

Lab 4: Eclipsing Binary Stars

(Due: 2017 Apr 05)

Binary Stars

Binary stars are systems in which two stars orbit each other under their mutual gravitational interaction. It is commonly claimed that most stars are members of binary or multiple star systems, so they are very common. However, it may be easy or difficult to determine if a particular star as seen in the sky is a binary or multiple star system. The direct way to tell is if one sees two stars visually close to each other (*visual binary*), but even then they may only *appear* near to each other. Observations over several years or decades may be needed to tell that they are indeed orbiting each other. The orbits are such that each star travels in an ellipse with the center of mass in the common focus of both ellipses (the more massive star has the smaller orbit), as shown in Figure 1a, below.

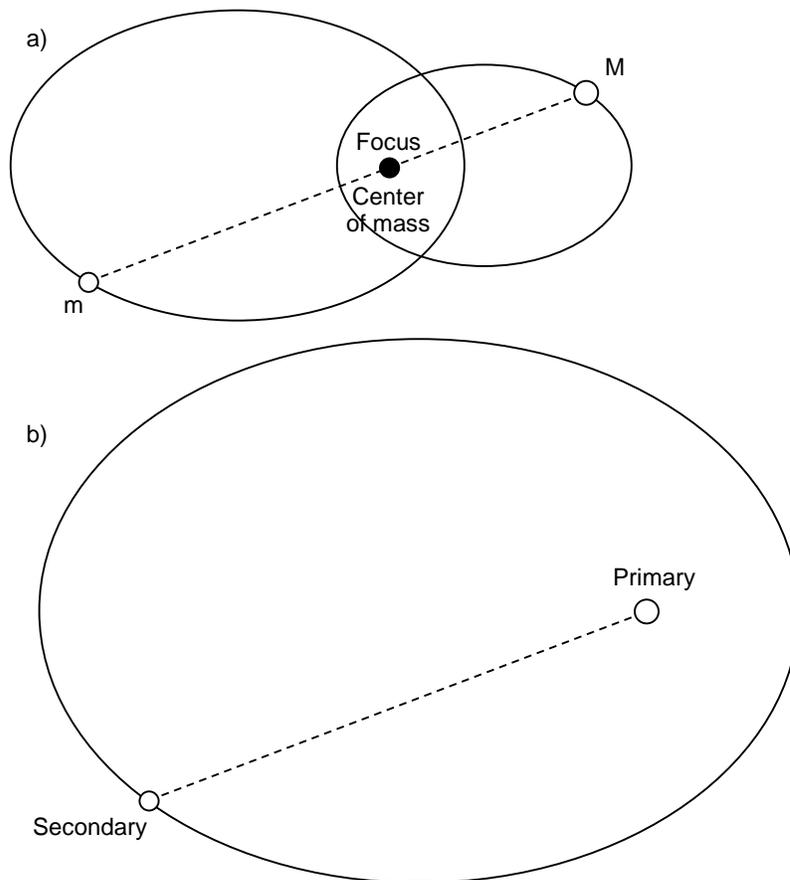


Figure 1: Orbits of the two stars of a binary system. a) One can consider the orbits relative to the center of mass of the two stars. The more massive star M has a smaller orbit than the less massive star m , but both orbit with the center of mass at one focus of their ellipses. b) The system can be considered equally well as one star (the secondary) orbiting the other (the primary), so long as the mass of the orbiting secondary is replaced by the “reduced mass” of the system. The dashed line representing the distance between the two stars at a particular moment in time is shown in both diagrams, with the same length and direction, to aid in relating the two equivalent ways of visualizing the geometry.

But one can also consider one star fixed, with the other star orbiting in a larger ellipse, as in Figure 1b, above. One caveat is that in treating this second system, one has to use the “reduced mass” of the system, $\mu = \frac{m_1 m_2}{m_1 + m_2}$, for the mass of the orbiting body. One can choose either star as the central star, but it is customary to choose the brighter star

(usually the more massive, but not always), and call it the *primary*. The other star is then the *secondary*. The primary star is then at a focus of the larger ellipse. The period of the orbits of such *visual binaries* is typically hundreds of years or more.

However, many binaries are so close to each other that they cannot be separated visually through a telescope. In that case, they may be detected using spectroscopic methods, and may have orbital periods of only days. These are called *spectroscopic binaries*. In these binaries, the spectral lines shift back and forth with the period of the orbit, due to Doppler shifts as the stars alternately move toward or away from us.

