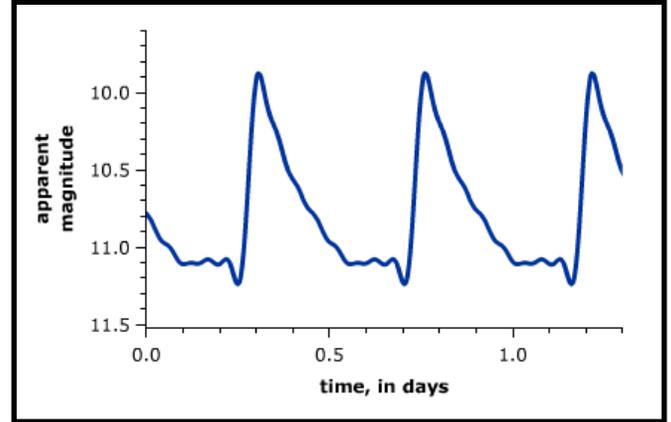


Variable Star Photometry – Student Guide

Background Material

Complete the following questions after reviewing the background pages entitled **Overview of Variable Stars** and **Properties of CCDs**.

Question 1: The light variation from a variable star is shown in the figure to the right. a) Identify the type of variable star and explain your criteria for classifying it as such, b) estimate the period of the variable star, and c) estimate its pulsation amplitude.

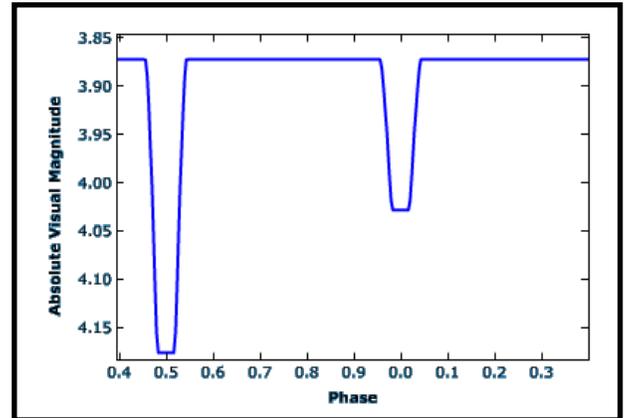


a) _____

b) _____

c) _____

Question 2: The light curve for a variable star is shown in the figure to the right. a) Identify the type of variable star and explain your criteria for classifying it as such, b) estimate the depth of the primary (deeper) eclipse, and c) describe what you can conclude about the period of the variable from looking at the light curve.



a) _____

b) _____

c) _____

Name: _____

Question 3: A CCD has a greatest possible pixel value of 4095. What is the bit level of this CCD?

Question 4: A star is being observed with an 8 bit CCD has a central pixel value of 82 counts when the exposure time is 10 seconds. What would the central pixel value be if the exposure time were 25 seconds? Explain your reasoning.

Question 5: A 12-bit CCD collects light from a star over a 10 second exposure and obtains a central pixel value of 1068. What is the longest exposure that could be taken of this star and still avoid saturation? Explain your reasoning.

Main Content

Part I: Registering Images

Open up the **Registration Simulator**. We will use this simulator to identify variables in sequences of CCD images.

There is a long history of “blinking” images in astronomy. Early in the 20th century photographic plates were placed in an apparatus known as a blink comparator where a mirror was rapidly flipped to swap different photographic plates in and out of the field of view. This was largely used to find objects (with large proper motion) that were moving relative to the background stars. Clyde Tombaugh discovered Pluto by this method in 1930. Blinking images also allows one to detect variable stars as their size on the image changes as their brightness changes.

Implicit in this discussion is the idea that the images are perfectly aligned. The motion of Pluto relative to the background stars (or the swelling of a variable star) can only be noted if these stars are perfectly aligned in the two views. This process of alignment is known as registration.

Name: _____

This simulator looks at three CCD images of a star field and addresses the issue that the center of each frame is not exactly in the same location. This naturally occurs due to minor errors in pointing and the telescope clock drive. You should experiment with the different features of the simulator, but your ultimate goal is to register (align) the three frames so that when the **switch on top field** button is repeatedly pressed the stars don't move.

The general procedure is:

- First align starfield 2 to starfield 1 (which stays fixed). You will want to hide starfield 3. It may also help to use the options **make top field transparent** and **invert colors**. Drag the top field and align its stars with those in the starfield below. When there is no star movement when switching different fields into the top position, then the fields will be aligned.
- Now repeat this procedure for starfield 3.

