Experiment - Eclipsing Binaries: Preliminary Light Curve Analysis

Name ____

Class ____

Lab Section ____

Introduction

The study of binary stars is vitally important in astronomy because it is only by carefully measuring the interactions between stars that we can accurately determine their absolute characteristics such as mass, luminosity, and radius. The determination of the masses of stars is especially critical in astrophysics since we know from the Russell-Vogt theorem that the equilibrium structure of a star is uniquely determined by its mass and chemical composition. Therefore, accurate knowledge of the masses of stars is the very foundation of our understanding of stars and stellar evolution.

Purpose

This experiment is designed to acquaint you with the techniques of light curve analysis of eclipsing binary stars. It is from careful analysis of the varying light from binaries, especially when they eclipse one another, that we infer their different parameters such as mass, temperature, and size. The simplest binary system would consist of two nearly spherical stars in a circular orbit around one another. But there are *many* other more complex and interesting systems that exist. We will be exploring real binary systems using a professional light curve program called ***Binary Maker 3***. After successfully completing this lab you will have an excellent grasp on the fundamental techniques that professional astronomers use to analyze light curves.

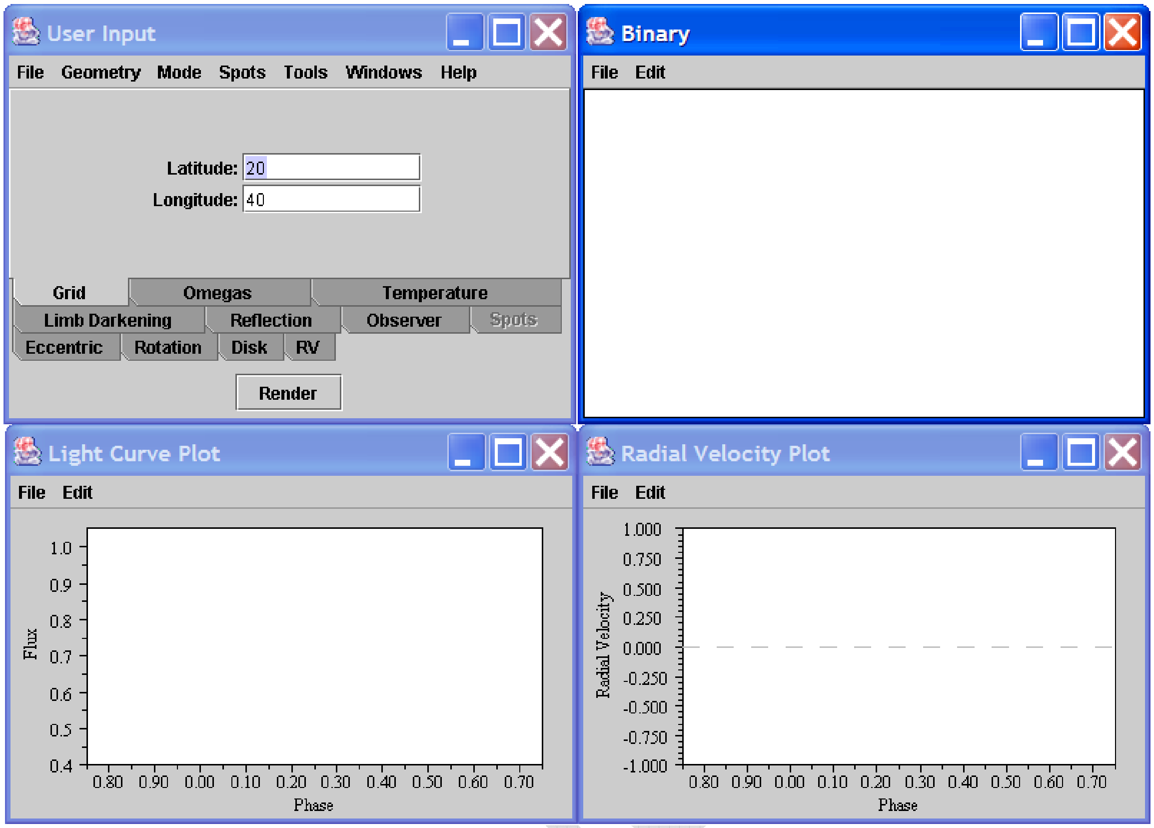
Note

In this lab you will be instructed to perform certain tasks using *Binary Maker 3*. Whenever you are to use the program, the instructions will be numbered and indented.

We will first look at a relatively simple binary system, GZ CMa.

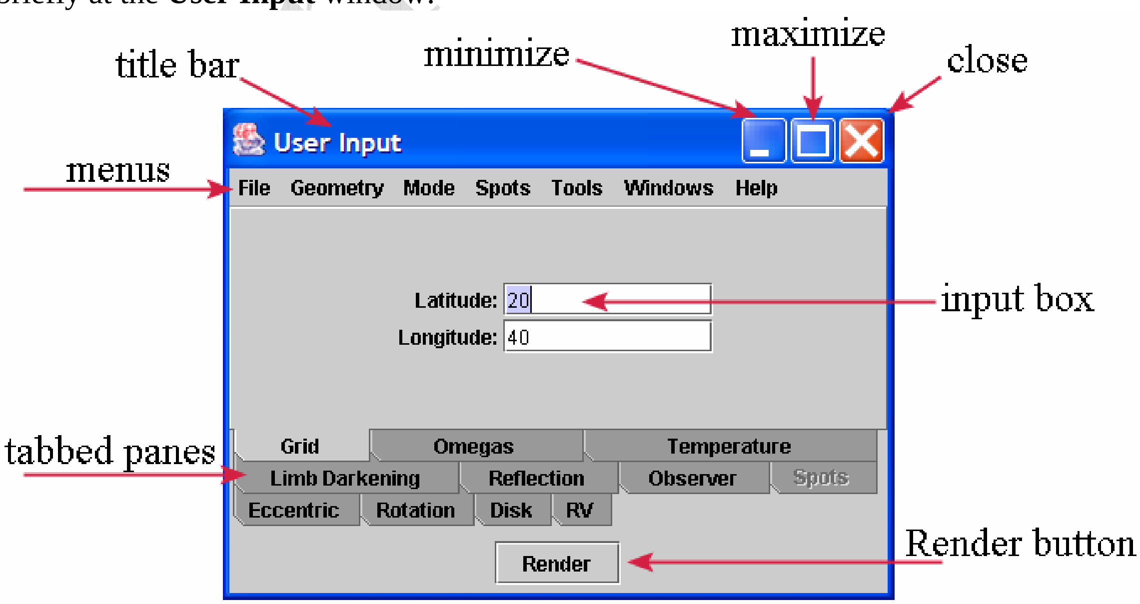
1. To begin ***Binary Maker 3***, double click on its icon on your desktop. The icon looks like this:

After the “splash” title screen is briefly shown, you will be presented with four display windows which will appear something like the following:



Initial screen layout of ***Binary Maker 3***

The four main displays of ***Binary Maker 3*** consist of the **User Input, Binary, Light Curve Plot** and **Radial Velocity Plot** windows. The main windows that you will be using in this experiment are the **User Input** and **Light Curve Plot**. Let's first look very briefly at the **User Input** window:



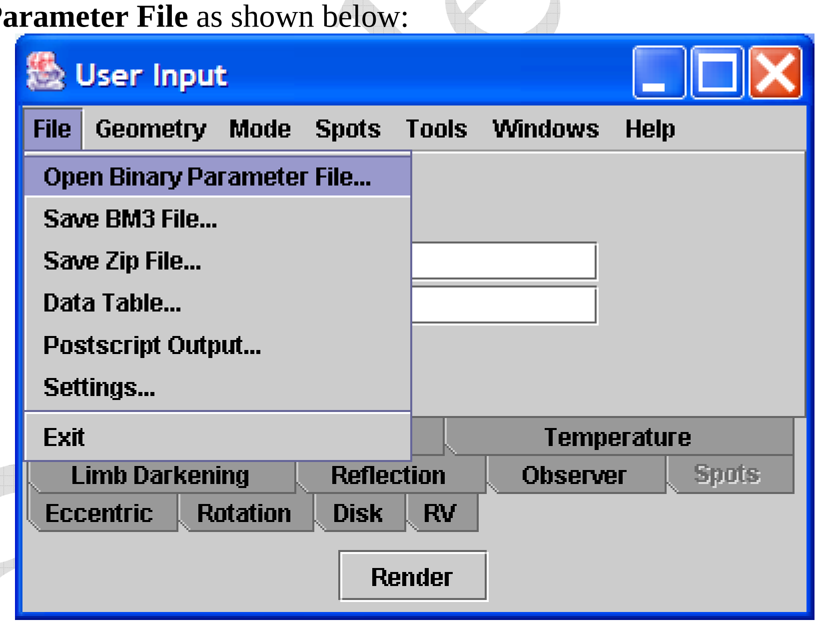
User Input window

Many of the features of the windows in ***Binary Maker 3*** are standard to the majority of windows-based programs. The position of the window on the screen can be moved by clicking with the mouse anywhere within the title bar and, while holding down the mouse button, drag the window wherever you want it. The three buttons in the upper right hand corner of the window are the minimize, maximize and close buttons. Clicking on the minimize button sends the window to the bottom of the screen (taskbar) hidden from view. Clicking on the maximize button fills the screen with that window. Clicking on the close button will exit the program if you are in the **User Input** window. The close buttons on all the other windows in ***Binary Maker 3*** simply hide that window from view and do <u>not</u> exit from the program. The windows can also be resized by clicking on an edge or corner and, while holding down the mouse button, simply move the mouse and the window will automatically resize to whatever size you desire.

