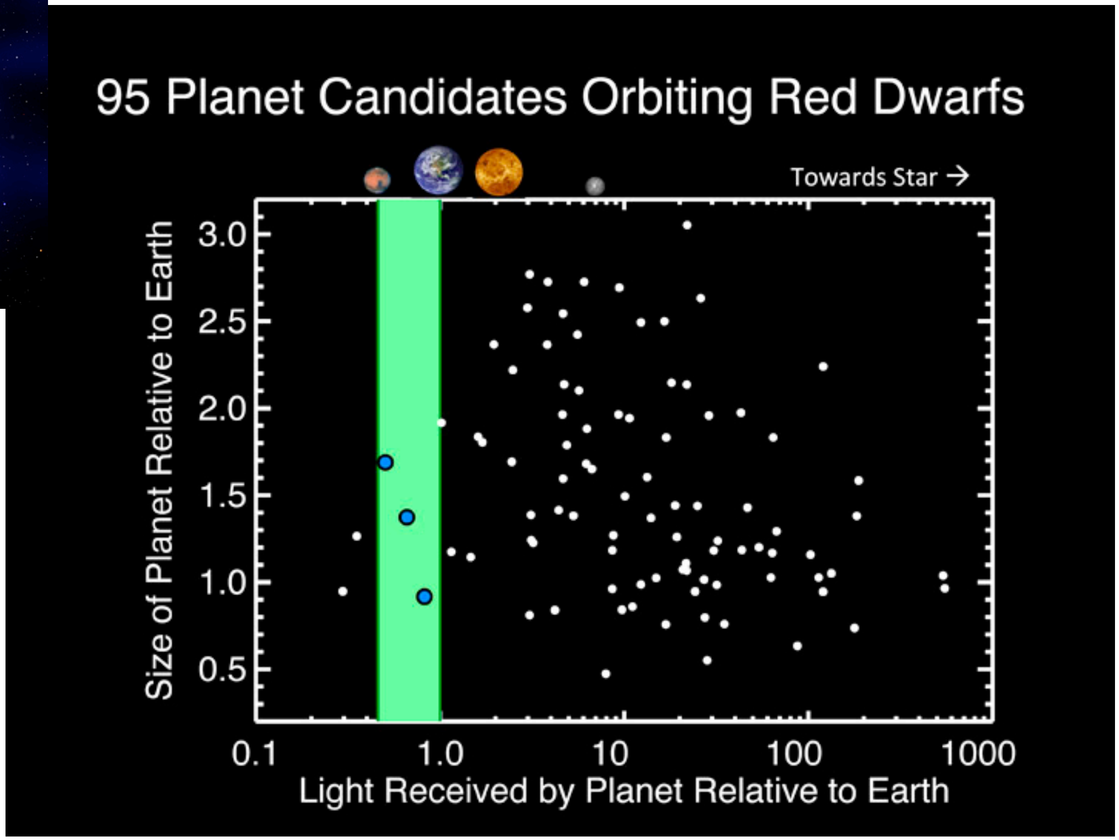
http://bustard.phys.nd.edu/MPS/

http://kepler.nasa.gov/

Earth-like Planets Are Right Next Door

- http://www.cfa.harvard.edu/news/2013/pr201305.html





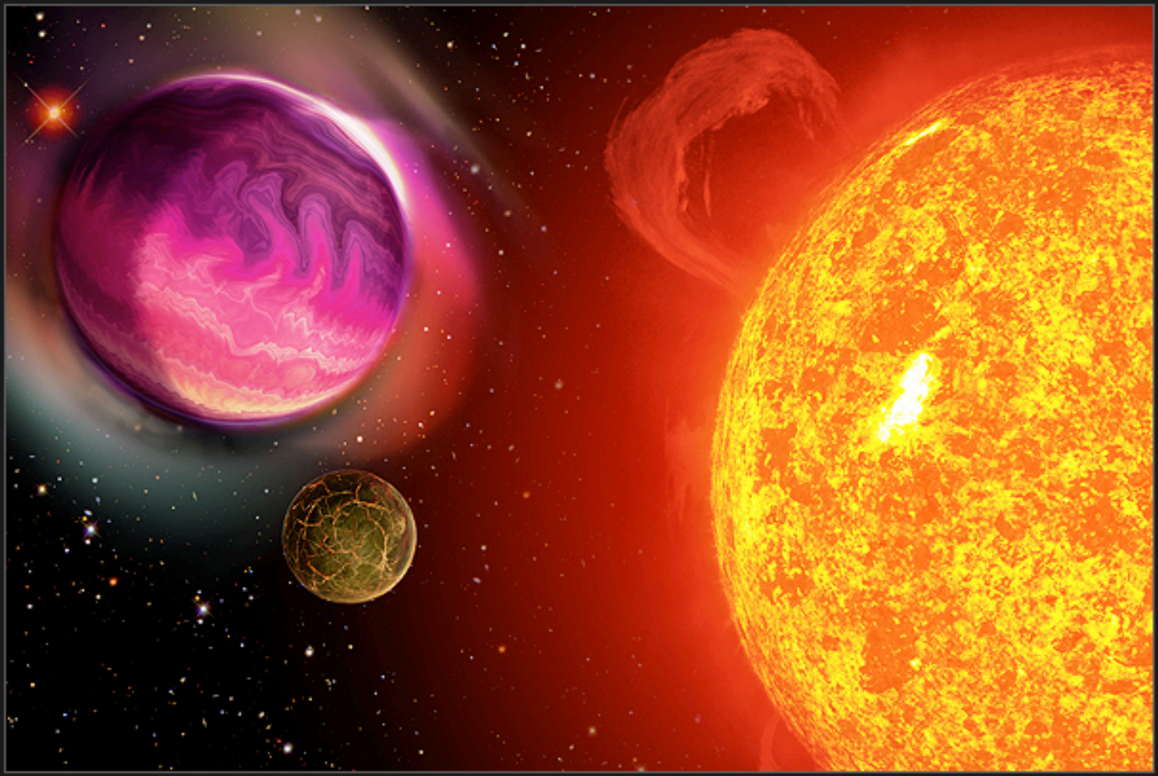
Earth-like Planets Are Right Next Door

- Many dim red-dwarf stars populate the galaxy…

SDSS-III MARVELS

