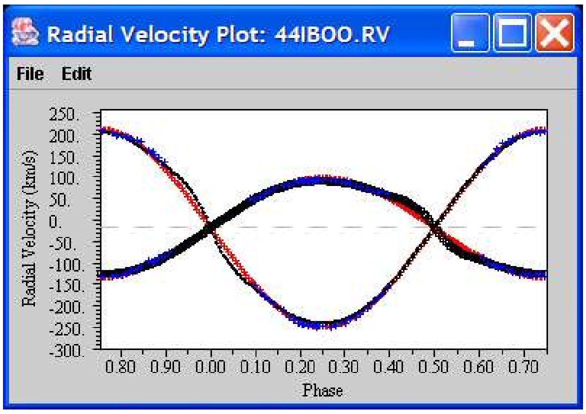
Binary Maker 3

Radial Velocity Parameters Introduction

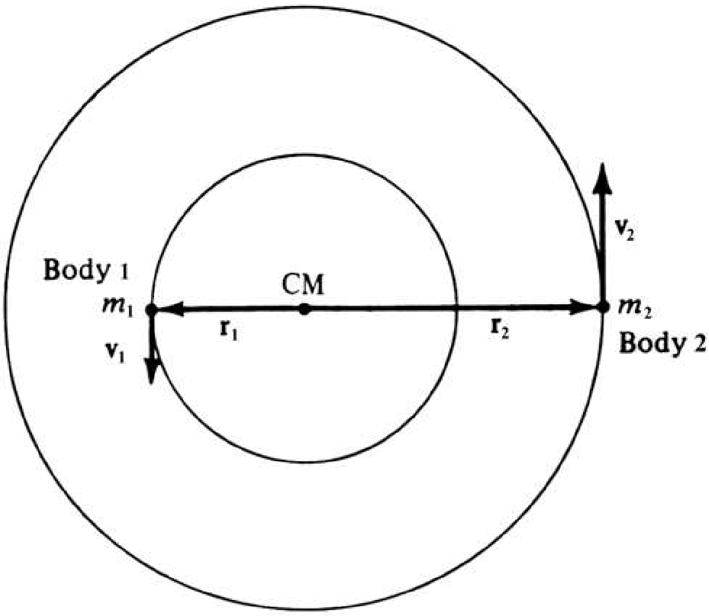


Radial Velocity window for 44 i Boo

The **Radial Velocity Plot** window displays the observed radial velocity curves for both stars in the binary system, as well as the theoretically generated *mass-centered* and *light-centered* radial velocity curves. These various curves will be explained on this page, and the myriad of features which allow the user to control the display of the window are described in detail under the **Radial Velocity Plot** window **Help** pages.

Radial velocity curves map out the velocity of each star as seen from Earth as measured from spectra which exhibit the periodic Doppler-shifting of spectral lines. As each star orbits the barycenter (center of mass) of the system, one star will be typically going away from the observer while the other star will be coming towards the observer. An approach of a star causes its spectral features to exhibit shorter wavelengths (blue-shift) than if it were at rest, and longer wavelengths (red-shift) when the star is receding. On a plot of these velocities, the convention is that red shifts (receding velocities) are plotted as positive quantities because the distance between the observer and the star is increasing (getting larger positively). Blue shifts are seen to be negative velocities because the star is approaching the observer and the distance between them is decreasing.

As stars orbit their common barycenter, they must always be exactly opposite each other, *i.e.*, you can always connect the mass centers of the two stars with a straight line which will also pass through the barycenter. Also, as shown in the diagram below, the distance from the more massive star to the barycenter compared to the distance from the less mass star to the barycenter is proportional to their masses, i.e.,



Mass Balance diagram for circular orbits: CM marks the barycenter (center of mass)