The dropdown menus are accessed by clicking on them with the mouse, and the tabbed panes reveal different input boxes for each required binary parameter. Mouse clicking on each tab also accesses these.

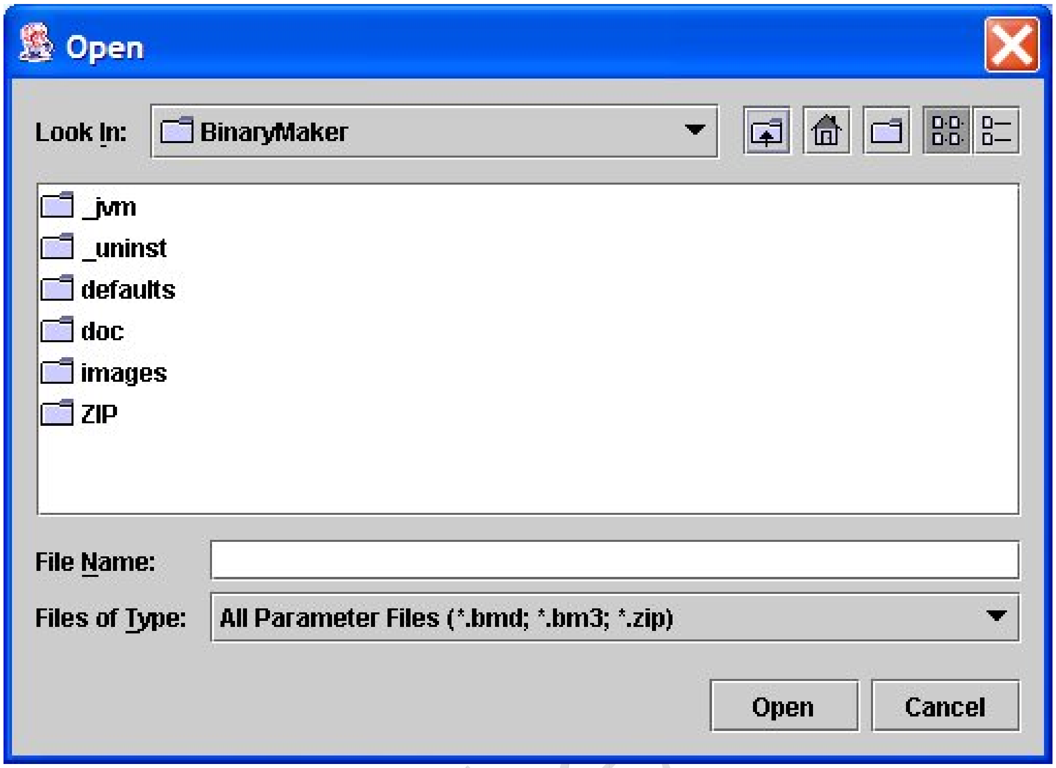
Let's now read in the parameters and observed light and radial velocity curves for GZ CMa.

2. Click on the **File** menu in the **User Input** window, and select **Open Binary Parameter File** as shown below:



Open Binary Parameter File under the **File** menu choice in the **User Input** window

After clicking on **Open Binary Parameter File** the following standard **Open** dialog window will appear:

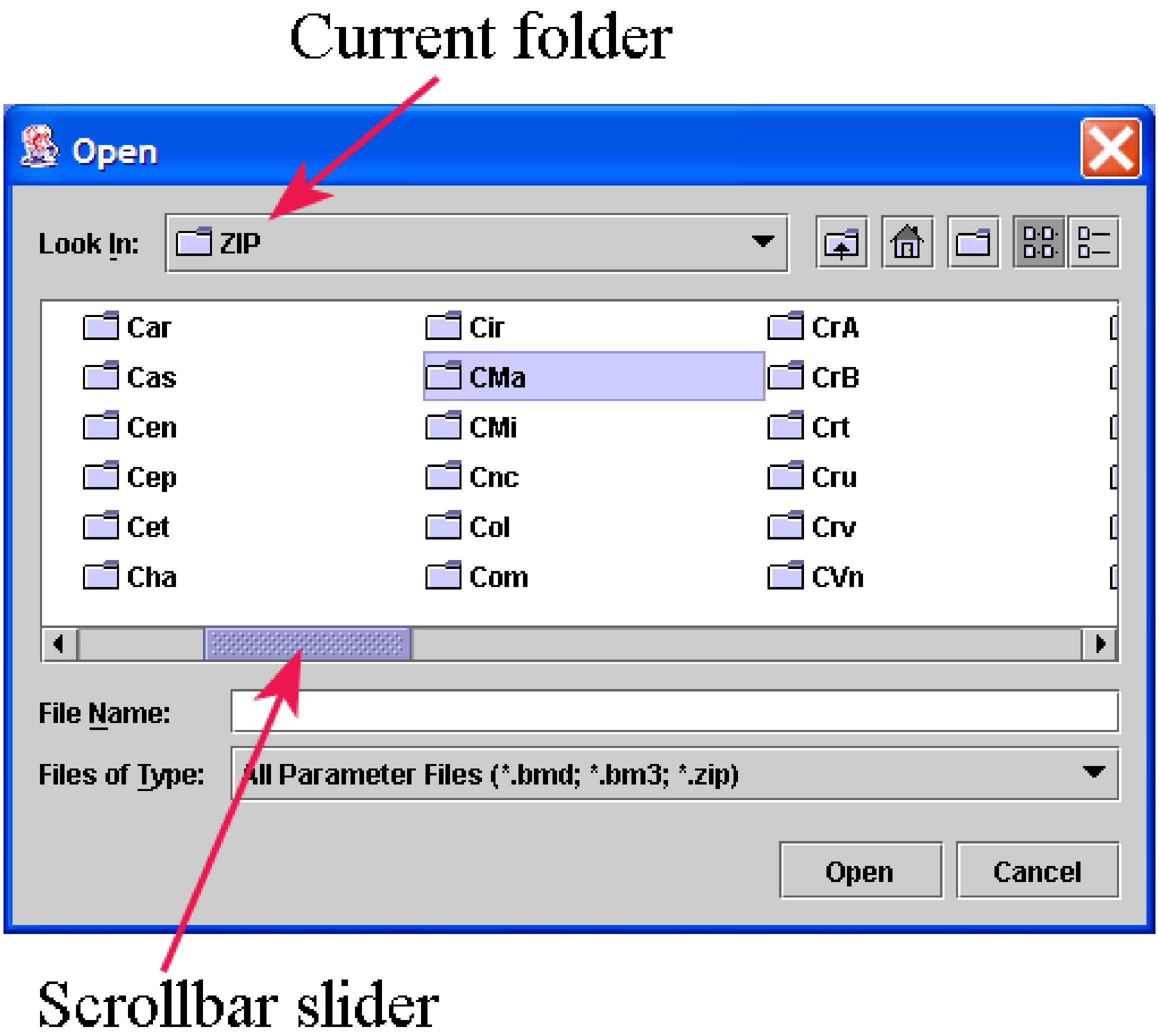


Open dialog

You need to be in the *ZIP* folder which contains all of the parameter and data files, unless told otherwise by your instructor. In the figure above, the **Open** dialog has found itself in the *BinaryMaker* folder, and to proceed to the *ZIP* folder simply double click on the *ZIP* folder itself.

3. Navigate within the **Open** dialog until you are in the *ZIP* folder. (double click on the *ZIP* folder if it is visible; otherwise ask your instructor)

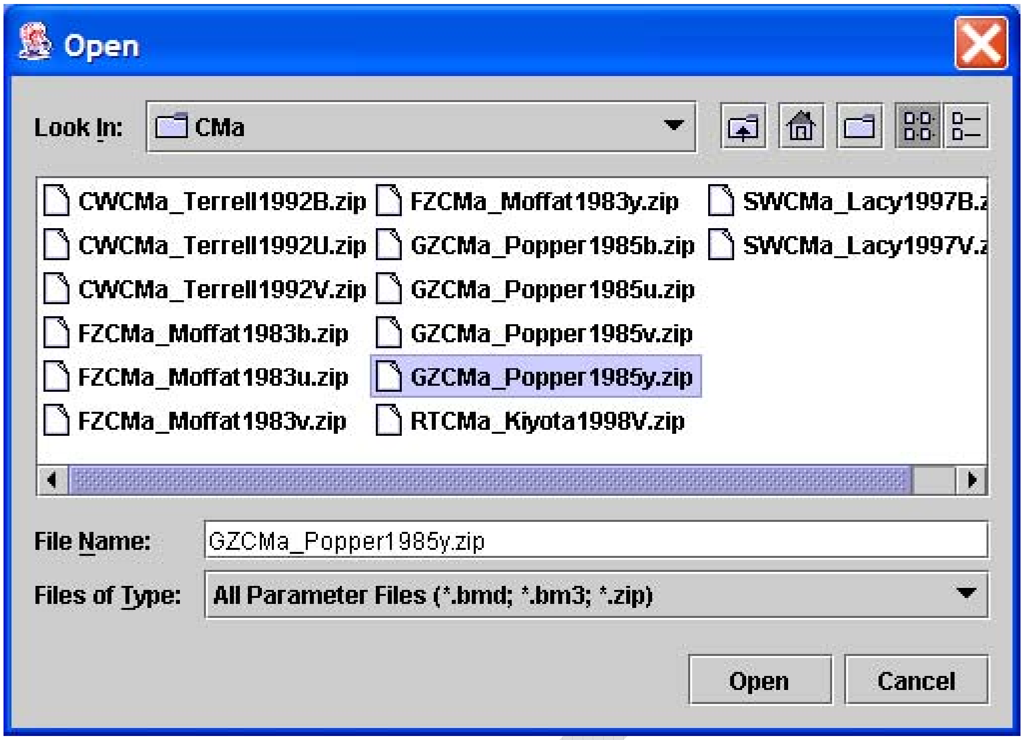
You should now find yourself in the *ZIP* folder with a multitude of folders named with constellation abbreviations, as shown below:



Constellation folders in the **ZIP** folder

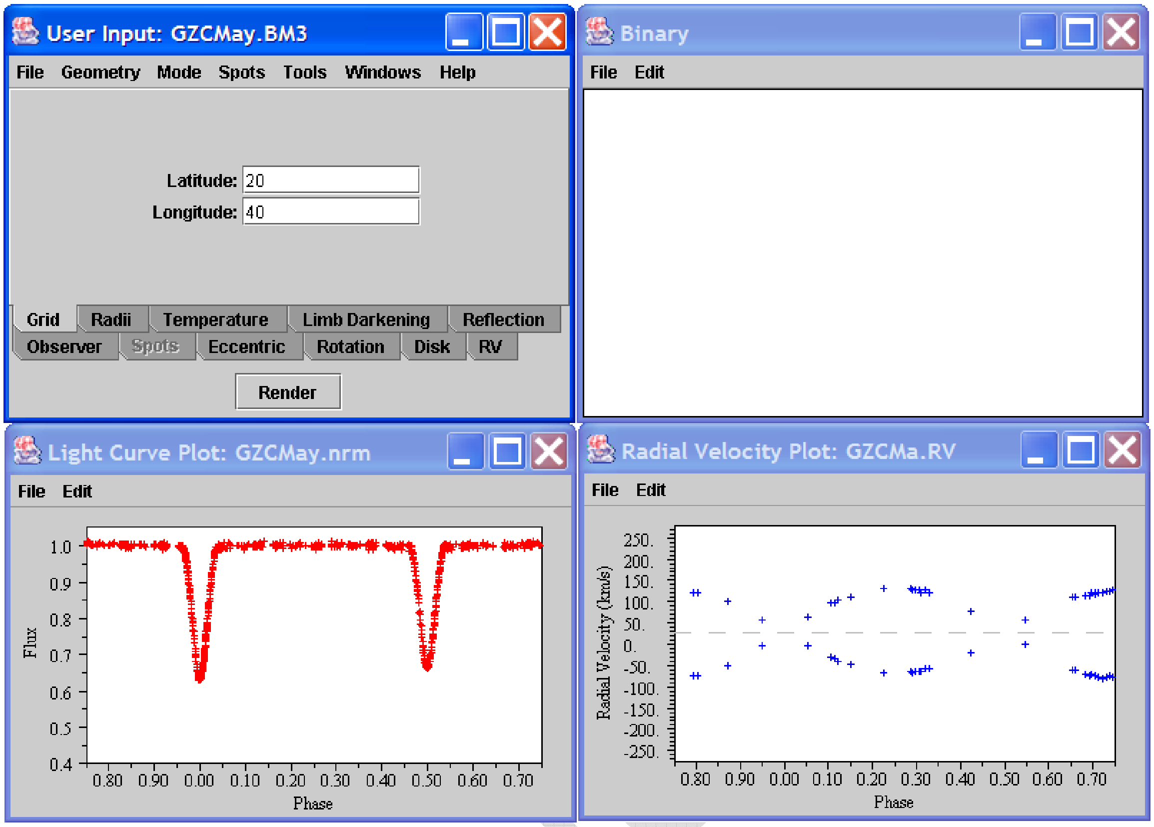
You can move around within the folder by sliding the scrollbar slider left and right using the mouse.

4. Find the folder named **CMa** (Canis Majoris) and double-click on it. Within the CMa folder find the file named *GZCMa_Popper1985y.zip* and click on it (as shown in the figure below). Its name will appear in the **File Name** input box. Click on the **Open** button to read in this file.



Open *GZCMa_Popper1985y.zip* file

The four displays of ***Binary Maker 3*** will now appear something like this:



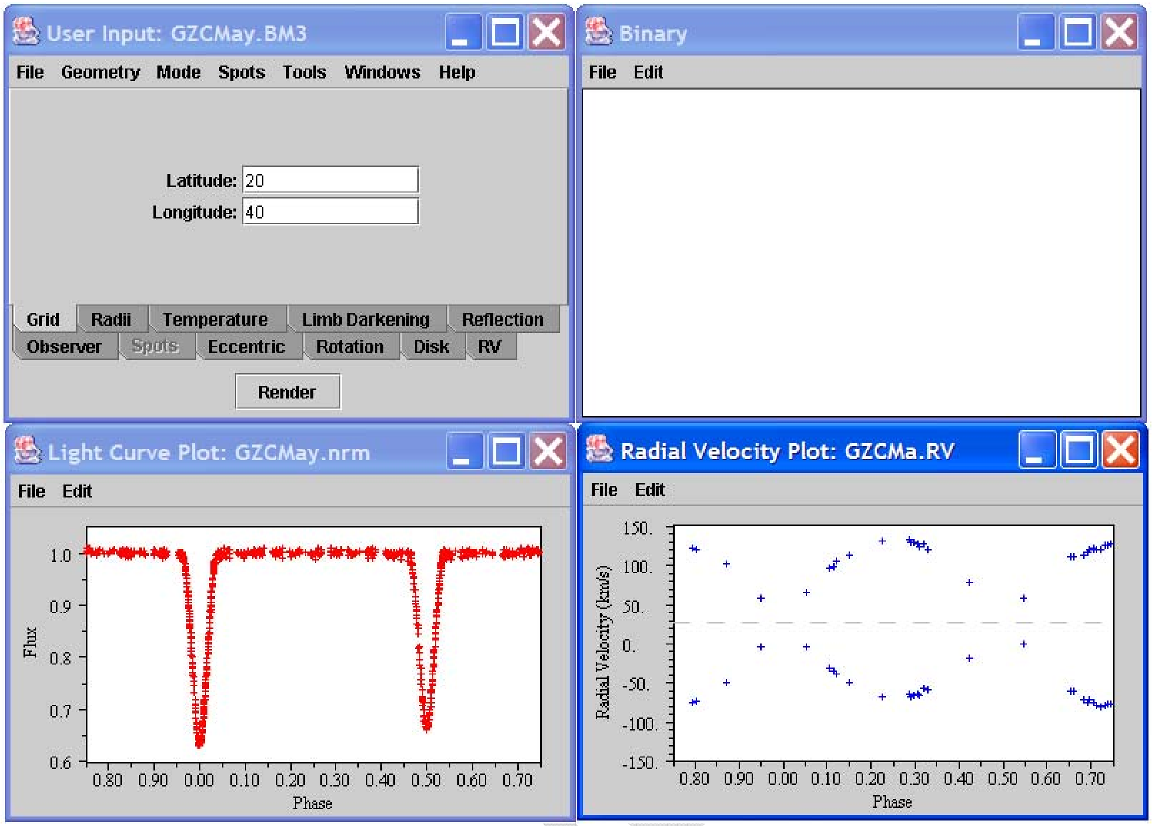
Four screen display after reading in the file *GZCMa_Popper1985y.zip*

The **User Input** window now has the input parameters for GZ CMa in the Strömgren *y* filter. The *y* observed light curve is displayed in the **Light Curve Plot** window, and the observed radial velocity curves are plotted in the **Radial Velocity Plot** window. We can improve the views of the data by rescaling the plots.

5. Move the cursor over the **Light Curve Plot** window and click the mouse once. (This gives the "focus" to this window.) Press the **F1** key (user function key at the top of the keyboard) and you will see the *Flux* (light) scale increase. Successive pressing of the **F1** key will expand the scale. Pressing the **F2** scale zooms out, and pressing **F3** resumes the default scaling. Using these key make the light curve "beautifully" fill the plot display.

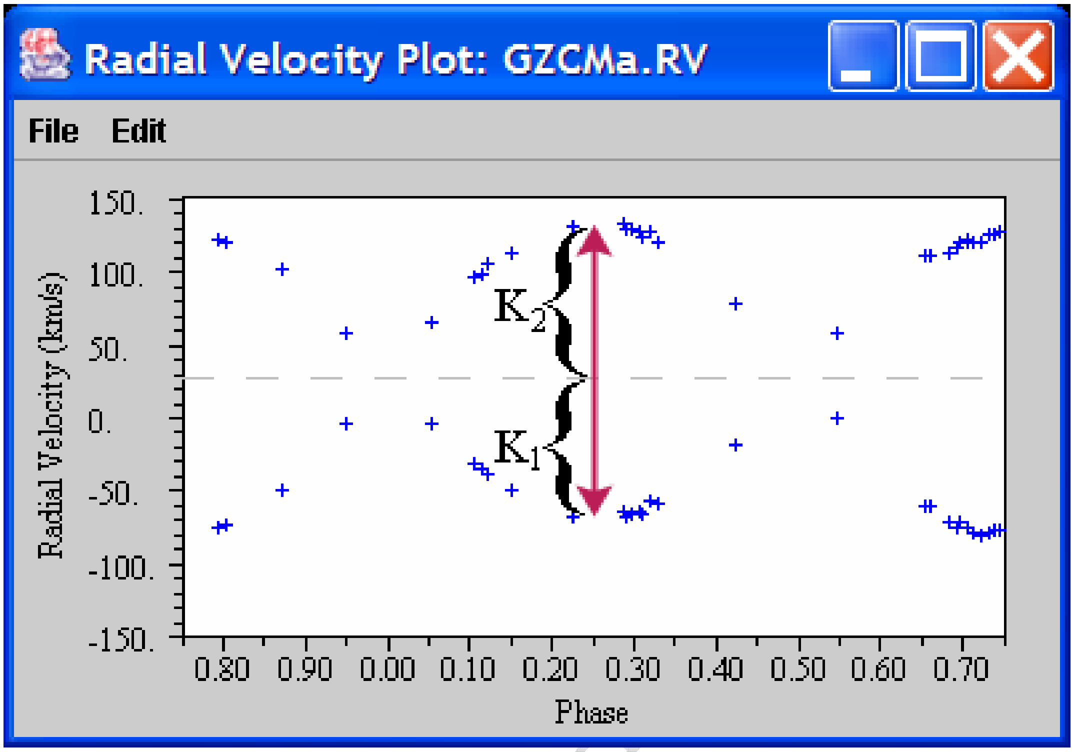
6. Similarly move the cursor over to the **Radial Velocity Plot** window and rescale that plot using the **F1**, **F2** and/or **F3** keys until the data fills the window.