Question 6: Enter the offsets you obtained for starfield 2 and starfield 3 in the table below.

	x offset	y offset
starfield 2		
starfield 3		

Part II: Identifying Variables

Open up the **Blink Comparator Simulator**. This simulator has a large number of images of the same starfield programmed into it. All of the frames have already been registered for you. The starfield contains several variable stars of different types with a wide range of periods. The individual observations are described by an epoch (the time from some arbitrary starting time) in days. You have the capability to add and remove images taken at different epochs from a blinking queue. You should experiment with this simulator until you are comfortable with its capabilities.

Question 7: The starfields of the blink comparator contain 5 variable stars. Create different blinking sequences in the simulator to identify the variables and record the x and y locations of the variables on this starfield. One variable star has already been located for you. Note that the coordinates do not need to be exact, you just need to be able to find the stars again in the next simulator

	x coordinate	y coordinate
Variable #1	64	114
Variable #2		
Variable #3		
Variable #4		
Variable #5		

Name: _____

Question 8: Hypothetically, suppose that you add a long series of observations all taken one day apart to the blinking queue. Would you be able to detect large amplitude variable stars with periods of a) 1.0 days, b) 0.5 days, or c) 0.75 days?

Part III: Obtaining Photometric Data

Open up the **Photometry Simulator**. This simulation consists of a CCD frame that contains many stars. Movable apertures allow you to zoom in on regions of the main image in sub-panels and read off the coordinates and values of individual pixels. We will ultimately use these apertures to determine the brightnesses of stars. Note that these are circular apertures – they appear jagged since an individual pixel must either be inside or outside of the aperture.

Drag aperture 1 (green) and center it on the bright star at $x = 359$, $y=129$. Roll the cursor over the Aperture 1 Info panel to explore the pixel values for this star.

Question 9: What is the range of pixel values inside the inner circle for this star? (Find the maximum and minimum values.)

	Pixel Values
Minimum	
Maximum	

We will now use this simulator to learn about how astronomers determine the brightnesses of stars from CCD images. Note that there are two components to the values of the central pixels — light actually coming from the star and a background reading from scattered light in the sky. Our goal is to separate the two components and have a reading solely representative of the star. Thus, the inner disc is designed to collect the vast majority of the starlight and should be sufficiently large to successfully accomplish this. The outer ring is used to sample the background sky brightness. Thus, the total number of counts representative of the star is defined as total flux $f = (\text{Counts in Inner Disc} - \text{Number of pixels in the Inner Disc} * \text{Average Value of Outer Ring})$.

Question 10: Determine the background sky brightness average counts per pixel for the star at $x = 359$, $y=129$.

Name: _____

Question 11: What are the radii of the inner disc and outer ring used to defined the apertures?

Astronomers typically describe the perceived brightnesses of stars in terms of apparent magnitudes – a logarithmic scale where smaller numbers reflect brighter stars. Since the quality of the observing conditions varies over time – i.e. thin clouds come and go – it is necessary to express the brightness of stars in terms of differential magnitudes. This is the magnitude of one star minus the magnitude of another. When determining the changing differential magnitude of a variable star over time it is very important to be certain that the second star really is a constant star and not another variable. This second star is known as a comparison star (and a third star used to verify the constancy of the comparison star is known as a check star). Differential magnitudes allow photometric observations to be made under imperfect sky conditions – whatever atmospheric turbulence, clouds, moon light, etc. – is affecting the variable star is presumably affecting the comparison star in the same manner.

Question 12: Use the simulator to determine the differential magnitudes for the following pairs of stars.

Star 1		Star 2		f_1	f_2	$m_1 - m_2$
x coord	y coord	x coord	y coord			
170	52	41	72			
41	72	170	52			
170	52	113	186			
348	33	279	262			

Question 13: Find a star (give its x and y coordinates) that is 0.63 magnitudes fainter than the star at $x = 29, y=157$.

Part IV: Analyzing Photometric Observations

Open the **Variable Star Photometry Analyzer**. This simulator has all of the same registered fields that you used in the blink comparator along with photometry for all stars in the field. The **Star Field Panel** in the upper left shows the field and allows you to select a “star of interest” and a “comparison” star. You can conveniently form differential magnitudes for all of the photometry for any two stars in the field. You should initially select a comparison star and a star

Name: _____

of interest. From then on clicking on a non-selected star makes it the star of interest while clicking on a star that is already selected swaps the comparison and star of interest designation. Note that the **show crosshairs** option allows you to read off the coordinates of stars.

