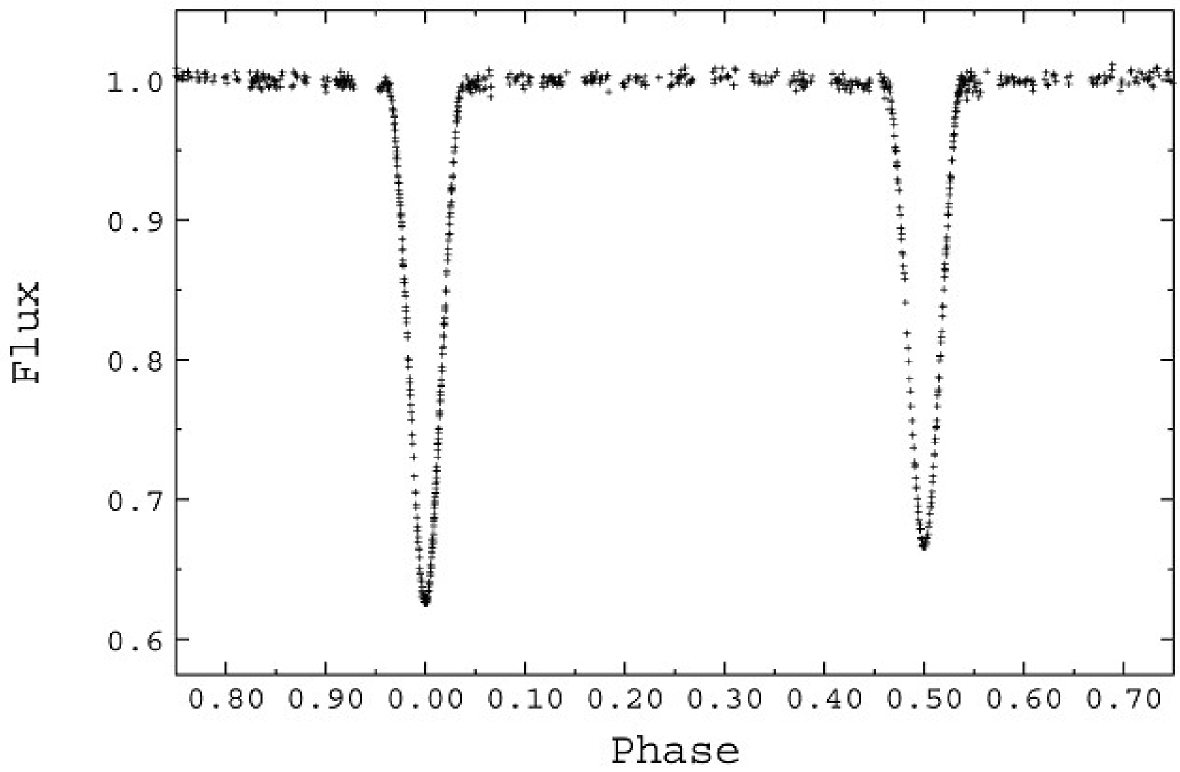
Rudiments of Light Curve Analysis - Part I

If you become familiar with the different shapes of eclipsing binary light curves, you will usually be able to quickly hone in on a reasonable solution using ***Binary Maker 3***. The key is in understanding why different types of binaries exhibit different shaped light curves, as well as understanding exactly what each light curve parameter does in the creation of a synthetic light curve. We will begin with showing sample light curves of the various binary types listed above and explaining why the light curves appear as they do. We will also initially limit our discussion to circular orbit systems.

Typical detached binaries consist of relatively spherical stars, and hence as they revolve about each other the light level remains fairly constant and so the out of eclipse light variation will be quite small. Let us look at the *b* (Strömgren blue) light curve of GZ CMa from Andersen *et al.* (1985), shown below:



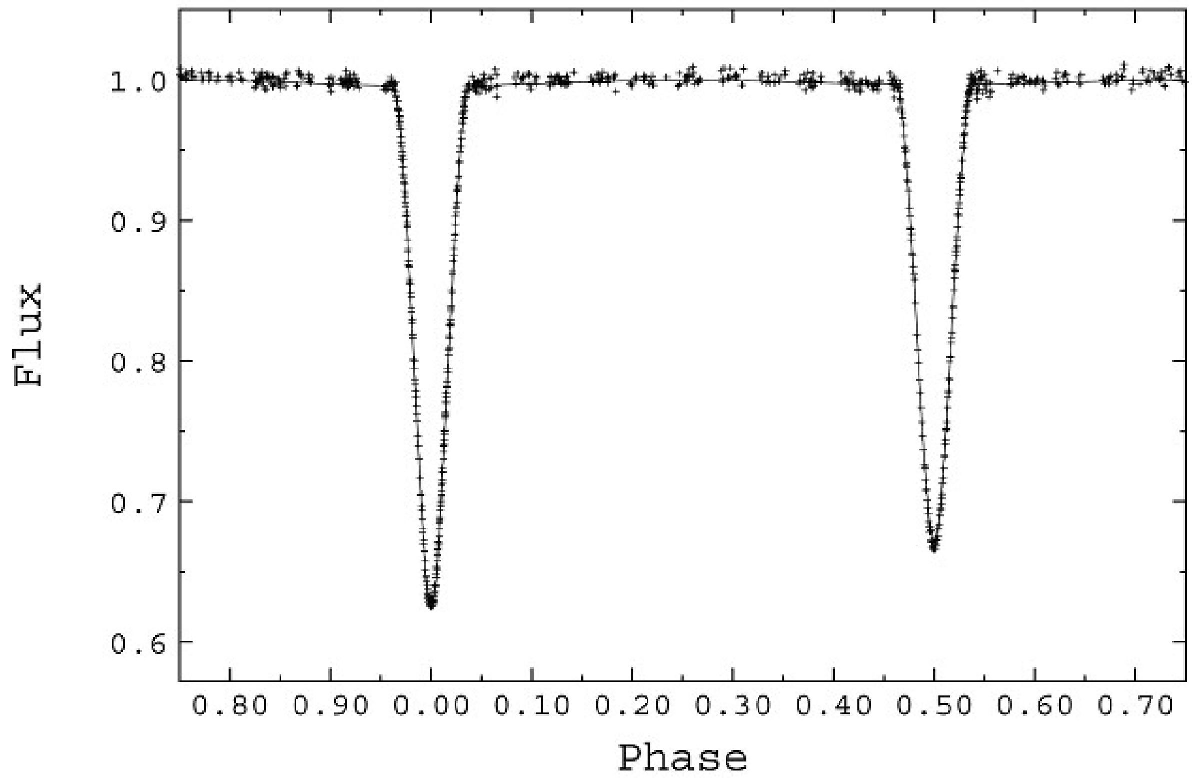
b (Strömgren blue) light curve of GZ CMa from Andersen *et al*. (1985)

The out of eclipse light level is indeed mostly constant, and the eclipses are well-defined and sharp, indicating that the stars eclipse each other partially or that the stars are the same size and shape (spheres). The difference in depths is mostly due to the fact that the stars must possess different surface temperatures. This makes sense because, for circular orbit systems, the amount of surface area eclipsed at both eclipses must be the same. Therefore, since the same area of star's surface is blocked at the eclipses, the difference in light loss must be primarily due to a difference in surface temperature. In other words, when the hotter component is eclipsed, you will lose more light than when the cooler component is eclipsed. So, in the case of GZ CMa, the deeper eclipse is caused when the cooler star blocks the hotter star. The width of the eclipses is a function of the sizes of the stars as well as their orbital inclination. The greater the inclination the wider and deeper the eclipses will be.