Your windows should now look something like this:



GZ CMa plots rescaled for a better view of the data

The light curve (**Light Curve Plot** window) is a plot of the flux (brightness) of the stars (on the ordinate scale) versus time (on the abscissa scale). In this case the time consists of one orbital period, called the phase, and it goes from 0.00 to 1.00, an interval of time equal to the period of the binary. The brightest part of the light curve is usually defined as being at a flux (brightness) = 1.00. The **Radial Velocity Plot** window depicts the radial velocity curves of the binary that are a mapping of the velocities of the two stars as a function of time (orbital phase). Although we are chiefly interested in studying the light curve in this experiment, it's useful to remember that the ratio of the velocities of the two stars equals the ratio of their masses. Therefore, for GZ CMa, the stars appear to be nearly the same mass because their velocity semiamplitudes are nearly the same about their systemic velocity (velocity of the barycenter - the dashed line on the **Radial Velocity Plot**).



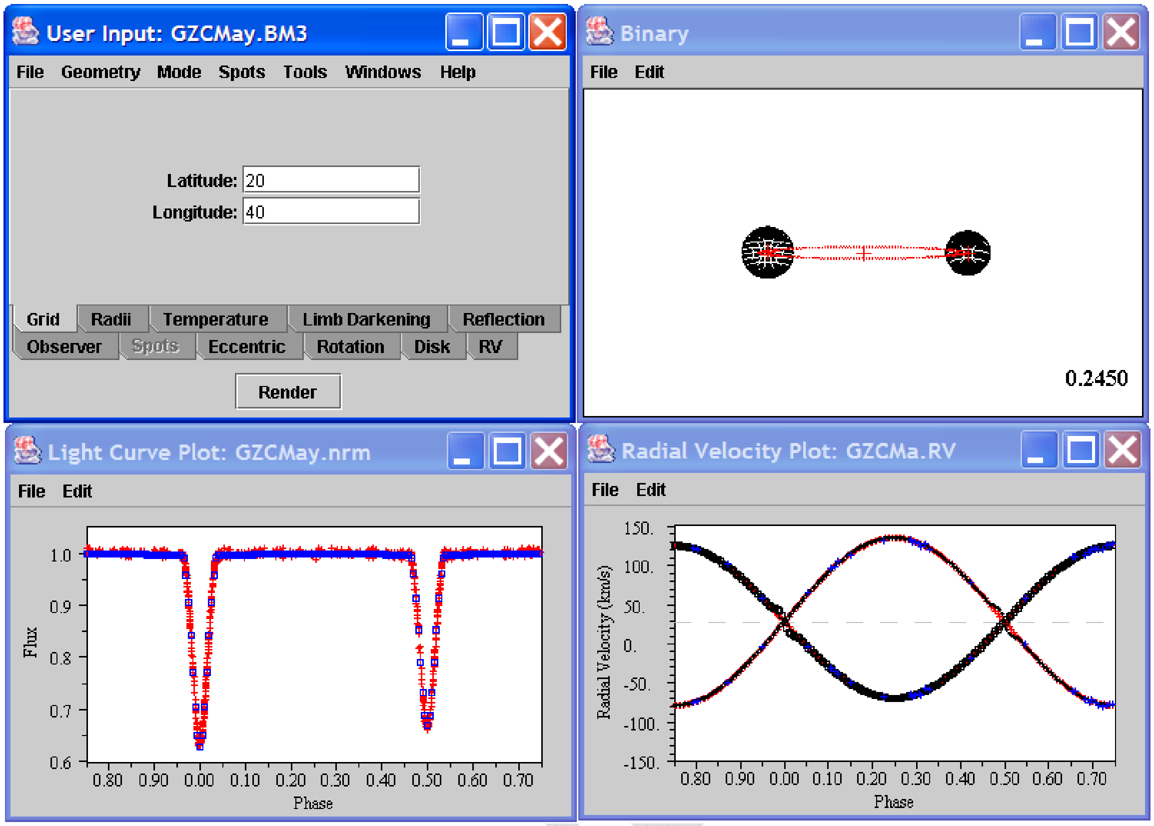
Velocity semiamplitudes K_1 and K_2:

$$\frac{K_1}{K_2} = \frac{m_2}{m_1} = mass\ ratio$$

Notice that the light curve is nearly flat in between the eclipses and that the eclipses are pointed and of similar depths. The deeper eclipse is defined as the *primary* eclipse and the less deep eclipse is termed the *secondary* eclipse.

We will now create theoretical light and radial velocity curves by calculating them via the parameters that were read in from the parameter file.

7. Press the **Render** button at the bottom of the **User Input** dialog and watch the blue squares (theoretical points) appear on the light curve plot as well as the three dimensional representation of the stars as the orbit each other in the **Binary** window.



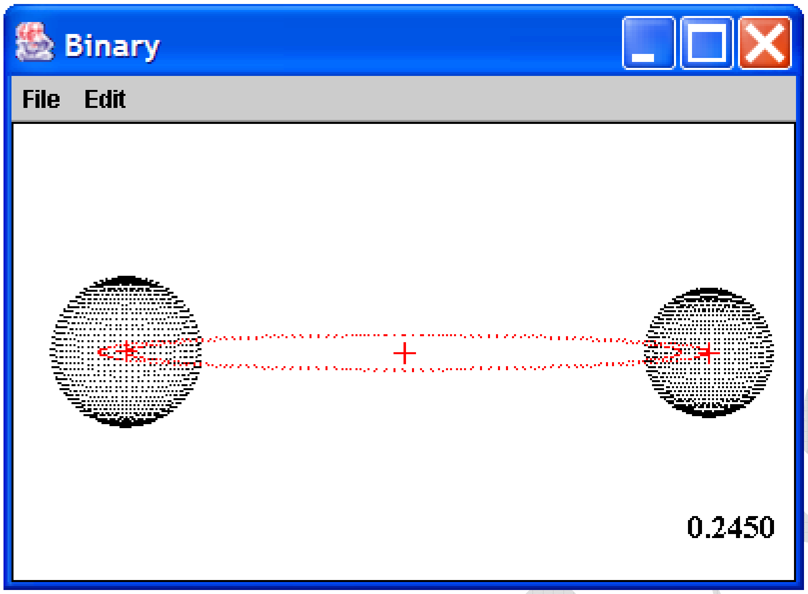
GZ CMa completed orbit after pressing the **Render** button

Many things were happening simultaneously after you pressed the **Render** button. The stars were created mathematically based upon the input parameters that had been read in and then they were revolved around each other (and they were also rotating synchronously) while the flux coming from each of them was calculated and plotted in the **Light Curve Plot** window as blue hollow squares. The theoretical radial velocities were also plotted in their respective window.

Note that the stars are nearly spherical, and that the light curve is essentially constant or flat for most of the orbit. But when one star eclipses the other, there is a substantial light loss. Let us now examine the stars more closely, as well as some of the other features of the ***Binary Maker 3*** program.

8. Click on the **Binary** window with the mouse to give it the focus. Next press the **F1** user function key to zoom in on the stars until they fill the window. If you go too far, **F2** zooms out and **F3** resumes the default scaling.

The **Binary** screen should now appear as shown below:

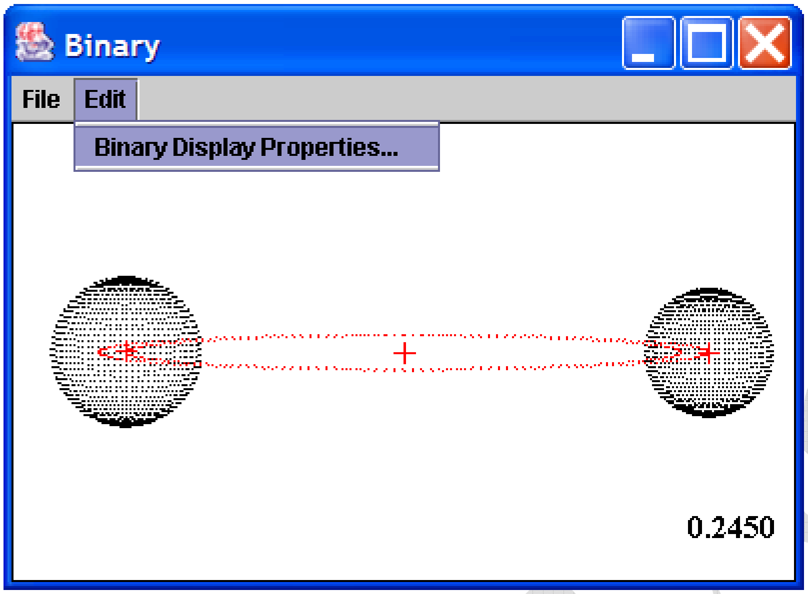


Binary window showing GZ CMa after zooming in using the **F1** key

The red crosshair at the center of the screen represents the *center of mass* (the "balance point") of the two stars, also called the *barycenter*. The mass centers of the two stars are also designated with red crosshairs, and their respective orbits about the barycenter are depicted as dotted circles (affectionately called "**breadcrumbs**" in this program). If you wish you can expand this window to full screen size by pressing the maximize button (the middle button in the upper right hand corner of the window) and enlarge the scale even more. The current orbital phase of the stars as displayed is shown at the bottom right hand corner of the window.