For any binary, there is a chance that the plane of their orbits may lie close to the line of sight. In that case, one star may pass in front of the other, and then one-half period later the other star passes in front (or the first star goes behind). Such eclipses are more likely, of course, when the stars are in close orbits with periods of only a few days or less. We normally see the light from both stars at once, but during a small part of their orbital period, when one star is partially covering the other, we see less light, so the combined brightness of the stars drops. Such systems are called *eclipsing binaries*. Eclipsing binaries are a type of variable star, because their light appears to vary. However, unlike many variable stars that are really (i.e. intrinsically) getting brighter and dimmer as they vary, in the case of eclipsing binaries the stars are not really changing brightness—it is only their apparent brightness that varies due to the eclipses.

This lab involves first planning observations of an eclipsing binary, and then taking a series of images near the time of eclipse. From the series of images you will do photometry and plot the brightness changes (such a plot is called a *light curve*). You will then analyze the light curve to attempt to make predictions about each of the stars (components) of the binary system.

Planning Observations

An excellent place to find information about the times of minimum of eclipsing binaries is the web site <http://www.as.ap.krakow.pl/o-c/cont.html>. Eclipsing binaries are designated as variable stars, so their designations consist typically of one or two letters (indicating the order of their discovery), followed by the three-letter abbreviation for the constellation they are in. We will use the example of FZ Ori, where Ori is short for Orion. On the above web site, click on the Ori link or scroll down to the list of eclipsing binaries for Orion, then look across the page for FZ. Click on it, and you will see some additional links and tables. The important things to look at for our purposes are *V* (the apparent visual magnitude) and *Depth*. For FZ Ori, *V* is 10.8, and *Depth* is Pri 1.0 and Sec -. The *Depth* entry tells you how many magnitudes deep the dip in brightness is. Pri stands for primary eclipse (the primary star is eclipsed, so this is the deeper eclipse), while Sec stands for secondary eclipse (the weaker dip in the light curve). The dash for FZ Ori means that the secondary eclipse is weak or not seen. Any star you choose should have a visual magnitude of at least 13 or so (9-12 is best), and Pri should be at least 0.3 or so, since it can be hard to detect a dip of less than that.

Also on this same page is a link that says “Current Minima.” Click this and you will get a list of future dates and times for the minimum eclipse. In the case of FZ Ori, for 2017 Mar 01 I see the following list:

```
Light elements:   HJD = 2452500.095 + E x 0.3999897

Current JD 2457814.11670

Current cycle (epoch) 13286
Current orbital phase 0.39635

Computed times of minima :
Date:           Time:   Type:   HJD:

01-03-2017 05:59 pri 2457813.95816
01-03-2017 10:47 sec 2457814.15816
01-03-2017 15:35 pri 2457814.35815
01-03-2017 20:23 sec 2457814.55815
02-03-2017 01:11 pri 2457814.75814
02-03-2017 05:59 sec 2457814.95814
02-03-2017 10:47 pri 2457815.15813
02-03-2017 15:35 sec 2457815.35813
02-03-2017 20:23 pri 2457815.55812
03-03-2017 01:11 sec 2457815.75812
03-03-2017 05:59 pri 2457815.95811
03-03-2017 10:47 sec 2457816.15811
03-03-2017 15:35 pri 2457816.35810
```

The first line is an equation $HJD = 2452500.095 + E * 0.3999897$. HJD gives the Heliocentric Julian Date (JD) for each minimum, with one minimum occurring at $JD = 2452500.095$, and all others occurring at times separated by 0.3999897 days. Thus, 0.3999897 is the period of the orbit, and the eclipses come every ~0.4 days, or every 9.6 hours. The list titled “Computed times of minima” show the future times of primary and secondary eclipse, in *local time*, i.e. in Eastern Standard Time (will be Eastern Daylight Time after the time change). Times in the past are shown gray. For this lab, you can figure that no observations are possible until 7 pm (8 pm after spring break), and we have to stop observing by 9 pm (10 pm after spring break). That means you want to find (primary) minima that occur some time around 8 pm, or 20:00 in 24-hour time. That way, we can observe the star for two hours and have the star’s brightness dip to its minimum and then rise again during the observations. The closest minimum in this list occurs at 20:23 on 02 March (8:23 pm), so if we were observing on that day it could be a suitable target. If we were observing on 01 March, though, we would have to skip this binary and look for another one (note that there is a secondary eclipse on 01 March, but since the secondary dip is not observable, we would be wasting our time trying to observe it).