To begin the analysis of a light curve, one needs as much information about the binary as possible. Especially useful is a color index or spectroscopic classification because either will allow an approximate temperature designation for the stars. Once an approximate temperature has been established, limb darkening coefficients can also be determined from the appropriate tables for the effective wavelength of the observations. Prior to 1993 the tables published by Al-Naimy (1978) were widely used and they are included in the Appendix of the User Manual. Van Hamme (1993) published completely revised modern limb darkening coefficients based upon Kurucz (1991) model atmospheres. A portion of these tables for commonly used bandpass filters can be found here and is also included in the Appendix in the User Manual through the kind permission of Dr. Van Hamme.

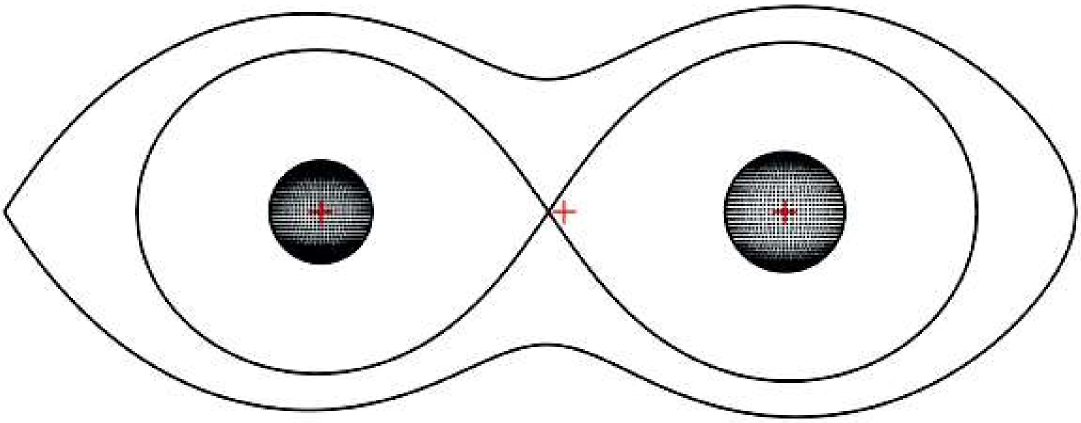
Perhaps the most elusive parameter is the mass ratio. For partially eclipsing systems the direct determination of this parameter is quite problematic because many different mass ratios can be used with various other parameters to mimic the observed light curves. A spectroscopic mass ratio is needed in order to pin down the mass ratio of partially eclipsing systems, as well as to allow the direct calculation of the absolute parameters of the binary (masses, radii, etc.). If you do not have a spectroscopically determined mass ratio but the system exhibits a total eclipse, then it is possible to determine a fairly reliable mass ratio because of the constraints inherent in a total eclipse (*i.e.*, the length of totality puts severe constraints on the relative sizes of the stars).

If the binary has no radial velocity curve and is partially eclipsing, then the best one can do is to make a series of models with a range of mass ratios (q) and plot the residuals for each fit versus the mass ratio used for that particular fit. This technique, sometimes called the "q-method," is certainly not guaranteed to determine the true mass ratio, but it is the best that can be done in the absence of more information. Certainly for detached systems like GZ CMa the mass ratio cannot be too far from unity since the stars are spherical and about the same temperature with fairly deep eclipses. Fortunately GZ CMa has an excellent radial velocity curve (Popper *et al.* (1985)) and a well-determined spectroscopic mass ratio of 0.909. Armed with this and color indices indicating surface temperatures close to 8500 º K, one can quickly converge to an excellent model for this system by trying different radii and inclinations until the light curve is closely approximated. The solution given by Popper *et al.* (1985) is shown below:



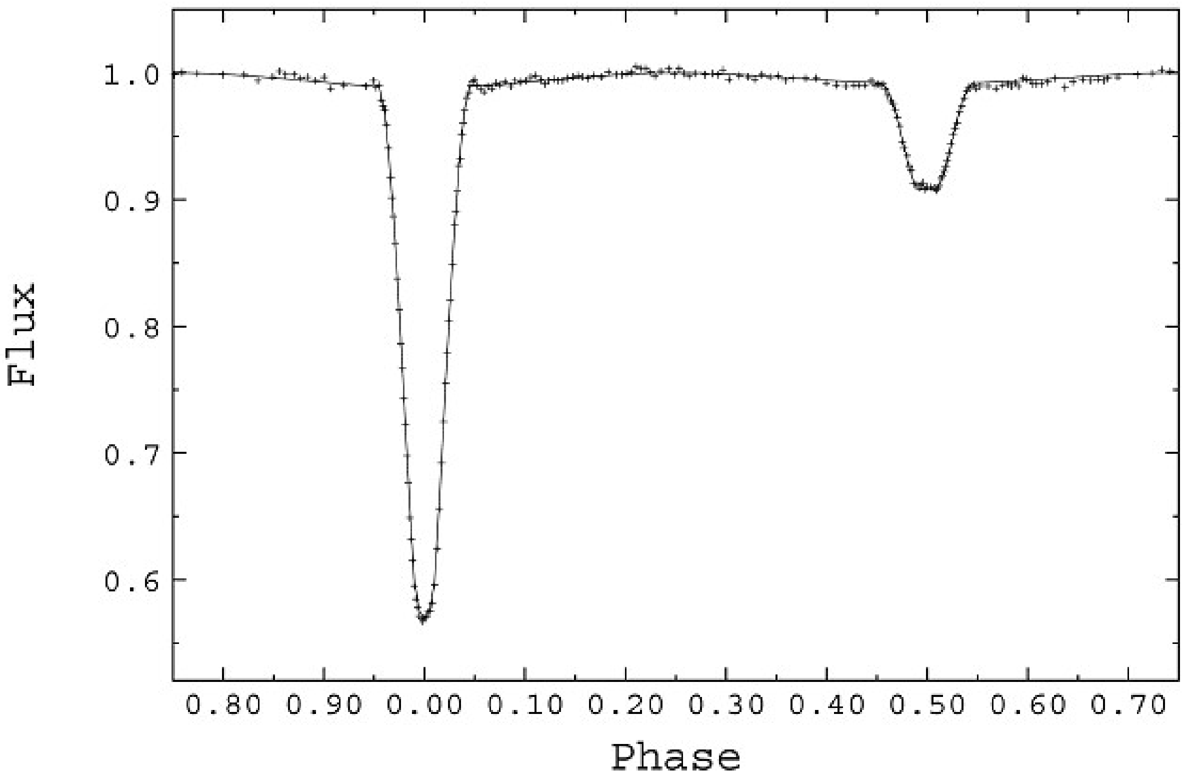
Solid curve represents the solution given by Popper *et al.* (1985) for the *b*-light curve of GZ CMa

The final parameters themselves can be found in the **Zip** archives of ***Binary Maker 3*** as well as on the **Catalog and Atlas of Eclipsing Binaries** (**CALEB**) at http://caleb.eastern.edu. The relative sizes of the stars and their inner and outer critical lagrangian surfaces are shown below. Note that the stars are well within their inner Lagrangian surface and therefore they are nearly spherical, hence the lack of out of eclipse light variation.