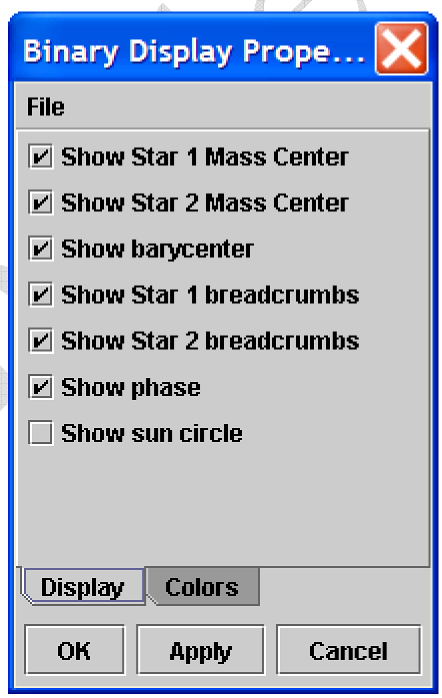
If a radial velocity curve has been read in (as with GZ CMa), we can call up a display that shows how large the Sun is compared to the stars in the binary.

9. Click on the **Edit** menu in the **Binary** window and then on the **Binary Display Properties** menu choice as shown below:



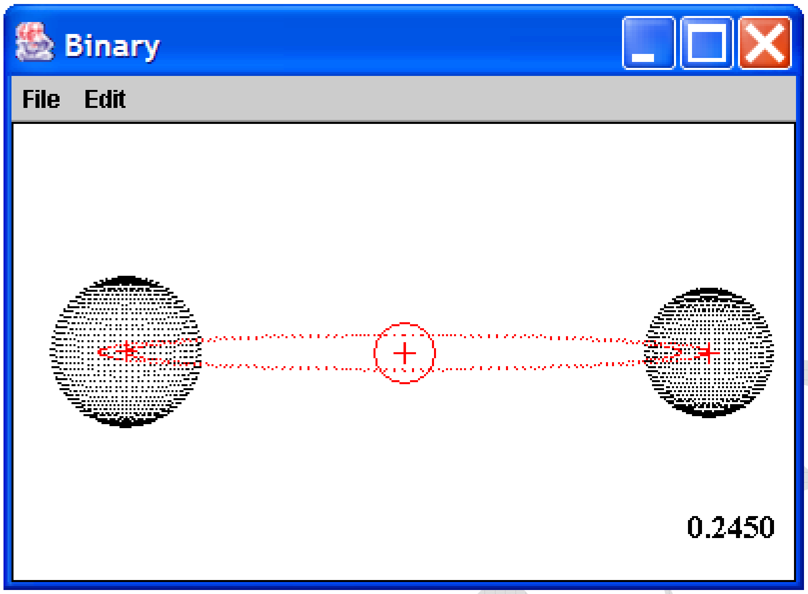
Binary Display Properties choice under the **Edit** menu in the **Binary** window

After clicking on **Binary Display Properties** the following dialog appears:



Binary Display Properties Display Tab showing the **Sun Circle** option

10. Click on the box next to “**Show sun circle**,” and then click the **OK** button. You will see the following in the **Binary** window:

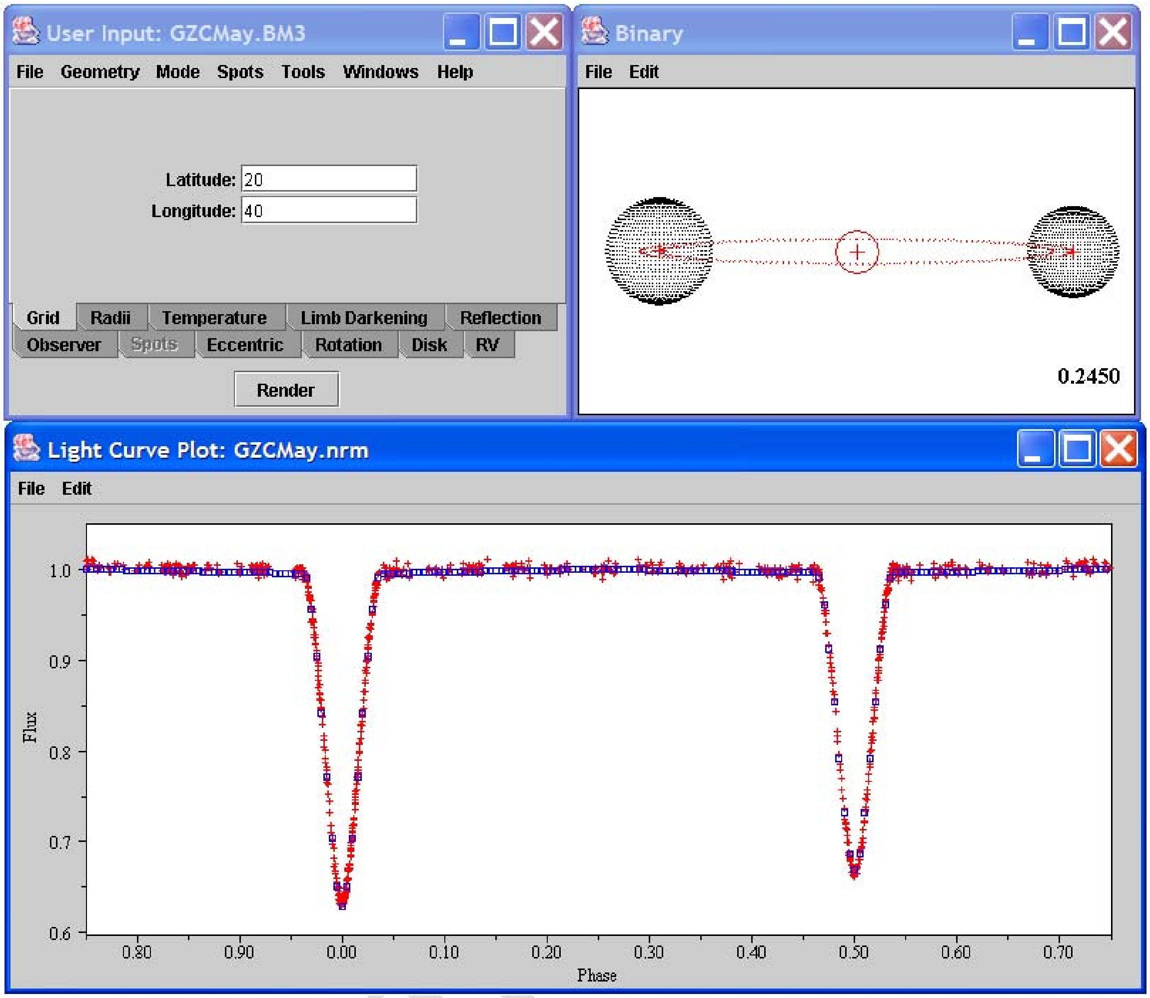


GZ CMa stars with **Sun Circle** to scale drawn centered on the barycenter

As you can see, the stars of GZ CMa are considerably larger than our Sun! If you want to turn off the **Sun Circle**, you simply go back into the **Binary Display Properties** menu again and click on the box next to "Show sun circle."

Let us now concentrate on the light curve of GZ CMa.

11. Hide the **Radial Velocity Plot** window by clicking on the close button in the upper right hand corner of its window (the rightmost button). Next move the cursor to the bottom right hand corner of the **Light Curve Plot** window until the little diagonal arrowheads appear and, while holding down the mouse button, drag the right hand corner to the right bottom of your screen, expanding the light curve plot to fill the bottom part of your screen as shown below:



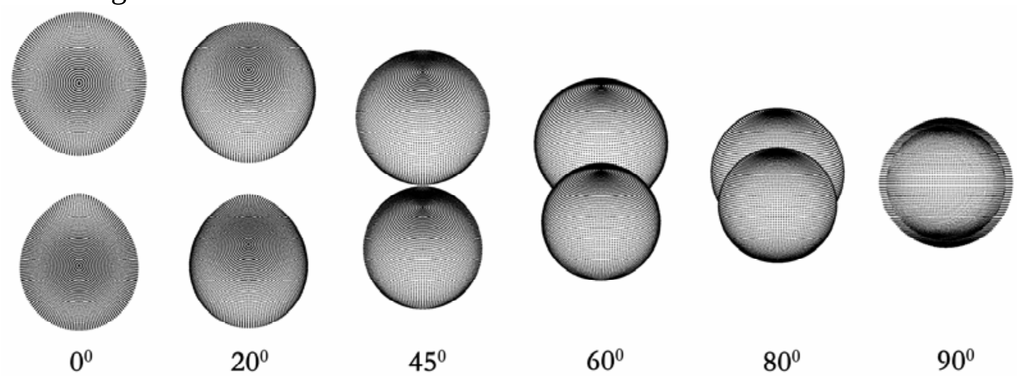
GZ CMa **Light Curve Plot** expanded using the mouse

In examining this light curve, which star (larger or smaller star) was being eclipsed at the deeper (primary) eclipse? If you have forgotten or didn't notice, simply press the **Render** button again and watch the stars as they orbit and note which one was behind at primary eclipse (phase 0.00).