Your first task, then, *to do before you come to class*, is to look at a star map (or Cartes du Ciel) and check which constellations are conveniently up in the sky in March (e.g. Orion, Gemini, Cancer, Leo, Canis Major, Canis Minor, etc.), then look through all of the possible eclipsing binaries until you find one with a decent brightness (9-12 magnitude),

deep enough primary minimum (>0.3), and that has a minimum near 20:00 local time on 08 March, or near 21:00 local time on 22 March. If we get a clear Wednesday, the possible dates are 08 Mar and 22 Mar. Once you find a good one, write down in your log book its designation (e.g. RW Leo), the HJD equation, the V and P values, and the date and time of primary minimum. You should each have a candidate to present to the class. We will then choose from among the candidates and agree on the star to observe. Once we choose the star to observe, everyone should write down the designation, HJD, V and P values for the chosen star.

Taking the Observations

This description assumes that the telescope has been pointed at the star, the camera is cooled to its operating temperature and the telescope is focused. As a class, we will expose an image and verify that the telescope is pointed correctly, with the star near the center of the frame. To find the star, click the Find (binocular) icon in Cartes du Ciel, select the “stars” tab, and select the GCVS radio button. GCVS is General Catalog of Variable Stars. Then type the designation of the star (i.e. RW Leo) and click okay. Click the 1' icon to zoom in, if necessary. Note that the positions of the stars in GCVS are often slightly wrong, so you may see a circle for the GCVS position and a displaced dot for the Tycho2 position. The latter is the more accurate one.

Connect to the telescope in the camera program, and take an exposure of 20 s, then submit the image to Astrometry.net to verify pointing. If the telescope position needs adjusting, do that and repeat the verification. Once you have the star near the center of the image, write down the plate solution information from Astrometry.net (center RA, center Dec, pixel scale and orientation).

Set up a sequence to take 60 images with 20 s exposures, but at the bottom of the Setup Sequence window, type 100 in the “Delay Between” box. This will take 60 images separated by 2 minutes, for a total duration of 2 hours. Do not forget to set the save directory, the file name (to the star designation, e.g. RW_Leo), and the start number to 1. Start the sequence. Once the sequence is started, there is nothing to do but wait 2 h for it to finish.

We are doing photometry, so it is important to take Flat frames. After the sequence is finished, then, we also need to take a series of Bias, Dark, and Flat frames, 20 of each.

Analysis

To analyze the data, you will first do the Set Calibration as in the earlier labs, to Auto-Generate the calibration file selection, and then create master frames. Then use the File/Batch Save and Convert menu item to calibrate all of the files and transfer them to a “Calibrated” directory.

We will all be using the same images, but ***the rest of the steps should be done by everyone individually***. Using the calibrated images, we need to read all 60 images into MaxIm DL and Align them, using the usual procedure. If you reject any images, be sure to write their numbers down so that you can delete them from the list.

The first person to do the procedure should Save the aligned images using File/Save All, but leave them open in MaxIm DL. Others can skip the save step. We are going to do all processing in MaxIm DL. The next thing to do is identify a few of the brighter stars in your image by comparison with Cartes du Ciel, and write down their magnitudes as given by Cartes du Ciel. It is a good idea to make a sketch of the relative locations of the different stars in your log book so that you can recall later which is which.

Going back to MaxIm DL, with all of the aligned images still open (or reopen them, if not), select Analyze/Photometry. This will open the Photometry window, as shown in Figure 2. Click on the drop-down box "Mouse click tags as..." and select New Object from the list. Identify the eclipsing binary, and click on it in the visible image. Three concentric circles will be drawn. The brightness in the inner circle, called the *aperture*, will be added up, so the star should entirely fit in the inner circle. The space between the inner circle and the next circle is called the *gap*, and anything in this space is ignored. The space between the second circle and the outer circle is called the *annulus*, and all brightness in this area is considered the background. This brightness is averaged, then subtracted from the aperture (star) brightness. Make sure that there are no stars or other non-background features in this space. You can adjust the size of the circles by right clicking and increasing or decreasing aperture, gap, or annulus.