The **PDM Plot and Period Selection** panel is at the bottom of the simulation. It automatically runs the PDM period determination algorithm on the differential magnitudes of the two selected stars. PDM calculates a statistical parameter θ for a specified range of trial periods. Relevant periods show up as minima of θ in PDM. Users who desire more information on exactly how PDM works should consult the optional supplemental page on it. The light blue triangle at the top of this plot allows one to select a period. One can zoom in on various regions of the graph by dragging through (and highlighting) a range of periods and then clicking in this range. Additional zooming functionality is supplied through four buttons on the left.

The **Observations Plot** panel illustrates the differential magnitudes for the two selected stars. This panel receives the selected period from the PDM Plot and Period Selection Panel. The **light curve plot type** is shown as time (in days) by default and the spacing of vertical lines illustrates the selected period. You can do a crude job of estimating the period by comparing the spacing of these lines to the data. However, typically you will wish to form light curves using the phase plot type option. Phases are calculated by using the selected period and some arbitrary starting epoch. Thus, you can select different periods in the PDM plot and form the resulting light curves in real time. A **Show Difference Tool** allows you to conveniently measure the amplitude of a variable star.

Question 14: Identify two constant stars in the star field and form differential magnitudes for them. Explain how you know that they are constant stars and not variables.

You should now verify the results you obtained from the blink comparator. Make certain that that you have correctly identified all of the variables in the field by noting the scatter in differential magnitudes about the average value.

Analysis of one Example Star

- Select the variable at $x = 64$, $y = 114$ and identify an appropriate comparison star (any other star that is not a variable). Make sure that the green circle is on the variable star otherwise you will see the light curve with the magnitudes reversed.
- Adjust the period cursor looking only at the spacing of the vertical bars in the Observations Plot. Certainly the period of the variable must be less than one day.
- Change the light curve plot type to phase in anticipation of exploring candidate periods.
- Zoom in on the period region of the PDM plot below one day. Note that there are a number of low values of θ (local minima) representing potentially relevant periods that need to be explored.

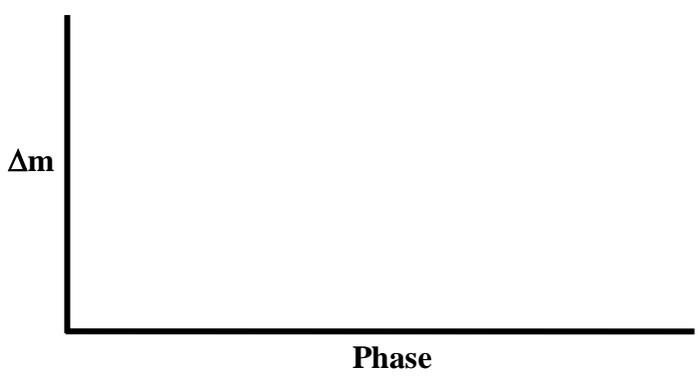
Name: _____

- The lowest value of θ occurs for a period between 0.30 and 0.35 days. Expand this region of the PDM plot so you can more accurately specify periods. After zooming in as far as possible it can be seen that the lowest value of θ occurs for a period of 0.3170 days.
- We now need to evaluate the light curve for this period – and it doesn't look that good since there is a fair amount of light curve scatter. Let's try and tweak the period to get a tighter light curve. It gets worse as the period is increased to 0.3185 days. It improves as one decreases the period. Whether the best period is at 0.3167 or 0.3168 or 0.3169 is a matter of taste. Note that our period resolution is limited in an effort to keep these simulators responsive to input. When astronomers run period searches on real data they often make use of 6 or more significant figures.
- A comparison with the light curves shown on the Overview of Variable Stars background page suggests that this is an RRc star. It certainly is in the right period range for an RRc and has the expected sinusoidal shape.
- We can now use the **show difference tool** to measure the light curve amplitude. You should try to ignore the scatter of the data when you do this. Simply measure the difference between the middle of the top of the light curve and the middle of the bottom. A value of 0.54 ± 0.02 magnitudes is reasonable.
- Although our results so far appear very reasonable, we still should check some of the other θ local minima.
 - The second lowest value is at a period of 0.4625 days. Although this period gets all of the high values of the light curve near one region of phase and all of the low values near another region of phase, there is still way too much scatter. It also doesn't look like any of the commonly occurring light curves. Making subtle changes to the period doesn't improve things.
 - Another low value occurs at a period of 0.2413 days. No reasonable light curve can be formed for any periods in this range.
 - Another low value occurs at a period of 0.6337 days. This period does yield a light curve with reasonable scatter. However, there is no known variable that has such a light curve. Note that this period is twice the value that we liked above. We are simply dividing the points up into two groups and "doubling" the true light curve. Most of the other periods that have low θ but don't yield good light curves have interpretations – reasons why they show up. These will be covered in an optional section on aliases.
- Thus, in our final analysis we conclude that this is an RRc type RR Lyrae star with a period of 0.3168 days and a pulsation amplitude of 0.54 magnitudes.