The mass balance equation says that $m_1 r_1 = m_2 r_2$. Note also that each star must complete its respective orbit in exactly the same amount of time (the ***period*** of the system). This necessitates that the less massive star, which has the larger orbit, must be traveling at a greater speed than the more massive star in order to complete its larger orbit in the same time as the massive star completes its smaller orbit. For circular orbits, the time it takes to complete the orbit (the period) will be

$$P = \frac{2\pi r_1}{v_1} = \frac{2\pi r_2}{v_2}$$

This becomes

$$\frac{r_1}{v_1} = \frac{r_2}{v_2} \; or \; \frac{r_1}{r_2} = \frac{v_1}{v_2}$$

From the mass balance equation we have that

$$\frac{r_1}{r_2} = \frac{m_2}{m_1}$$

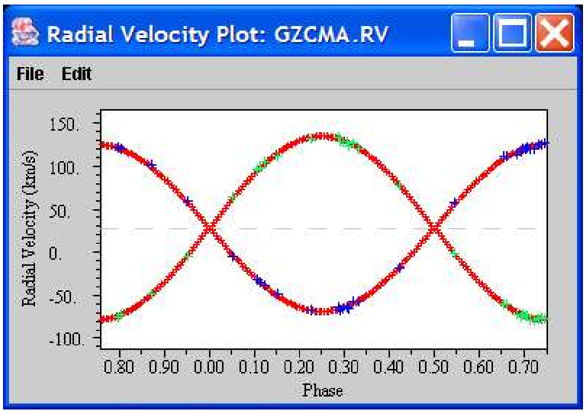
So that finally we see that the ratio of the velocities of the two stars is inversely proportional to the mass ratio of the stars, *i.e.,*

$$\frac{r_1}{r_2} = \frac{v_1}{v_2} = \frac{m_2}{m_1}$$

Therefore if we can measure the velocities of the two stars, then the ratio of their velocities tells us the ratio of the masses, an extremely important value to ascertain in the study of binary stars.

Let's return to the radial velocity curves. If we consider the stars to be point masses, their radial velocity curves will be sinusoids (for circular orbits). The theoretical radial velocity curves generated with the assumption of the stars being point masses are called the ***mass centers*** radial velocity curves. The ***mass centers*** approximation assumes that the center of the star's mass coincides with the center of the star's light output (the ***light center***), *i.e.*, that if you average the light output of the star over its entire surface it would be equal to that of a point source located at the mass center. This is valid if the stars are spherical, but it is not true is the stars are non-spherical.

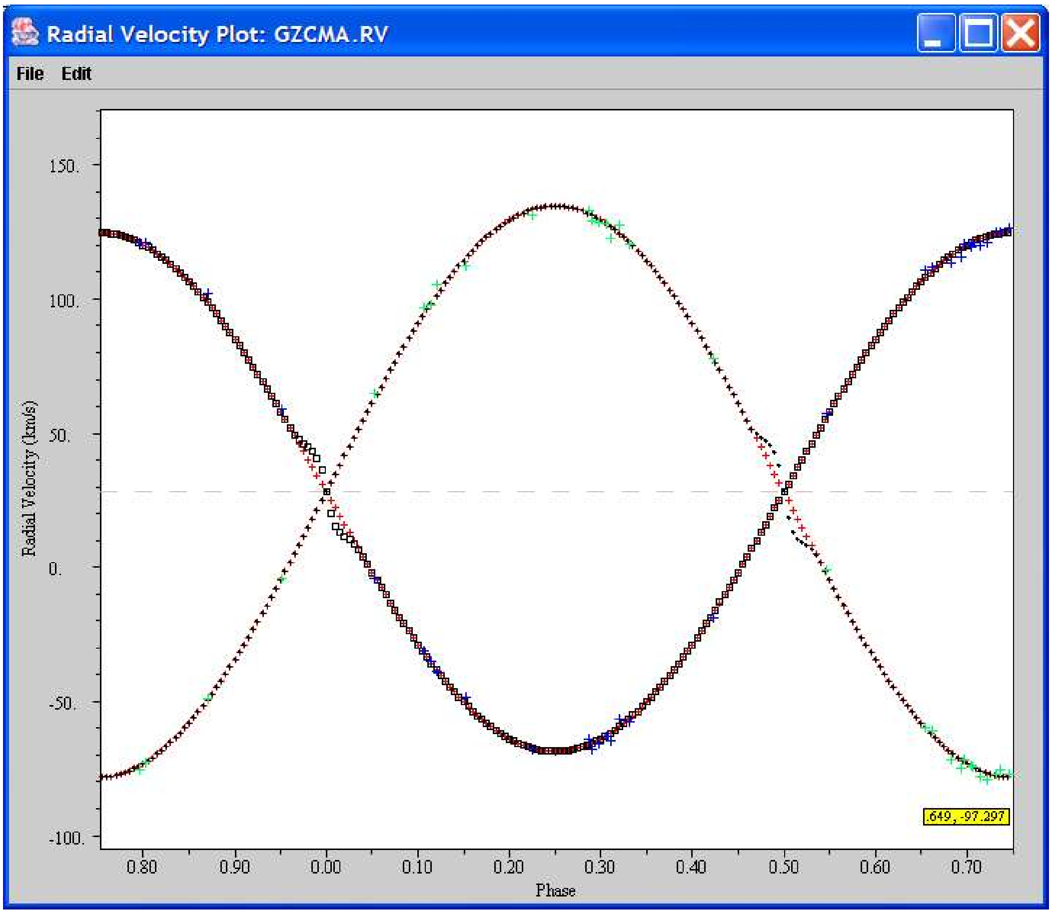
In the **Radial Velocity Plot** the ***mass centers*** curves for each star are plotted as red crosshairs, as shown below for the detached binary GZ CMa:



Radial Velocity Plot for GZ CMa showing the ***mass centers*** theoretical curves (red crosshairs); the blue crosshairs are the primary stars radial velocity data points, the green crosshairs those of the secondary star

As can be seen in the above plot for GZ CMa, the mass centers curves fit the observations extremely well. This is because GZ CMa is a detached system with two nearly spherical and nearly identical stars, so the ***mass centers*** approximation to reality is very adequate.

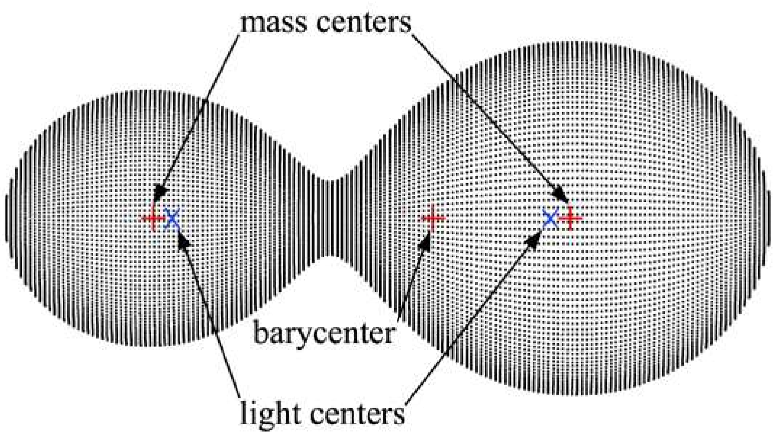
With spherical stars the center of light coincides with the mass center of the stars (e.g., GZ CMa), but with non-spherical stars (overcontact binaries in the extreme) the light centers are both closer to the barycenter of the system. When the light centers radial velocity curves for GZ CMa are added to the graph (black crosshairs for the secondary star and black squares for the primary), it can be seen that they are nearly identical to the red mass centers curves, as shown below:



GZ CMa radial velocity curves with light centers points added (black squares for primary star, black crosshairs for secondary)