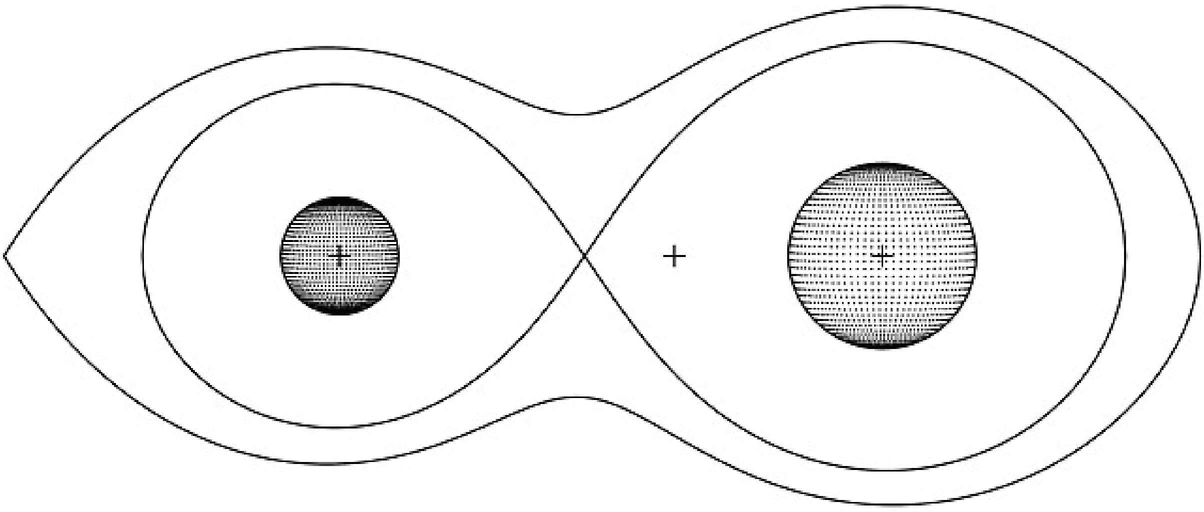
Components of GZ CMa relative to each other and their inner and outer critical Lagrangian surfaces. The plus sign between them is the barycenter (center of mass).

Let us explore another detached binary, EE Peg, whose *B* light curve from Ebbighausen (1971) is shown below. This system is not only obviously detached (as evidenced by its relatively flat out of eclipse light curve) but its components possess very different surface temperatures as seen from the large difference in eclipse depths. The secondary eclipse is also total, which again greatly constrains the model.



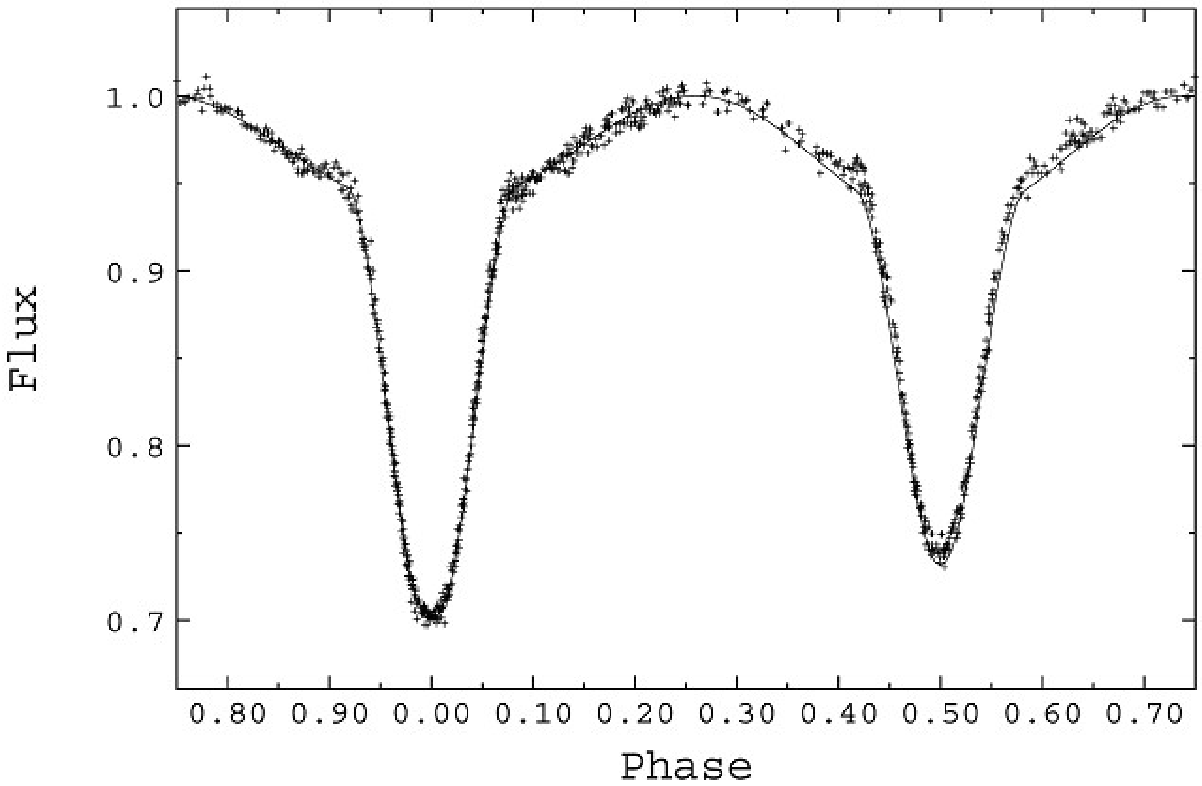
*B*light curve from Ebbighausen (1971) and solution (solid curve) of EE Peg from Lacy & Popper (1984)

These stars are also mostly spherical, but less spherical than GZ CMa, and the out of eclipse light variation is more evident than in the light curve of GZ CMa. The stars of EE Peg are shown below with respect to their Lagrangian critical surfaces. Note that the larger, more massive and hotter star is slightly more ellipsoidal than the larger component of GZ CMa and causes most of the out of eclipse light variation seen in the light curve.