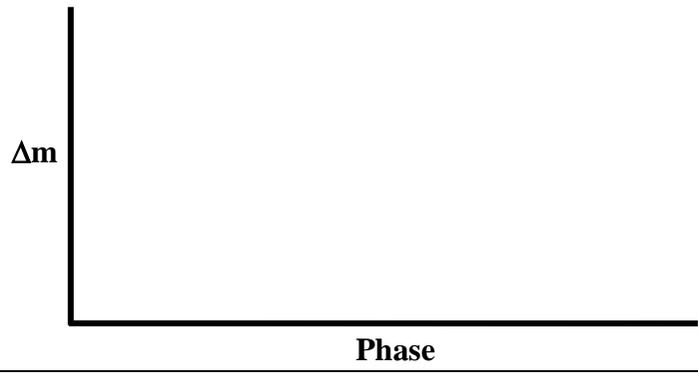
Question 15: Analyze the observations for each of the other four variable stars in this field. You should determine the period, light curve amplitude, and the type of variable. You should clearly discuss what factors led you to classify the variable star in the manner you did (which may involve a process of elimination).

Name: _____

Variable #2

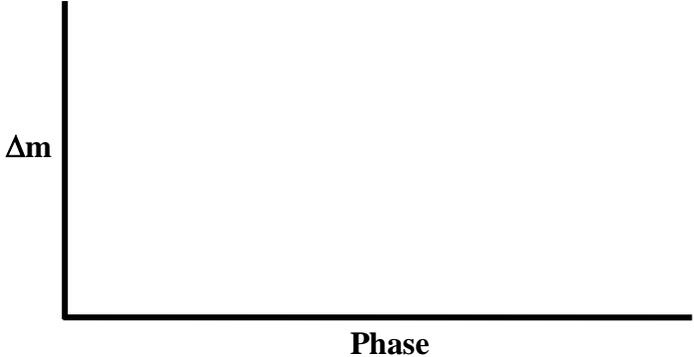
x =	y =
Period =	Amplitude=
Sketch of Light Curve	
	
Type of Variable =	
Discussion of Classification	

Variable #3

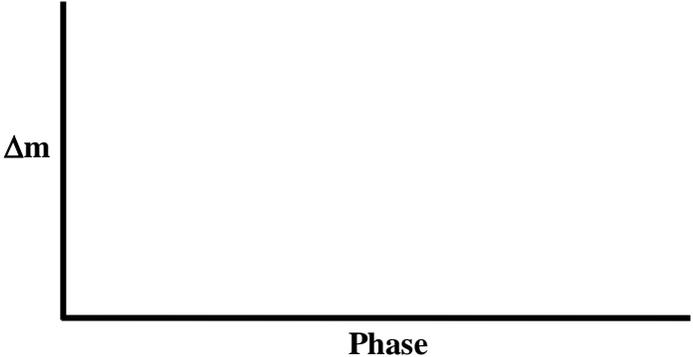
x =	y =
Period =	Amplitude=
Sketch of Light Curve	
	
Type of Variable =	
Discussion of Classification	

Name: _____

Variable #4

x =	y =
Period =	Amplitude =
Sketch of Light Curve	
	
Type of Variable =	
Discussion of Classification	

Variable #5

x =	y =
Period =	Amplitude =
Sketch of Light Curve	
	
Type of Variable =	
Discussion of Classification	

Name: _____

Question 16: Based on your experiences with the **Blink Comparator Simulator** and the **Variable Star Photometry Analyzer**, how do you think variable stars are detected today?

Part V: Period Accuracy (Optional)

Set up the analyzer to investigate the variable at $x=64$ $y=114$. Zoom in as much as possible on the deepest dip in the PDM Plot which is at 0.3168 days. (You'll know if you've zoomed in as far as possible since further attempts at zooming will shift the plot left or right but won't increase the zoom level.) Select 'phase' for the light curve plot type and position the period cursor at 0.3168 days. Although there is some scatter due to noise, the data points from different cycles all fold together to make up a clear and distinct light curve.

Question 17: Now slowly move the period cursor away from 0.3168 days. Describe what happens to the points in the light curve as you do this.

Question 18: Drag the cursor to 0.3158 and then to 0.3178 days and note the appearance of the lightcurve. These values are 0.001 day away from the best fit period. How good is the fit? Could you reasonably mistake these values for the true period?