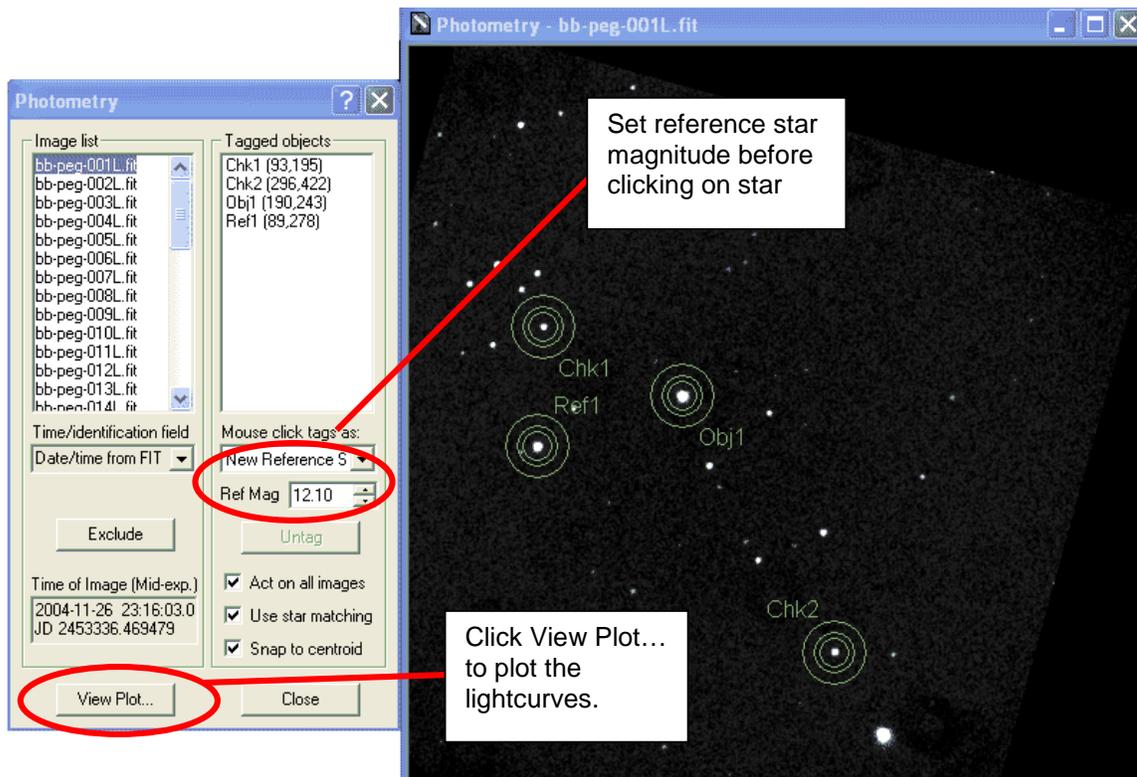


Figure 2: Using the photometry window. One may select objects under study (New Object), reference stars (New Reference Star), or check stars (New Check Star), by first selecting the type of object in the "Mouse click tags as" box, then clicking on the star or object. Here, the eclipsing binary BB Peg is chosen as the object (Obj1), the star TYC1682-01530-1 star is chosen as the reference star (magnitude 12.1), and two check stars are chosen.

After setting the object, repeat for the reference star and any check objects you want. First, select New Reference Star in the drop-down list, setting its magnitude (as given by Cartes du Ciel—use the red magnitude or visual magnitude, not the blue one), and then clicking on the reference star in the image. Then select New Check Object in the drop down list. The reason for selecting check objects is that the reference star could be variable. If your check objects' lightcurves are not flat, you might want to choose a different reference star. You should choose bright stars for reference and check objects, but they must be well isolated from other stars. Once you have selected your object, reference star, and one or more check stars, click View Plot... You should see a plot similar to the one shown in Figure 3.