MARVELS: Characterizing Extrasolar Planets

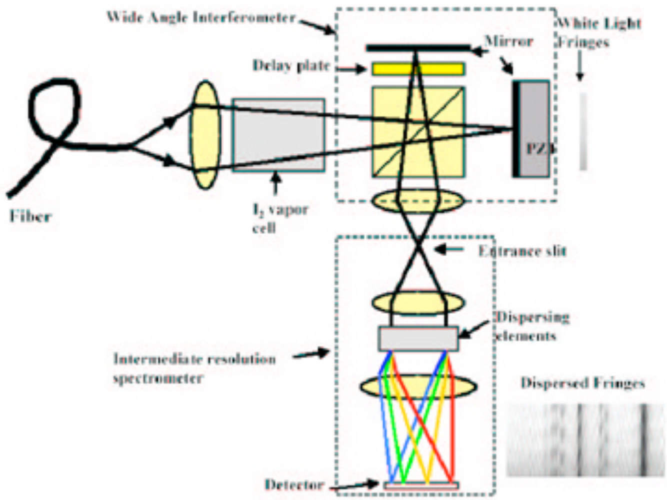
The Multi-object APO Radial Velocity Exoplanet Large-area Survey (MARVELS) will monitor the radial velocities of 11,000 bright stars, with the precision and cadence needed to detect gas giant planets that have orbital periods ranging from several hours to two years.