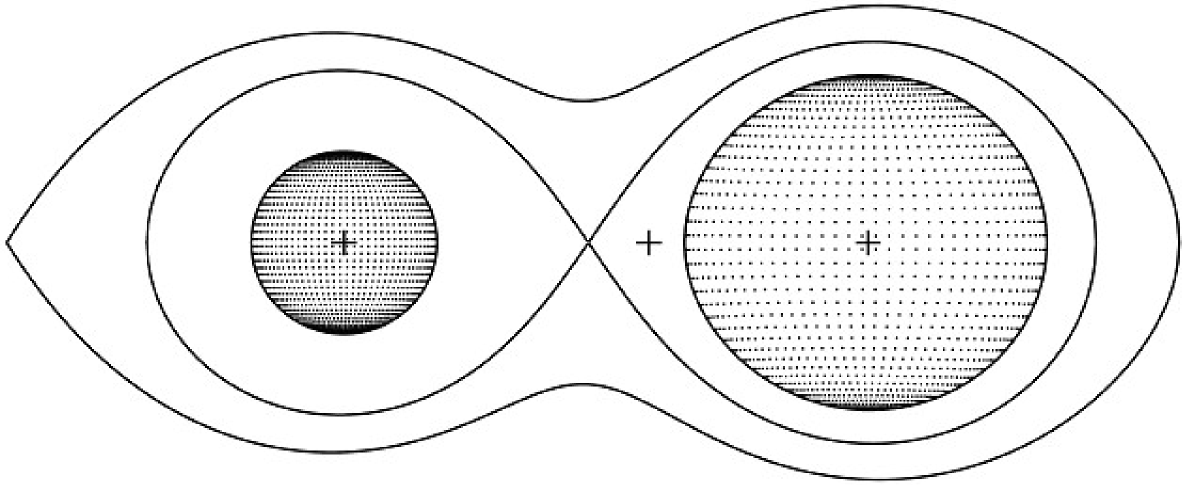
Components of EE Peg relative to each other and their inner and outer critical Lagrangian surfaces. The plus sign between them is the barycenter (center of mass).

If the stars are closer together and/or their surfaces are in close proximity to the inner Lagrangian surface, their shapes will begin to distort roughly into ellipsoids. Thus, because the stars are "football" shaped, their light curves will vary continually even when not eclipsing because their visible cross-sectional areas will be continually changing. We expect the out of eclipse portions of the light curve to not be flat but varying in flux, as seen in the close binary system NN Cep whose light curve from Güdür *et al.* (1983) is shown below:



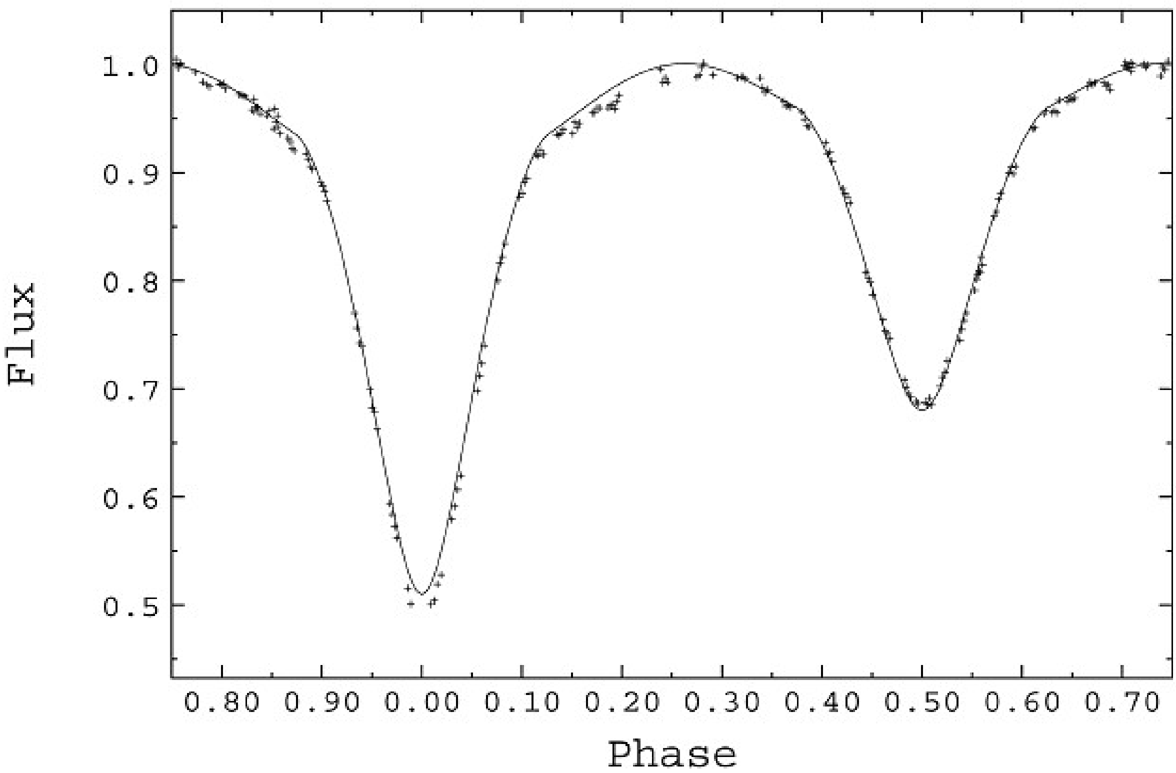
V light curve of NN Cep from Güdür *et al.* (1983) with synthetic model shown as the solid curve

The model of NN Cep from Güdür *et al.* (1983) is shown below where the larger component is fairly close to its inner critical surface and the smaller component is also close and therefore both stars are distorted from spheres and create varying light levels even out of eclipse.

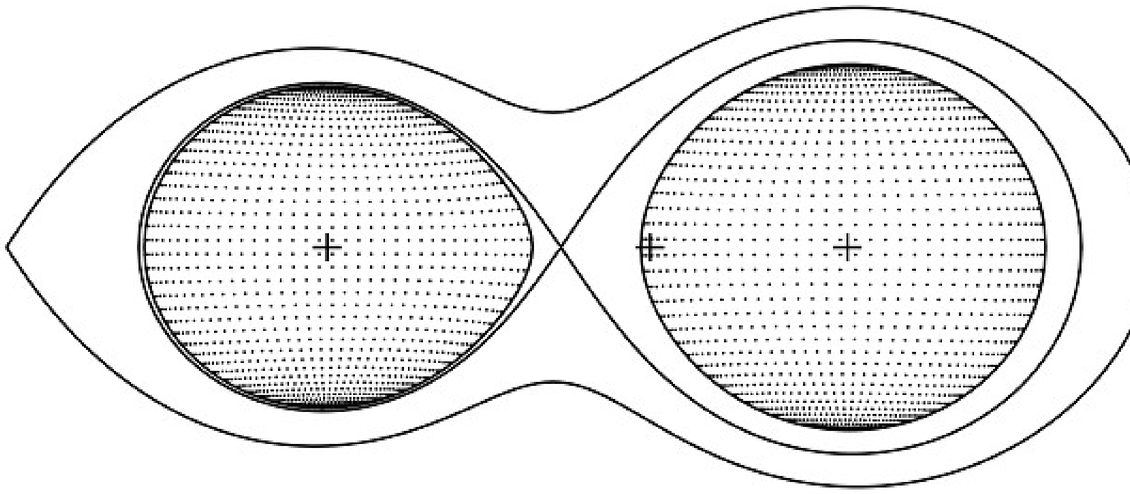


Critical surfaces and model of NN Cep: both stars are relatively close to their inner critical surfaces, resulting in non-spherical stars and subsequent out of eclipse light variations

Another system where both stars are very close to their inner critical surfaces is AI Cru, whose light curve from Bell *et al*. (1987) is shown below and the model of the system itself is shown below that:



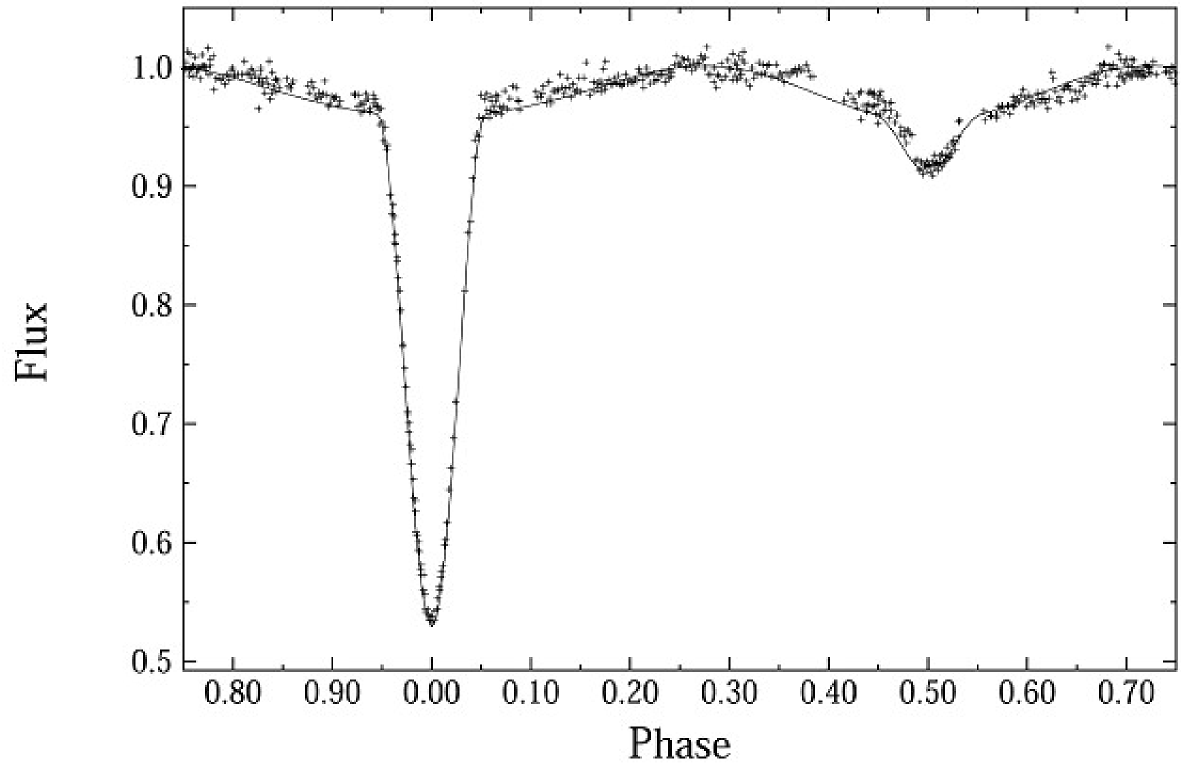
y light curve of AI Cru and synthetic light curve (solid curve) from Bell *et al*. (1987)



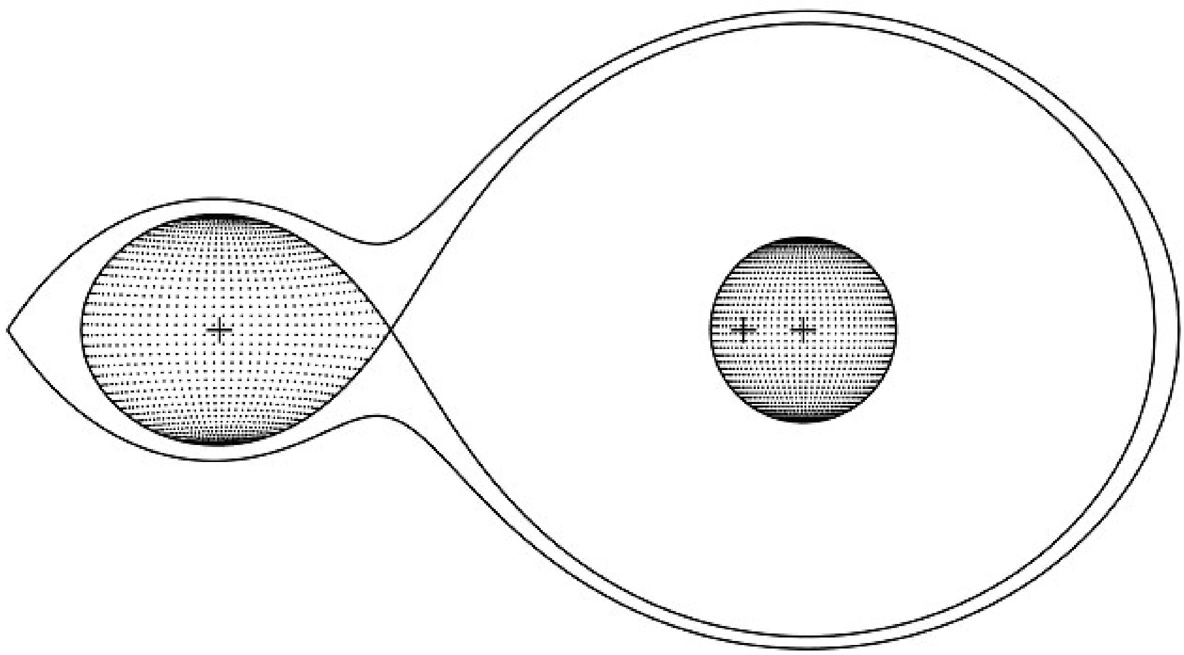
Critical Lagrangian surfaces and model of AI Cru

Note that the light curve of AI Cru is reminiscent of NN Cep except that the eclipse depths are more dissimilar in AI Cru and the widths of the eclipses are wider. Thus the stars of AI Cru must be both fairly different in temperature (different eclipse depths) as well as much larger stars relative to each other (to explain the longer eclipse durations).

What will happen if one of the stars reaches its inner Lagrangian critical surface before its companion (as usually happens)? The star that reaches its inner Lagrangian critical surface first is the more massive star and gas from it will be dumped onto its companion beginning a mass transfer that will ultimately lead to an ***Algol*** system. The current less massive star (originally the more massive star) is in contact with its inner critical surface and the now more massive component is typically a main sequence star, usually well within its inner critical surface. The stars are said to be a ***semi-detached*** system. This strange situation, where the more massive star of the system is the less evolved component, is known as the ***Algol Paradox***. A typical Algol system, AS Eri, is shown below and its critical surfaces and model are also shown below.