Question 19: Now select the variable at $x=124$ $y=260$ for comparison. You have already determined a period for this star (it should be somewhere between 8.5 and 9.0 days). Zoom in on

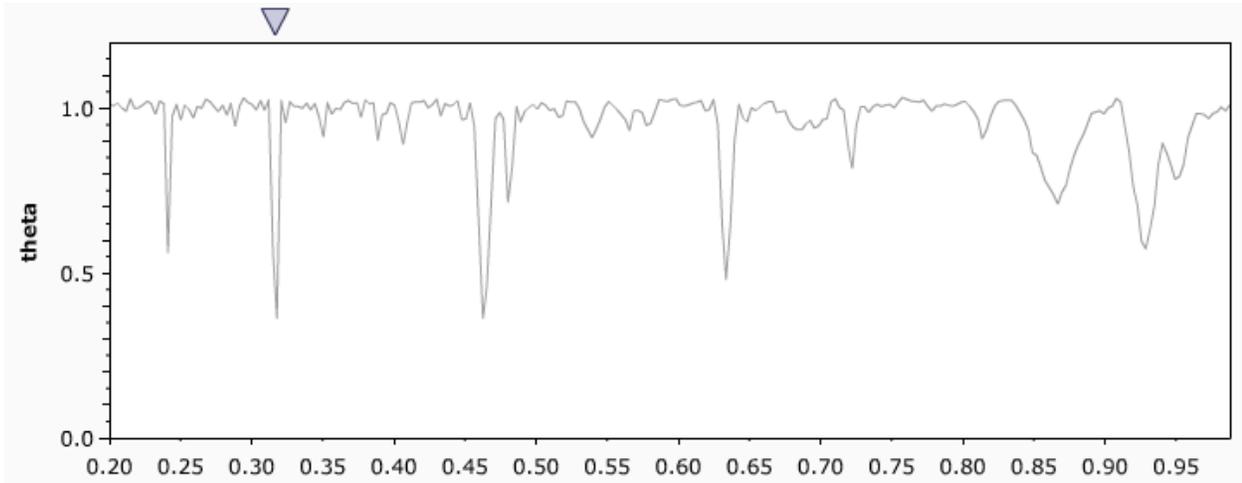
Name: _____

the PDM Plot as much as possible and position the cursor at the period you determined. Now drag the period cursor around. Compare what you see to your observations for the previous star. What happens when you drag the cursor to values at 0.001 day away from the period you determined? Is there much difference in the light curve?

Question 20: Why does a small change (0.001 day) in the period have such a different effect on the light curves of these two stars? (Hint: the observations in the simulator were taken over 20 days. Consider the number of cycles each star went through during this interval.) Which star's period is more precisely known? What advice would you give an astronomer who is trying to determine a variable's period as precisely as possible?

Part VI: Aliases (Optional)

Our analysis of the variable at $x = 64$, $y = 114$ showed that it was an RRc star with a period of 0.3168 days. However, we had to rule out other significant minima in θ based upon the appearance of the light curve. Note that there are two main reasons that aliases – other periods besides the correct one – show up in the period search.



Many aliases are integer multiples of the true period. Doubling the period simply splits the data into two pools – one pool into phases from 0.0 to 0.5 and one from 0.5 to 1.0. Tripling the period would split the data into three pools.

Period	Interpretation
0.2406 days	One Day Alias
0.3168 days	Correct Period
0.4637 days	One Day Alias
0.4812 days	Twice One Day Alias
0.6336 days	Twice Correct Period
0.9274 days	Twice One Day Alias

A second reason is that the manner in which we collect our photometry artificially introduces periodicities into the data. Astronomers typically observe in the early evening and possibly into the morning hours if they are not teaching the next day. Thus, much of the data has a built in 24 hour periodicity. Aliasing can also be seen for lunar periods (astronomers trying to observe around new moon) and seasonal yearly aliases in long term observing projects.

We can calculate the one-day aliases from adding frequencies (much like beat problems in physics).

$$\frac{1}{P_{New}} = \frac{1}{P_{True}} + 1 = \frac{1}{(0.3168 \text{ days})} + 1$$

$$P_{New} = 0.2406 \text{ days}$$

$$\frac{1}{P_{New}} = \frac{1}{P_{True}} - 1 = \frac{1}{(0.3168 \text{ days})} - 1$$

$$P_{New} = 0.4637 \text{ days}$$

Question 21: Find and identify 3 alias periods for the variable at x = 131, y = 202.

Period	Interpretation