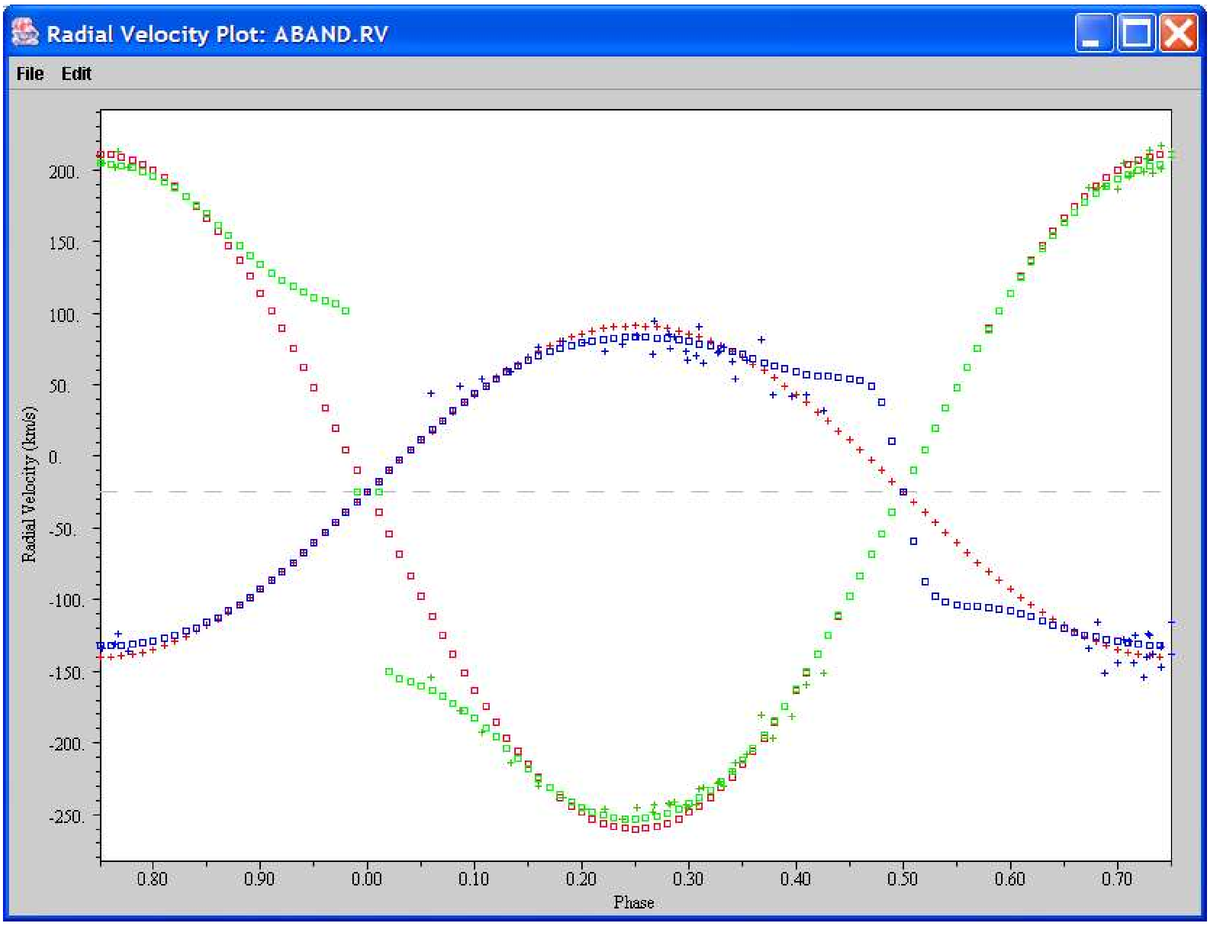
Although very close to the ***mass centers*** curves, the light centers curves are <u>not</u> exactly the same. They deviate slightly in the quadrature phases (0.25P and 0.75P) and especially around the eclipses (phases 0.00P and 0.50P). Note the strange bump in the primary's light center curve near 0.00P and a similar strange bump in the secondary's curve around 0.50P. This bump is known as the *Rossiter effect* and will be explained below.

The mass centers approximation does not take into account the fact that the stars can be ellipsoidal nor does it take into account eclipse effects which show up because the stars are rotating about their respective axes as well as revolving about the barycenter. Let's first address the non-spherical issue. When a star is large relative to its inner Lagrangian surface, it becomes roughly ellipsoidal in shape due to tidal forces between the two stars. What this does to the star's light output is to shift its ***light center*** towards the barycenter because of the star's elongated shape. Consider the diagram below which shows the mass centers and light centers for the overcontact binary AB And:



AB And showing the barycenter and the difference between ***mass*** and ***light centers***

The ***light centers*** will naturally have smaller radial velocities because they are closer to the barycenter, and therefore the amplitudes of the observed radial velocity curves will be slightly less than those predicted by the ***mass centers*** theoretical radial velocity curves. This can be seen in the comparison of AB And's observed versus light centered and mass centered radial velocity curves plotted below:

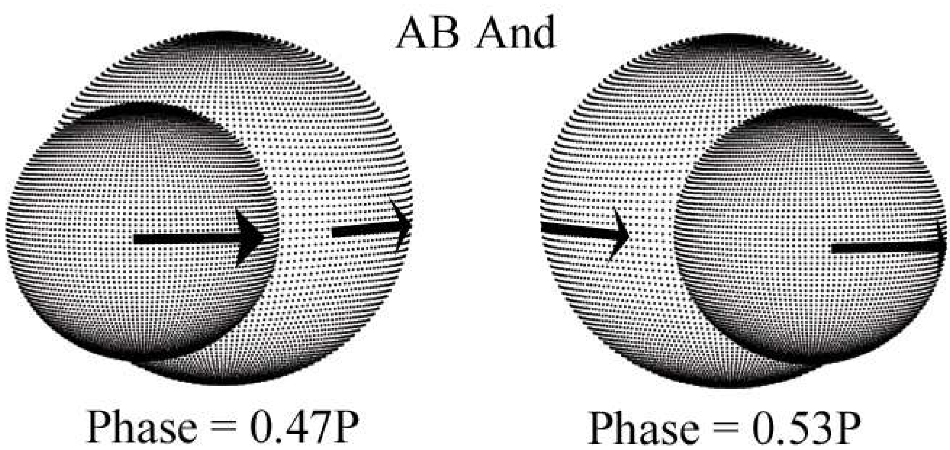


Observed and theoretical radial velocity curves of AB And: blue crosshairs are the primary observed data, blue squares the theoretical ***light centers*** curves; green crosshairs are the secondary observed data green squares the theoretical ***light centers*** curves. The red crosshairs are the primary's theoretical ***mass centers*** radial velocity curve, the red squares the secondary's theoretical ***mass centers*** curves.

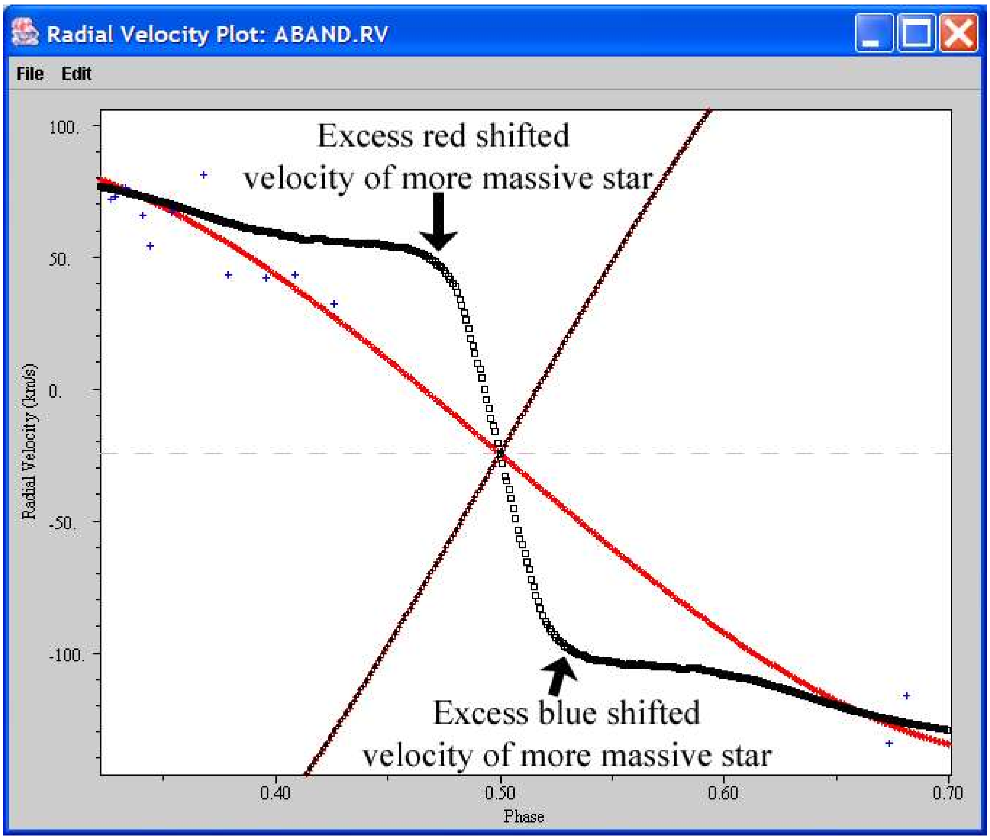
Although a very busy diagram, the above plot demonstrates that the light centers theoretical curves (blue and green squares) fit the data and they are smaller in amplitude than the mass centered curves (the red crosshairs and red squares).