Which star (larger or smaller) was eclipsed at the shallower (secondary) eclipse?

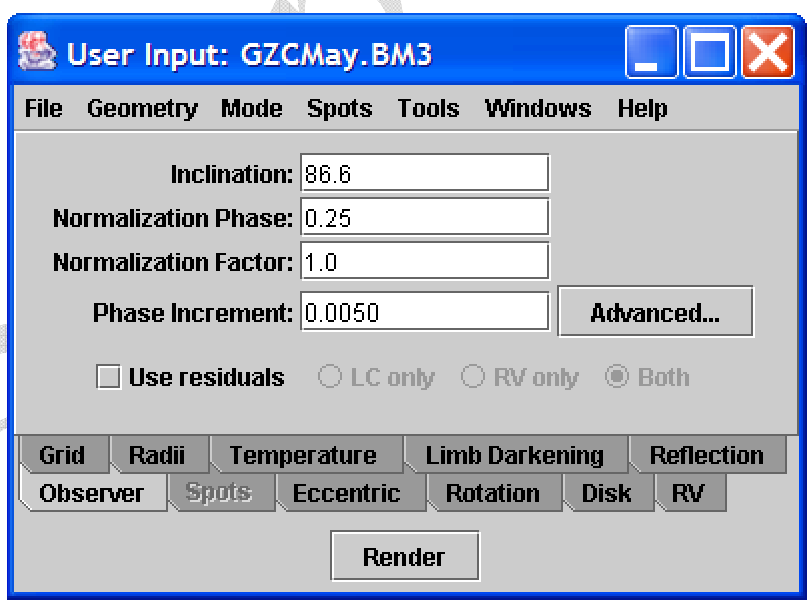
From these observations, which star is the hotter star, and which one is the cooler star? How do you know?

Next we will experiment with the tilt (**inclination**) of the orbital plane of the system. The inclination of a binary refers to the angle between the orbital plane containing the stars and the apparent plane of the sky perpendicular to the line of sight of an observer on Earth. If the orbital plane of the binary is in the plane of the sky, then we will observe the system “pole down,” *i.e.*, the stars will orbit and there will not be an eclipse. If the orbital plane of the stars is 90º (perpendicular) to the plane of the sky, then the maximum blockage of the stars will occur. The diagram below illustrates AI Cru at various inclination angles:



AI Cru shown at various inclination angles

12. In the **User Input** window click on the tabbed pane near the bottom of the window labeled **Observer**. You should see the following:



Observer Pane showing the **Inclination** input box

Note that the inclination of GZ CMa is 86.6º. Let’s change the inclination to 90º and **Render** the light curve again.

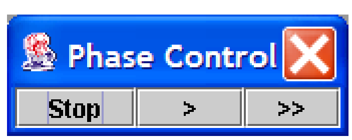
13. Click on the input box next to the label **Inclination** in the **Observer** pane and type in 90.0 for the inclination angle. Press the **Render** button and carefully observe the new light curve that is constructed. [Remember that if the light curve doesn't fit in the plotting window that you can adjust the scaling by pressing the **F1**, **F2** or **F3** user function keys if the **Light Curve Plot** window has the focus. To give it the focus simply move the mouse cursor anywhere over the **Light Curve Plot** window and press the mouse button once.]

How does the light curve calculated at 90º differ from the original one at 86.6º? Specifically why did this change occur?

14. Click on the input box next to the label **Inclination** in the **Observer** pane again and type in 80.0 for the inclination angle. Press the **Render** button and carefully observe the new light curve that is constructed.

How does the light curve calculated at 80º differ from the original one at 86.6º? Specifically why did this change occur?

15. Through trial and error, find the inclination angle at which eclipses are *just* noticeable. You can stop the light curve at any point and start over with a new inclination by clicking the **Stop** button on the **Phase Control** dialog that appears just after you press the **Render** button as shown below. The ">" key single steps through the orbit, and the ">>" key resumes the automatic calculation of the orbit.



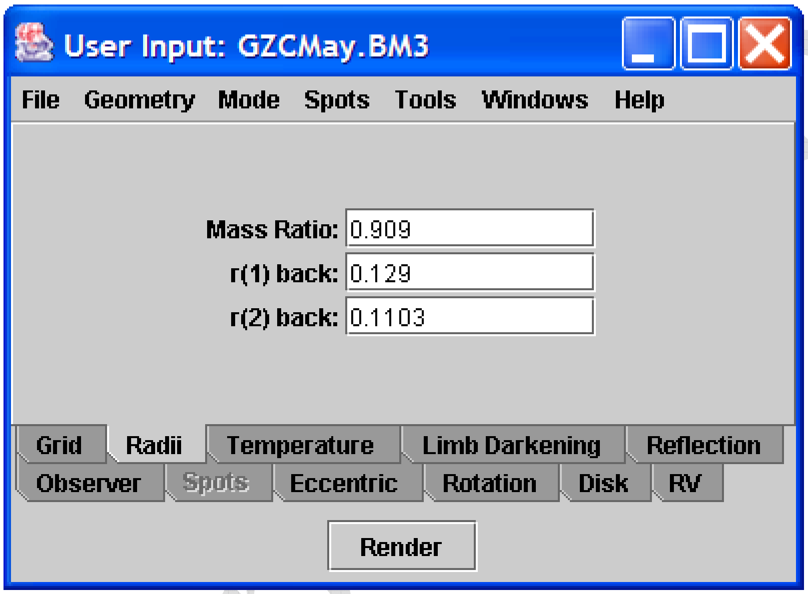
Phase Control dialog

Minimum inclination at which eclipses occur for GZ CMa = ____________

We turn now to adjusting the sizes of the stars to see how that affects the light curve. Let's make the larger star even larger, as well as setting the inclination angle back to the original 86.6°.

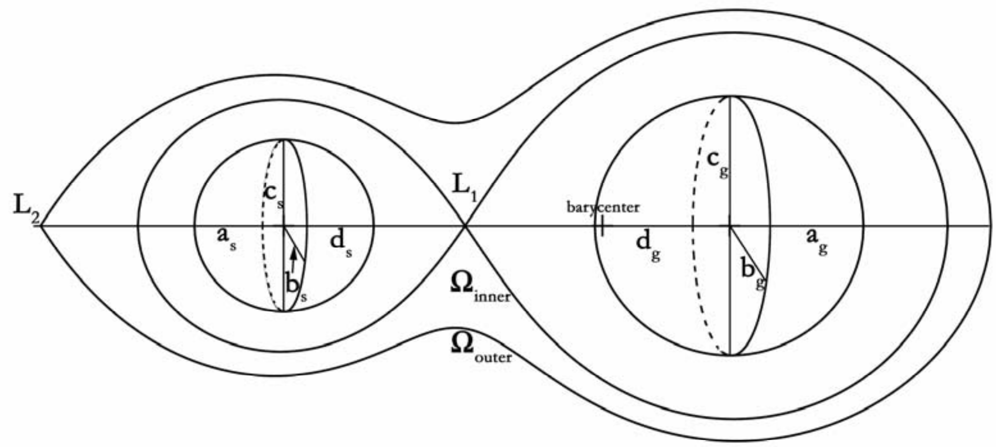
16. On the **Observer** pane change the inclination angle to 86.6.

17. Click on the **Radii** tabbed pane. You should see the following view in the **User Input** window:



Radii input pane for GZ CMa

The numbers shown represent the radius r_{back} (also called $\boldsymbol{a}$) for the stars in terms of their separation distance, which for circular orbit systems equals 1.00. Binary stars are actually given four distinct radii because they are very rarely spherical (as we shall see shortly), and r_{back} is the radius directly opposite the direction of the companion star as shown in the diagram below:



$a_s = r_{2(back)}$ $\quad a_g = r_{1(back)}$

$b_s = r_{2(side)}$ $\quad b_g = r_{1(side)}$

$c_s = r_{2(pole)}$ $\quad c_g = r_{1(pole)}$

$d_s = r_{2(point)}$ $\quad d_g = r_{1(point)}$

Various standard radii for binary systems

18. Change the radius of star 1 (the larger, more massive star) from its original value of 0.129 to 0.300. Revolve the system by pressing the **Render** button and observe the new synthetic light curve. [You will probably need to zoom out a little in the **Binary** window to fit the stars in the view. Click on the **Binary** window (to give it the focus) and press the **F2** key a few times until the large star fits.]