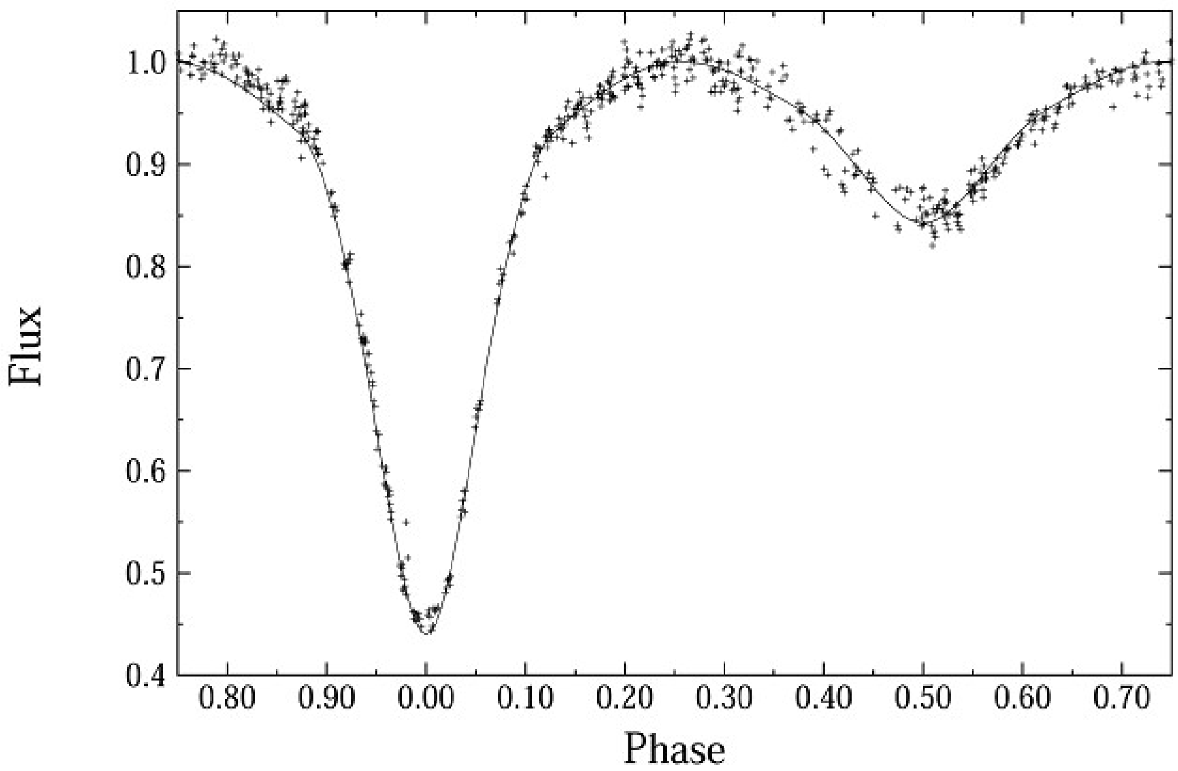
V light curve (Koch 1960) and synthetic model (solid curve) (Van Hamme & Wilson 1984) of AS Eri



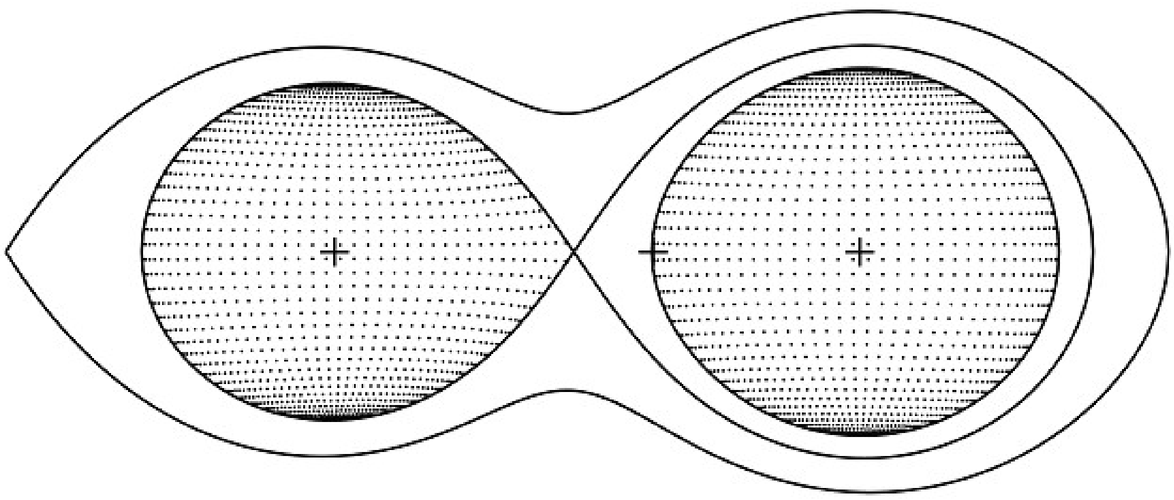
Critical Lagrangian surfaces and model of AS Eri

The large difference in eclipse depths, typical of Algol systems, belies the very large difference in surface temperatures between the main sequence massive star and the much cooler evolved star which is in contact with its inner critical surface.

When one star is in contact with its inner critical surface and its companion is nearly in contact with its critical surface, the binary has been described as a ***near contact*** system. The light curve changes in magnitude throughout the orbit but the stars are usually quite different in temperature, as can be seen in the near contact system AK CMi shown below.

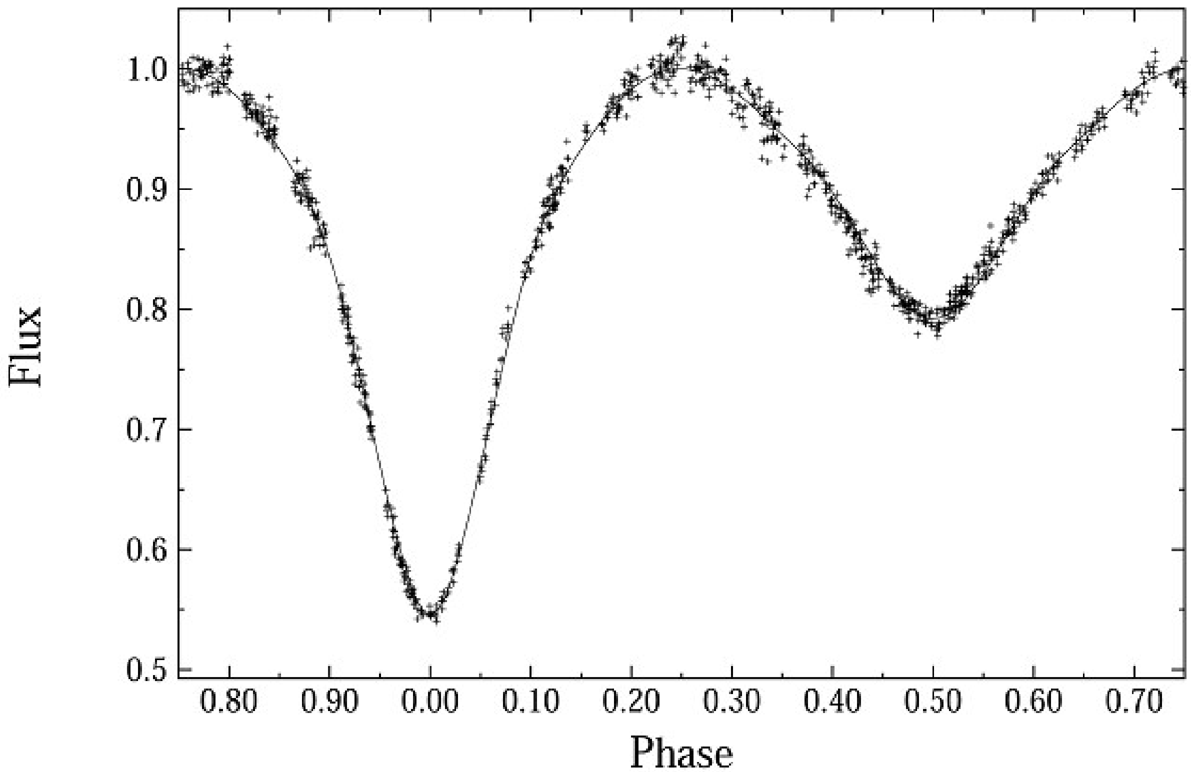


V light curve of AK CMi and solution (solid curve) from Samec *et al.* (1998)