Also note the strange divergences near the eclipses (phases 0.00P and 0.50P) first noticed in the plot of GZ CMa's radial velocity data. What is causing this strange perturbation from the mass centered curves? This is caused by the fact that at the eclipses one of the stars is being hidden as its companion crosses in front of it. It is the way in which the star is being hidden that is causing an increase in apparent radial velocity known as the ***Rossiter effect***. Let's look at what's happening in more detail.

Consider the views of AB And at phases 0.47P and 0.53P shown below:



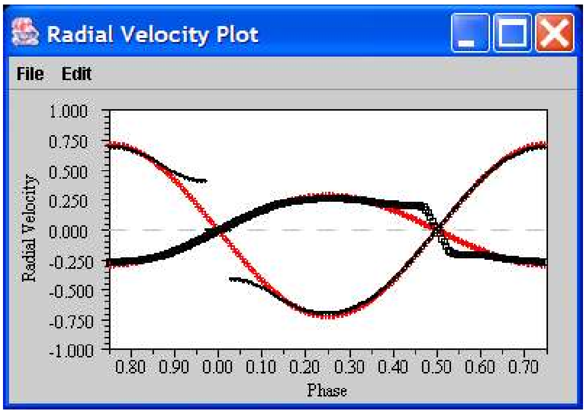
Remember that the stars are revolving and rotating simultaneously. If a star is rotating and its disk is entirely visible (like the smaller star in front in the figure above for AB And), one edge (here the "left" edge) is "approaching" us and the other (right side) is receding. The light coming from the approaching side will be blueshifted (wavelength shortened) and the light coming from the receding side will be redshifted (wavelength lengthened). If both sides are visible, these Doppler shifts are essentially equal and merely broaden the spectral features. But, if one of the stars is eclipsed, then the light from the side that is eclipsed will not be seen, leaving an unequal amount of Doppler shifted light coming from the unblocked side of the star. So, returning to AB And at phase 0.47P, the smaller star is blocking the approaching side of the larger star which would have emitted blueshifted light because of its rotation. However the receding limb of the larger star is still mostly visible so its redshifted light will still be contributing to the spectral features. Therefore the lines of the more massive star will be preferentially increased in redshift (velocity of recession) as is seen at near phase 0.47P in the above radial velocity plot and the zoomed in version of this plot centered near the secondary eclipse.



Close up view of the Rossiter Effect for AB And around secondary eclipse 0.50P

Similarly, after secondary eclipse (phase 0.50P), the approaching limb of the larger star is being revealed while the receding limb is being covered up. This reverses the process so that now the spectral features of the more massive star will be preferentially blueshifted because of the approaching limb, and this is exactly why the radial velocity points are more negative. The same phenomenon occurs with the less massive star at the primary eclipse (0.00P).

In the absence of velocity semiamplitudes and a systemic velocity, only dimensionless synthetic radial velocity curves ("normalized" radial velocity curves) can be drawn which contain the factor P/(2 π a), where **P** is the period of the binary and **a** is the semimajor axis. A typical synthetic radial velocity plot might look like the following:



Normalized radial velocity curve for the overcontact system AE Phe which had no observed radial velocity data as of 2004

Note that the scale goes from -1 to +1 with the systemic velocity set at zero. To convert normalized radial velocities into actual velocities you would need to know the velocity semiamplitudes K_1 and K_2 as well as the systemic velocity V_o. The conversion equation is:

$$\text{radial velocity (km/s)} = (\text{normalized radial velocity})(K_1 + K_2) + V_o$$