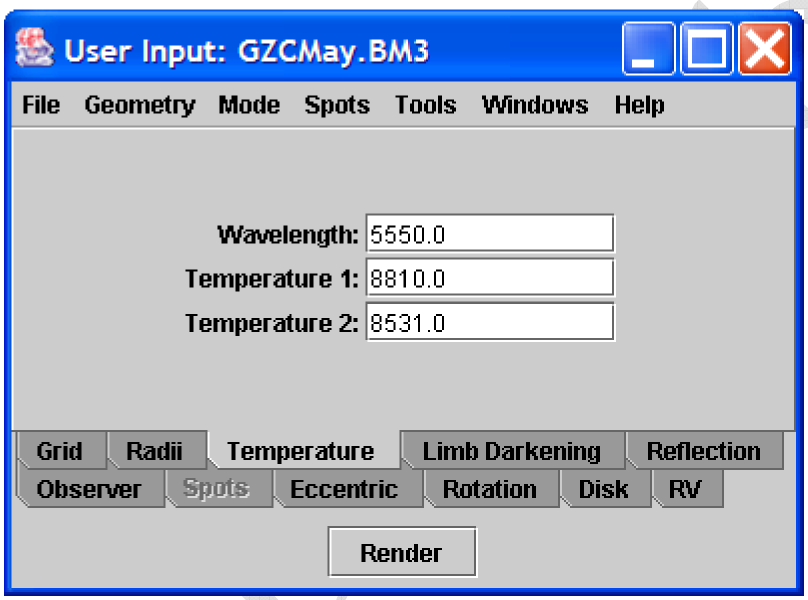
Carefully examine the differences between this new light curve and the original light curve as represented by the observed data points. Describe at least three differences between the two light curves.

Knowing that these changes in the shape of the light curve came about from simply increasing the size of the larger star, explain why the new light curve changed in each of the ways you described above. [Hint: Is the larger star *spherical* now? What difference would that make?]

You can see that light curve analysis very quickly becomes very complicated! One parameter change can lead to several major changes in the shape of the light curve.

Let's change one more parameter within the original input parameters of GZ CMa before we go on to explore other binary systems.

19. Change the radius of star 1 back to the original value of 0.129. Then click on the **Temperature** tab and you should see the following display:



Temperature pane for GZ CMa

20. Change the temperature of star 2, but this time ***you*** decide by how much and in what direction. Increase or decrease its temperature by a reasonable amount (*i.e.*, by a few thousand degrees) and write down on the line below exactly how much you changed its temperature and whether it was an increase or decrease.

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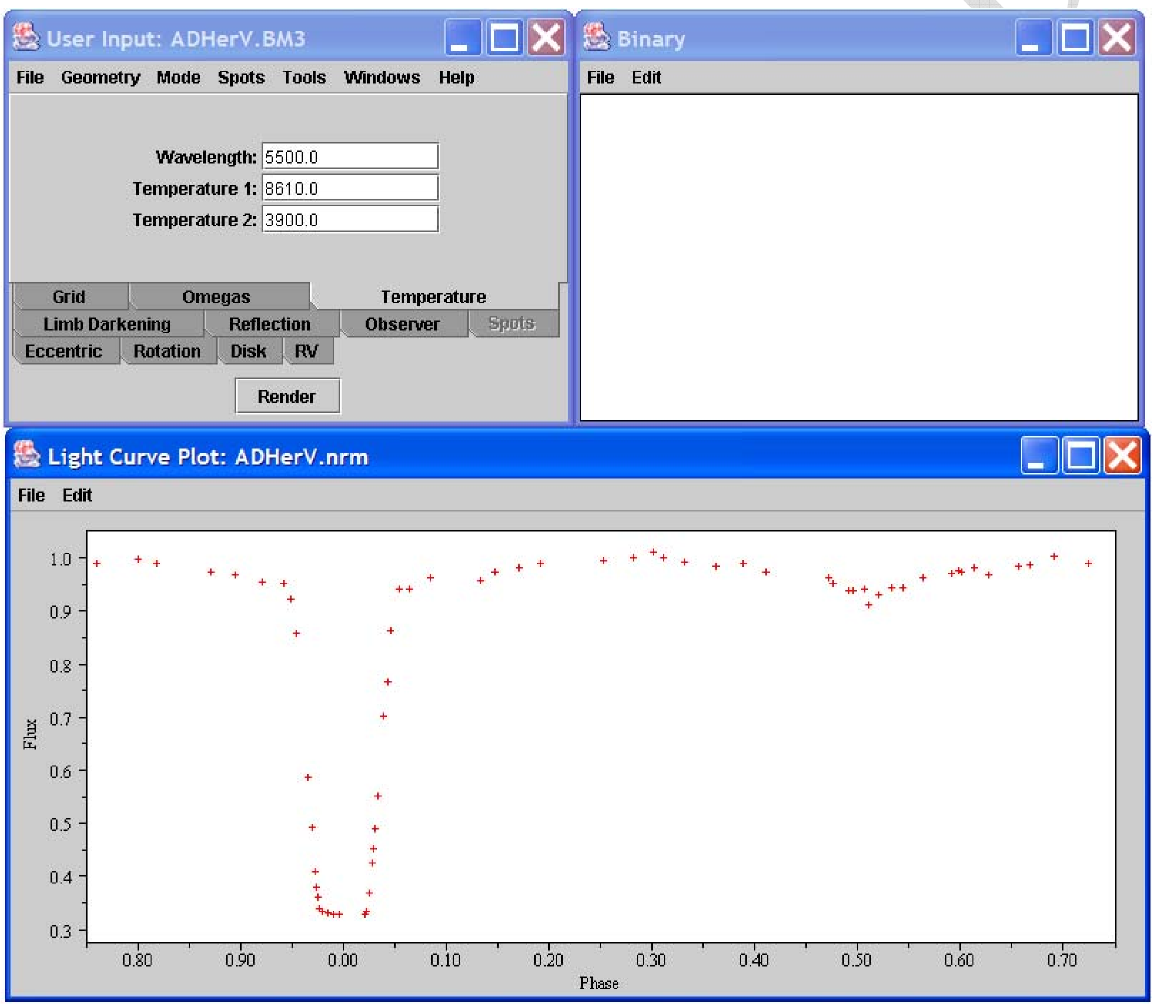
21. After typing in your new temperature for star 2, press the **Render** button and watch the new light curve being plotted. Write down how your temperature change affected the light curve compared to the original one (the observed points) and explain why this change makes sense relative to the temperature change you made to star 2.

It's time to leave GZ CMa and explore some new binary systems.

22. Click on the **File** menu in the **User Input** window and select the **Open Binary Parameter File** option. Within the **ZIP** folder find the binary file in the **Her** folder (Hercules) entitled *ADHer_Mardirossian1980V.zip* and read it into the program. Adjust the scaling of the **Light Curve Plot** window using the **F2** key to fit the new light curve. Your screen should look something like the following:



AD Her *V* light curve after rescaling using the **F2** user function key

This light curve looks very different from GZ CMa! Write down some of the differences between the light curves of GZ CMa and AD Her.

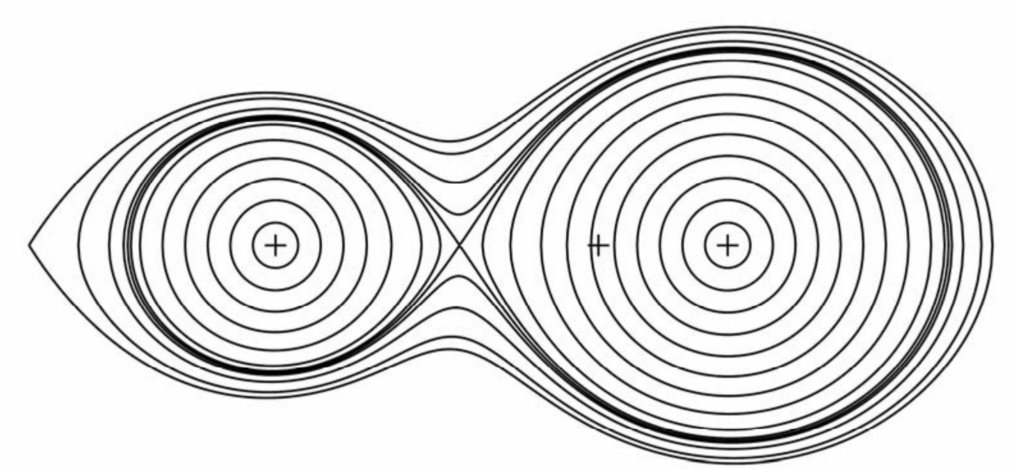
23. **Render** the system and watch carefully as the stars orbit and the light curve unfolds. You will need to zoom out in the **Binary** window in order to fit both stars in the view.

Notice how large these stars are relative to our Sun! What can you tell about the differences of the two stars in AD Her from its light curve? Other than the fact that the stars' temperatures are listed above, how do you know that the larger star is indeed the cooler star from the light curve?

Let's take a closer look at the two stars. You've probably noticed the strange shape of the larger star, in this case the less massive star, which you can tell because of its greater distance from the barycenter or center of mass (red crosshair between the two stars). Like balancing a seesaw with an adult and a child, the more massive star is closer to the center of mass.

24. **Maximize** the **Binary** window by clicking on its maximize button (middle button of the three in the upper right hand corner). Just for the fun of it, press the **F1** key to zoom in on the stars until they fill the screen. This *really* puts the huge size of the stars relative to our Sun in perspective. Now, successively press the **F2** key until the view is zoomed out such that the stars merge into a tiny point! This is exactly what they look like in a telescope because they are so far away that they cannot be discerned as two individual components! Restore the original scale of the stars by pressing the **F3** key and then restore the **Binary** window to its original size by clicking on the **Restore** button (the middle button of the three in the upper right hand corner of the window).