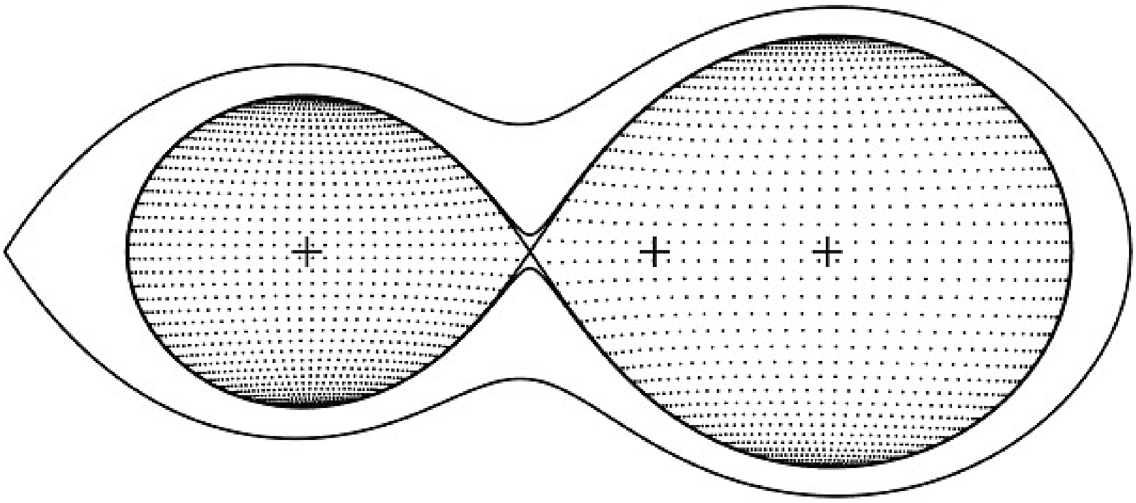


Critical Lagrangian surfaces and model of AK CMi

The next possibility is the ***contact*** system, when two stars both exactly fill their inner Lagrangian surfaces. The stars typically possess considerably different temperatures, and of course because they are very much distorted from spheres, the light levels vary throughout the entire orbit. It is often difficult to distinguish between a near contact system and a contact system, and careful light curve analysis must be used to discern which type the binary is. Usually the temperatures of the stars are not quite as disparate as in a near contact system, probably because the stars are in a stage where the smaller star is beginning to steal energy from the hotter, more massive component as they come into contact. A good example of a contact system is BX And, whose light curve and model are shown below:



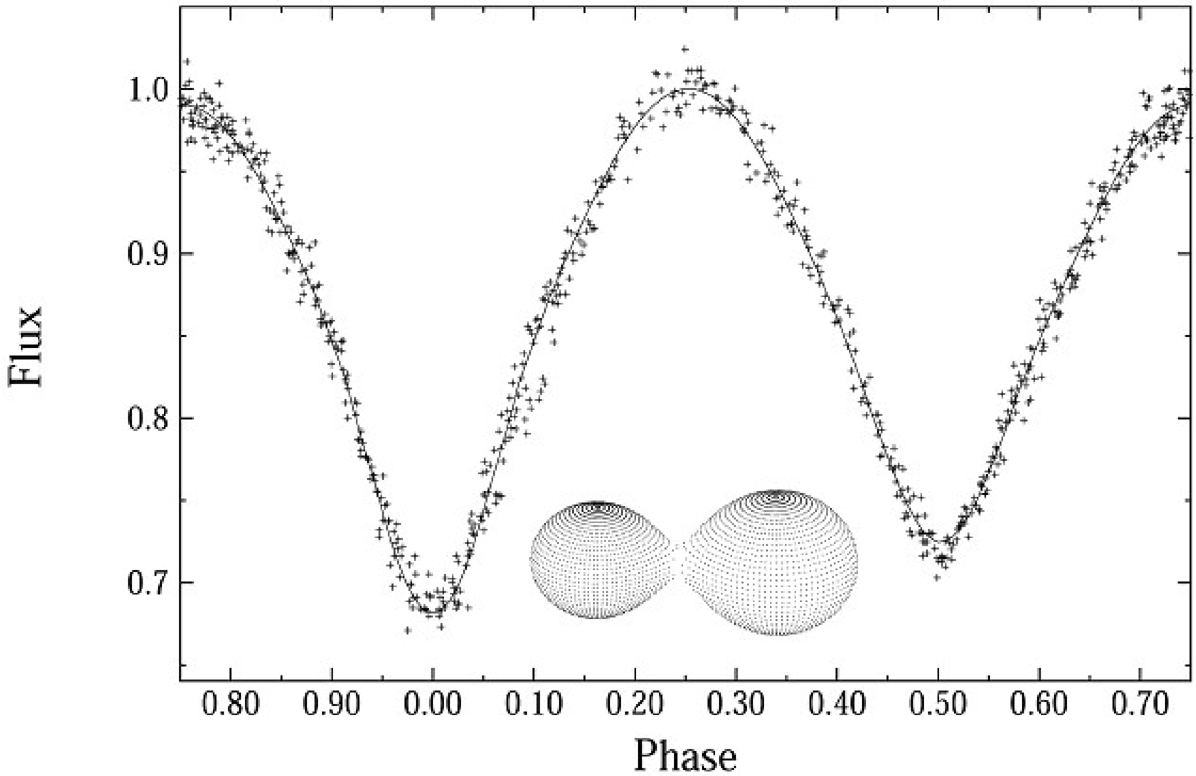
V light curve and solution (solid curve) of BX And from Samec *et al.* (1989a)