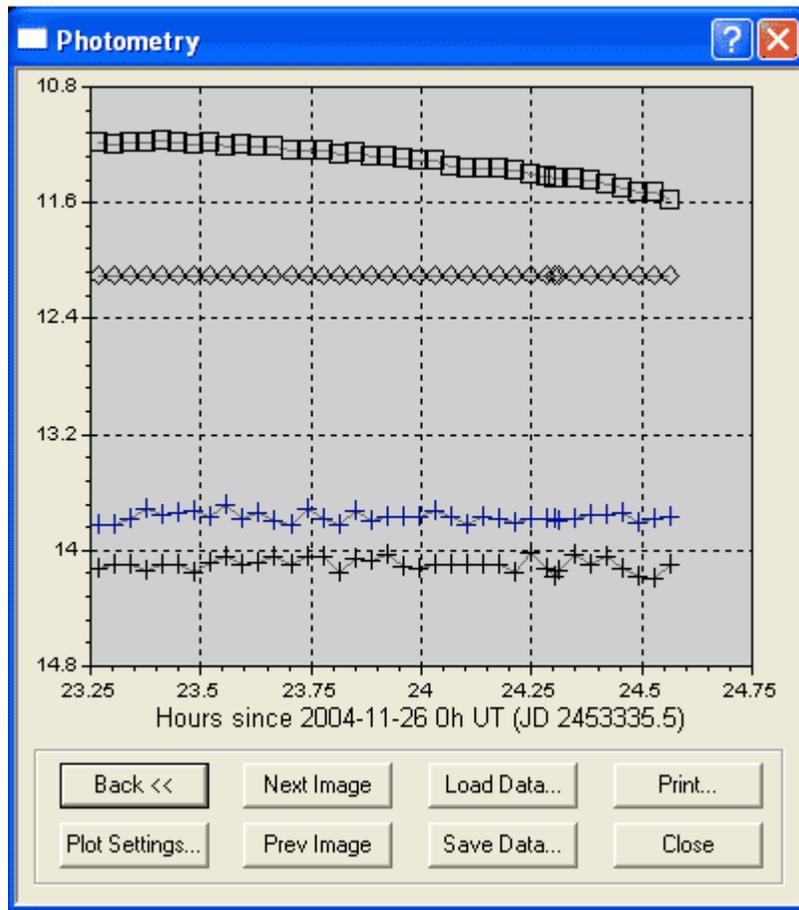


Figure 3: The lightcurves for BB Peg, the reference star (constant magnitude 12.1), and the two check stars. The dropping brightness of BB Peg, as it goes into eclipse, is apparent.

When you are happy with your choice of stars, and the plot looks good, save the data by clicking on the Save Data... button and naming your file with the star name and your initials. You will read the data into Excel as a “comma-separated variable” (.csv) text file.

Plotting the Results

After saving your .csv file, you should be able to open it in Excel simply by double clicking the file. You will have columns of T(JD), Obj1, Ref1, and Chk n , where n is 1, 2, ... depending on how many check stars you chose. The T(JD) column is the time in Julian Days. This is the time format that astronomers use so that dates and times can be added or subtracted directly.

After opening your file, type the equation in an Excel cell that you wrote down from the eclipsing binary web page. For BB Peg it is $HJD = 2452500.0321 + E \times 0.3615024$. You basically want to solve for E, where HJD is the time in the T(JD) column. Create a column titled Orbit, and write an Excel formula that converts the values in the T(JD) column to the values E. For BB Peg, for example, the first row of values has a T(JD) value of 2453336.469, so solving for E gives 2313.781. This is the number of orbits the star has gone through since the reference date (2452500.0321) in the equation. Make another column, titled Phase, and use an Excel formula to remove the integer part. The value for the first row of the BB Peg file, after subtracting 2313, is 0.781. This is the “orbital phase” for that time. Your orbital phase should start around 0.8 to 0.9, and go through 1, where the dip in the lightcurve should be greatest.

Finally, create an Excel plot of the data by choosing x-y scatter plot as the plot type, and plotting a series. Use the phase values as the x-axis, and the Obj1 column magnitudes as the y-axis. Give your plot a title of the star name and the date. Right click on your plot’s y-axis, choose Format Axis, and then choose “Values in reverse order” and the “scale” tab, so that magnitudes increase downward. Set the plot max and min values to whole numbers, so that the magnitude is easy to read.

Conclusion

Compare your measurements to the V magnitude and Depth values that you wrote down for the star. Do they compare well? If they are off, this may be due to an incorrect magnitude for your reference star, or it may be due to use of the Luminance filter instead of the exact astronomical red filter. Look carefully at your phase plot. How accurately can you determine the minimum phase? Is it precisely 1.000? Give the phase of the minimum with an estimate of the error, and convert this phase error to the fraction of a day (negative if the minimum occurred early, or positive if it occurred late. Go back to the web site <http://www.as.ap.krakow.pl/o-c/cont.html> and look up the star. In the Current Minima page is a plot called an O-C diagram. Click on it and save the image for inclusion in your report. This gives the difference in “observed minus calculated” (O-C) value of the minimum, in days on the left axis, and in phase on the right axis. Add your measured point and error bar. Is it consistent with the plot?

As a class, we will investigate what else we can learn from the lightcurve of an eclipsing binary star.

Bulletized Synopsis

Purpose: Measure the lightcurve of an eclipsing binary star, and determine its O-C minimum time.

- Plan for observation of an eclipsing binary, to ensure that the images cover the time just before and after minimum brightness.
- Take a series of images separated by 2 minutes, and calibrate for Bias, Dark, and Flat.
- Align the images, and then do photometry relative to a reference star in the same field, to determine the lightcurve.
- Use Excel to plot the lightcurve vs. phase of the orbit.
- Fit the lightcurve to determine the minimum time, and calculate the O-C time for your observation. Discuss the results.