Obviously the larger star has a very strange shape, and this is because the shape of binary stars depends upon the gravitational interaction between the two stars as well as their orbital motion around each other. Component stars in a binary take on shapes called Roche surfaces, where the gravitational potential is the same all over that surface. For single stars that are not rotating, this equipotential surface is a sphere. If the single star is rotating, its equator bulges outward and the poles flatten due to centrifugal forces. For a pair of rapidly rotating stars, their mutual tidal gravitational forces augment the deformation of the stars resulting in the strange shapes we call Roche surfaces. Like water seeking its own level, the gas that comprises a star will find an equilibrium condition such that the gravitational potential energy everywhere is the same over its entire surface. The figure below shows various equipotential surfaces that a binary of mass ratio 0.40 can have. Looking at this figure, you can see one particular equilibrium surface crosses itself and looks like a "figure 8." This particular surface, called the inner critical Roche surface or Roche lobes, contains what is called the *inner Lagrangian point* L_l where the gravitational forces of the two stars exactly balance. In other words, a gas molecule placed at the L_l point would be equally attracted to both stars, and a "nudge" either way would send the gas molecule to either star. This inner critical surface also demarcates the limiting size that a star can possess since if a star expands (due to evolution) to a size greater than the critical surface, the gas will tend to flow away to the other star in a process called *mass transfer*. **Stars whose surfaces fill or nearly fill this inner critical Roche surface will be distorted far more than stars that lie well within this surface**. The outermost surface is called the outer critical Roche surface and is the largest surface that the two stars can share because any equipotential larger than this is not a closed surface and gas would escape from the binary.

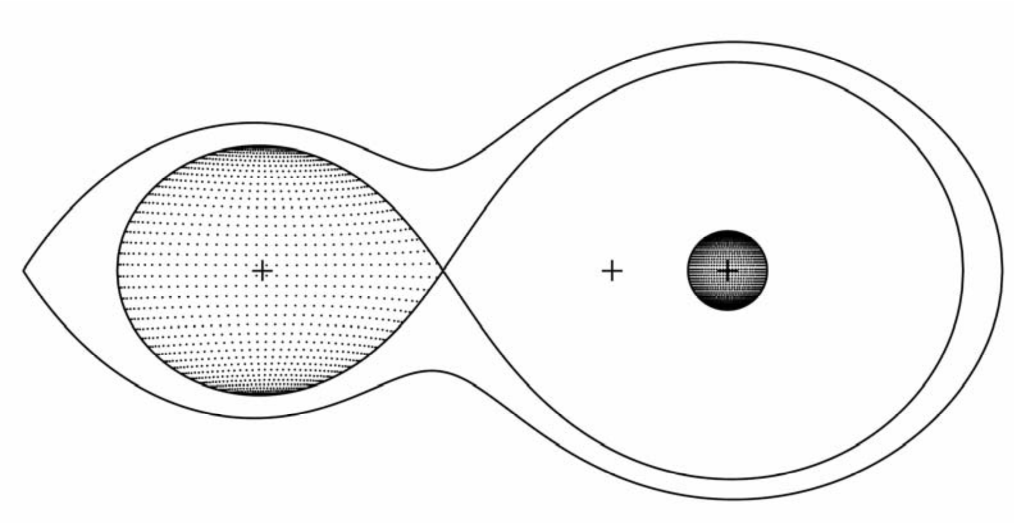


Cross sectional diagram depicting sample equipotential surfaces for a binary having a mass ratio of 0.40. The stars could find themselves taking any of these figures to define their surfaces. The crosshair between the two stars marks the barycenter (center of mass) of the system. If the distance between the two stars is defined as 1.00, the barycenter is exactly 0.40 away from the more massive star for a mass ratio of 0.40.

It is interesting that the less massive star in the binary is the larger star. In terms of stellar evolution, the more massive star evolves faster and becomes a giant star more quickly than a less massive star. Assuming that the two stars in a binary are coeval (formed together at the same time), how can the less massive star be the more evolved one (*i.e.*, a giant star) when the more massive star still resides on the main sequence? The answer is that there has been a significant amount of mass transfer between the two components, so much so that the evolved star ("the pointed one," which evolved first because it was *originally* the more massive star) is now the less massive star by a factor of 3! When it evolved it reached its inner critical Roche surface and began spilling material onto its originally less massive companion. This process continued until so much mass was transferred that the less massive star became the more massive one, and vice-versa. It is still on the main sequence only because it has just recently become a massive star and hasn't had time to evolve as such.

A binary in which one of the components is in contact with its inner critical Roche surface is called a **semi-detached** system. Let's take a look at the Roche surfaces for AD Her and a few other binaries.

25. Click on the **Window** menu in the **User Input** window. Click on the box next to the menu choice **Surface Outlines**. A new window will appear showing the binary in cross section at phase 0.75 with its inner and outer Roche critical surfaces.



Critical Roche surfaces for the semidetached binary AD Her

Note that the larger, less massive star does indeed exactly fill its inner critical Roche surface. Let's look at the surface outlines for our old friend GZ CMa.

26. Click on the **File** menu in the **User Input** window and once again select the **Open Binary Parameter File** menu choice. Open the *GZCMa_Popper1985y.zip* file once again in the **CMa** folder. Click on the **File** menu in the **Surface Outlines** window and then click on the **Refresh from current inputs** menu choice. Notice how the stars of GZ CMa lie well within their inner critical Roche surface.

GZ CMa is an example of a *detached* binary. In studying the **Surface Outlines** window of GZ CMa, why does it make sense that these two stars are both nearly spherical?

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One might wonder whether there exist binaries where both stars' surfaces lie close to their inner critical Roche surfaces. Indeed there are! Let us look at one such system, V1010 Oph.

27. Click on the **File** menu in the **User Input** window and select the **Open Binary Parameter File** menu choice. Open the *V1010Oph_Leung1974v.zip* file in the **Oph** folder (Ophiuchus). Click on the **File** menu in the **Surface Outlines** window and then click on the **Refresh from current inputs** menu choice. Look at the system displayed in the **Surface Outlines** window.

V1010 Oph is a good example of a binary where both stars are almost in contact with each other, called a *near-contact* system.

28. Close the **Surface Outlines** window and **Render** V1010 Oph to see the stars orbit each other.

Is it possible that the stars in a binary could actually be in contact with each other? Absolutely! CC Com is a good example, the shortest period (5^h 16^m) overcontact binary known.

29. Click on the **File** menu in the **User Input** window and select the **Open Binary Parameter File** menu choice. Open the *CCCom_Bradstreet1985B.zip* file in the **Com** folder (Coma Berenices). Open the **Surface Outlines** window again by clicking on the **Windows** menu in the **User Input** window and selecting the **Surface Outlines** choice. Examine CC Com displayed in the **Surface Outlines** window.

Here we see an example of an overcontact binary where the two stars overflow their inner critical Roche surface and the two stars are actually “touching” each other as they revolve and rotate synchronously.

Can we infer some properties of CC Com by inspecting its light curve?

30. Close the **Surface Outlines** window by clicking on its **Close** button in the upper right hand corner of its window. **Render** the light curve of CC Com.

What can you tell about the temperatures of the two stars from the depths of CC Com’s eclipses?

Why does this make sense in light of the fact that the two stars are in contact with each other, even though they are very different in mass from each other?

Let us conclude this lab by looking at a few other exotic binaries. The first is the most extreme mass ratio binary known, AW UMa. The more massive star is nearly 14 times more massive than its companion!

31. Click on the **File** menu in the **User Input** window and select the **Open Binary Parameter File** menu choice. Open the *AWUMa_Pribulla1999V.zip* file in the **UMa** folder (Ursa Majoris) and **Render** the light curve.

This is one of the most amazing binaries known. Its extreme mass ratio and incredible shape give one the impression that the more massive, larger star is eating its companion, and in fact that is most probably exactly what is happening! Eventually AW UMa will likely become a rapidly rotating single star! Similar to the light curve of CC Com, you notice that the eclipse depths are nearly equal, even though the stars are very different in mass and size. This should confirm the answer that you wrote above concerning the temperatures of the components of CC Com.

As an example of a very heavily spotted star (magnetically-induced cool regions as on our own Sun) let's take a look at ER Vul. It consists of two nearly identical stars, both of which are very much like our own Sun except that they are rotating 40 times faster than the Sun because of their tidally induced synchronous rotation.

32. Click on the **File** menu in the **User Input** window and select the **Open Binary Parameter File** menu choice. Open the *ERVul_Guinan1991V.zip* file in the **Vul** folder (Vulpecula) and **Render** the light curve.

Note the very asymmetric light curve, much of which is caused by the two huge cool spots near the pole of one of the stars. An interesting thing to do is to "shut off" the effects of the spots and then re-calculate the light curve.

33. Click on the **Spots** menu in the **User Input** dialog. Then click on the first menu choice **Enable Spots**. This will toggle the spots off. Now press the **Render** button and watch how the light curve would appear <u>without</u> the presence of spots.

Finally, let's investigate the binary V471 Tau that consists of a white dwarf and a K2 main sequence star.

34. Click on the **File** menu in the **User Input** window and select the **Open Binary Parameter File** menu choice. Open the *V471Tau_Bradstreet2004B.zip* file in the **Tau** folder (Taurus) and **Render** the light curve. (Be sure to <u>rescale</u> the light curve plot to better see the peculiar light curve!)

Explain why the light curve of V471 Tau appears as it does. Why is there no noticeable secondary eclipse? Why does the light curve fluctuate outside of eclipse? (Hint: There are two reasons for the outside of eclipse variations…)

To summarize, we have looked at several examples of binary light curves and seen that by carefully studying them we can infer many useful characteristics of the stars themselves. It is only through the analysis of light curves of eclipsing binaries, coupled with spectroscopic analysis of their radial velocity curves, that we can measure the absolute properties of stars and begin to understand something concerning their origins and evolution.