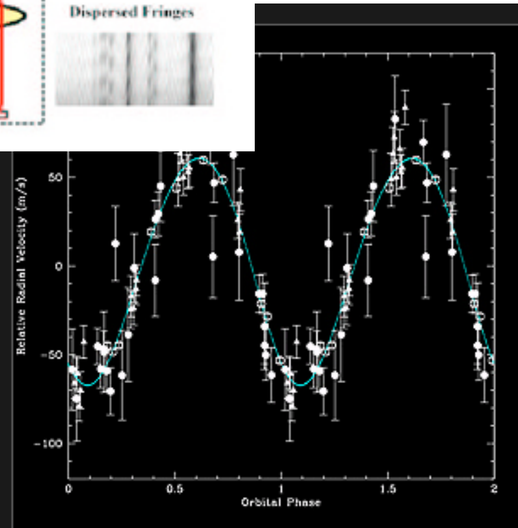


Artist's conception of an extrasolar planetary system (credit: T. Riecken)

With well-characterized sensitivity and a broad range of target star properties, MARVELS will provide a critical dataset for testing theoretical models of the formation, migration, and dynamical evolution of giant planet systems. It will have unique sensitivity to rare systems such as extreme eccentricity planets or objects in the "brown dwarf desert."

http://www.sdss3.org/instruments/marvels_spectrograph.php





Radial velocity curve of an extrasolar planet discovered by a prototype of the MARVELS spectrograph at Kitt Peak National Observatory.

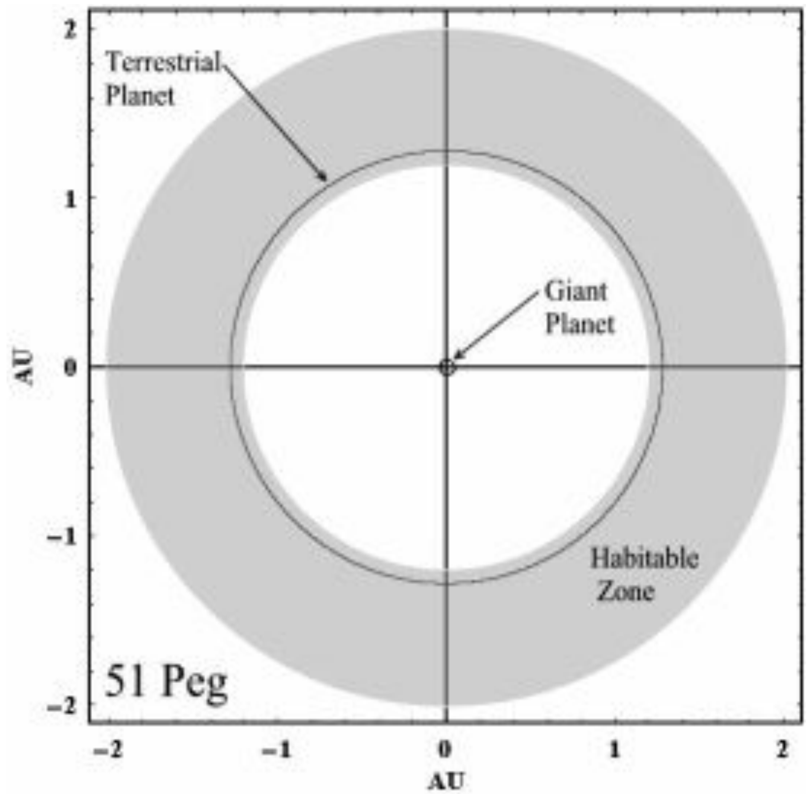
MARVELS at a glance
Bright time observations
Fall 2008 - Spring 2014
Two 60-fiber interferometric spectrographs (one initially)
10,000 main sequence targets, 1,000 giant targets, V=8-12
25-35 observations per star over 18 months
Velocity error 12 m/s at V=10
Mass sensitivity at P=100 days: 0.35 M_{Jup} (V=9.5), 0.7 M_{Jup} (V=11.5)

For a detailed description of MARVELS, see section 6 of the Project Description, available as a PDF document.

http://www.sdss3.org/collaboration/description.pdf

Habitable Zones

- "Goldilocks"…requires perfect (at least) adequate conditions….



Habitable Zone … where Temperatures could be conducive to the formation of "Life"…