Critical Lagrangian surfaces and model of BX And

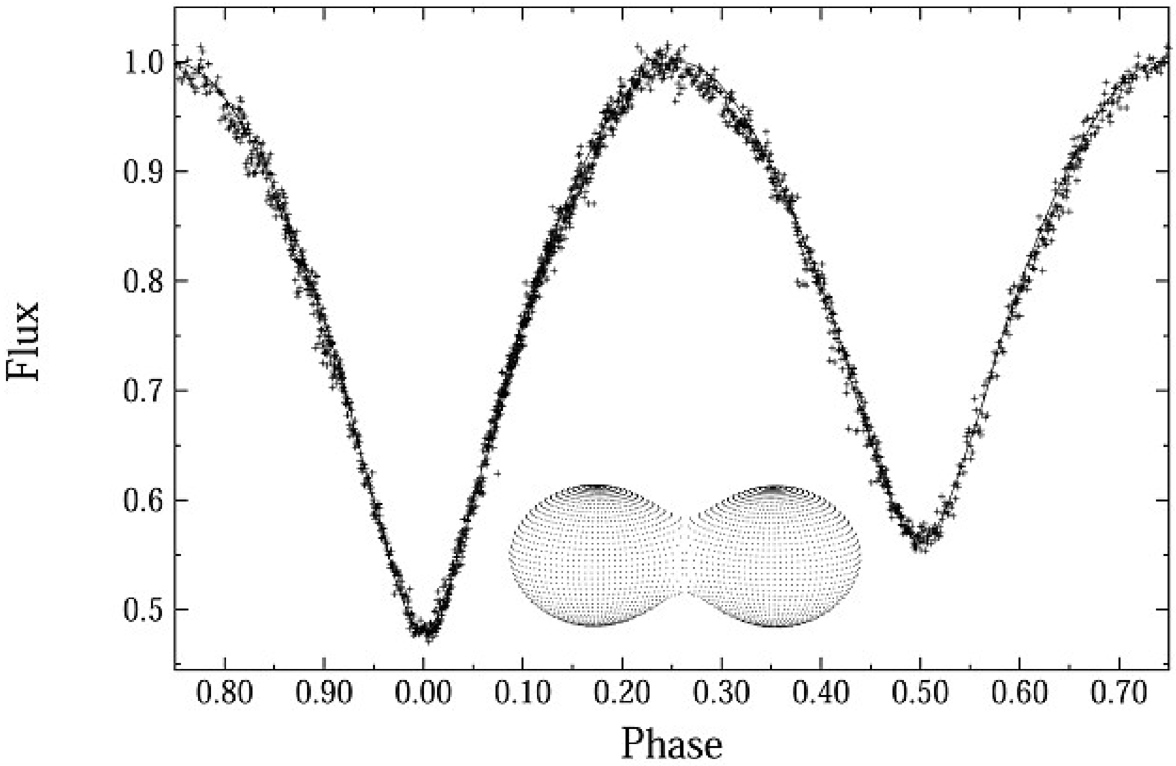
A careful comparison of the light curves of AK CMi (near contact) and BX And will reveal more similarities than differences, the main difference being the greater depth of the secondary eclipse demonstrating that the secondary (less massive, smaller, cooler) star is more nearly the same temperature as the primary (more massive, larger, hotter) star.

It is believed that the stage after contact systems is the ***overcontact*** binary. These stars have been in contact for a long enough period of time such that their surfaces have come into an approximate thermal equilibrium and their surfaces have extended beyond their inner critical surfaces. This results in light curves that are continually changing in the flux level and the eclipse depths are nearly equal because of the nearly equal surface temperatures. Shown below is a typical overcontact binary (fillout = 0.14), AD Cnc (Samec *et al.* 1989), which demonstrates the characteristics of this type of light curve.



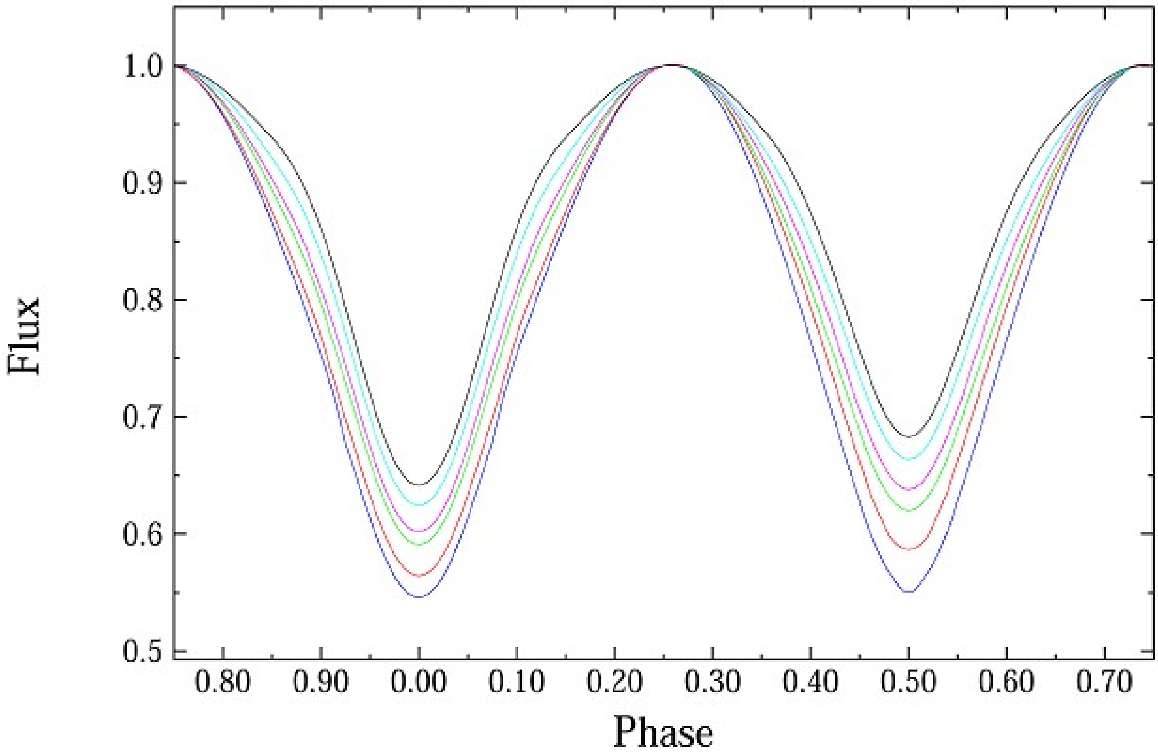
V light curve and solution (solid curve) of AD Cnc (Samec *et al.* 1989b) which has a fillout = 0.14. The system at phase 0.25P is shown below the light curve.

If the shoulders of the eclipses are steeper than AD Cnc, then this is an indication that more light is being cut off more quickly, and this often means that the stars are even more extended beyond their inner critical surfaces, *i.e.*, their fillout is larger than the average value of 0.15 for most overcontact systems (Robertson & Eggleton 1977). This is shown below for AW Lac, an overcontact system with a large fillout = 0.60.



V light curve and solution (solid curve) of AW Lac (Jiang *et al.* 1983) which has a fillout = 0.60. The system at phase 0.25P is shown below the light curve.

The diagram below shows synthetic light curves for a typical overcontact binary (SS Ari - see Kim *et al.* 2003) but for six different values of fillout. The top curve represents a fillout = 0.00 demonstrating broad shoulders and the slowest drop-off in light level. Each successive curve represents an increase in fillout of 0.20 (*i.e.*, 0.20, 0.40, 0.60, 0.80 and 1.00) up to the maximum allowed of f = 1.00. It is easily seen that as the stars increase in size they block off more light and at an accelerated pace as evidenced by the steep eclipse shoulders as the fillout increases. Note that no other binary parameters were changed other than the value of the fillout; the inclination was not changed.



The effect of varying the value of fillout on the shape of an overcontact binary light curve. The top curve shows the system with a fillout = 0.00, and each successive curve has a larger fillout by increments of 0.20 (i.e., 0.20, 0.40, 0.60, 0.80 and 1.00).

Continue on to Light Curve Analysis Part II