A Neophyte's Determination of EY Ceph Curves and Orbital Constants

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Abstract: Using amateur level equipment, and with a beginner's knowledge of photometry, I have built the light curve for the eclipsing variable EY Ceph (subject suggested by Claud Lacy). This 10mag star has two 0.6mag eclipses per cycle, with a period of 7.97 days. The good observing news is that it is circumpolar (so easily visible), the bad news is that if the eclipses are not visible at night at your location (or if you miss them), you have to wait 6-8 months before they return. Combine this with only three days notice to start the campaign, no experience in precision photometry, and limited (but good) equipment, the amazing thing is that I achieved success in the first week (then the weather deteriorated...). I will present intensity curve results to date, discuss how I got to them, and provide the results of a preliminary calculation of the system parameters (orbits, sizes, etc).
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Introduction

EY Cepheus is a 10mag eclipsing variable with a 7.97 day period (RA=03d40m15s Dec= 81d01m45s). In the late 1980's, Dr. Claud Lacy (Department of Physics, University of Arkansas) and others investigated the star using spectroscopic techniques and determined its period and relative velocities. However, because the period is almost an integer multiple of the day, it will take approximately 8 months to develop the full light curve. Without the light curve data, it is impossible to compute many of the characteristics of the star system.

In late 2001, I had corresponded with Claud Lacy (one of our dome customers from our days as owners of Technical Innovations) concerning his use of the automated RoboDome for his long-term variable star studies. I expressed interest in photometry, and in early February he suggested I try EY as a project. He noted the 7.97144 day period, which conflicted with the period given in standard tables of 5.51672 days (such discrepancies are not uncommon). During the following week, I imaged the star field (C11/ST7 on AP1200), was able to identify which star was which, and saw BOTH eclipses (occurring within an hour of the predictions of ten years before)! I was hooked.

In this paper, I will describe the steps I took in learning how to do photometry with the equipment on hand. I am a physicist, and have many years' experience with advanced amateur equipment, which I have used primarily for a variety of imaging. However, I am almost a complete neophyte in the far more arcane art of photometry but decided that it looked interesting, and was both a way to learn a new field and to contribute to some real science.

Equipment

This observing campaign would involve very long runs over many months, with the goal of high accuracy measurements. I would need to use at least some photometric filters to improve the quality of the results, and to allow intercomparison with the work of others. I would also have to improve the quality of the tracking and other features of the observing setup.

I have used a 6" f12 refractor on an AP1200 with an ST7 ABG for many years. The equipment is housed in a remote controlled ten foot ProDome about 400 feet from our house operated over a local network. However, the need for better sensitivity caused me to upgrade to the ST7E NABG. I also

installed a C11 OTA in place of the refractor (using a 6.3 reducer, the FOV is about 9x14 amin). Unfortunately, although optically acceptable, the C11 ultimately proved to have terrible mirror flop—so bad that I could not properly polar align the mount nor perform orthogonality correction. The pointing accuracy was about 15amin or worse. After months of frustration, I finally opened the C11 and found that the mirror was in effect supported by silicone caulk at the rear of the center hole, thus allowing the mirror to tilt as the tube changed direction. I installed a temporary fix to make the mirror rigid with the cell. Although the fix caused astigmatism (which does not hurt the photometry), it did solve the flop: the system now points accurately, and tracks within about 2-3 amin over 10-11 hours with no guide star. Thus I could start an observing run, go to sleep, and have an excellent chance of having good data the next morning. This is the way to go!

After the first week of gathering EY Cep data using the ST7E directly, I obtained a set of photometric filters and borrowed a filter wheel. Unfortunately, the filter wheel was old and its dimensions did not quite match the filters. No problem, just machine down the filters, and trim the threads with a file.

Software

I have used MaxIm DL for several years for both CCD control and image processing. I noted that the new V3 includes a set of photometry tools. These include the ability to measure dozens of stars on about 125 images at a time, and graph and save the results. The tools are extremely easy to use, and include many very nice features.

Unfortunately, the algorithm forces the user to choose a reference star; i.e., it will not measure the intensity of stars on an image except by comparison to one of the stars on the same image. This makes it impossible to move the data to a spreadsheet where the user can analyze and compare different combinations of stars among different images. After discussion, Ajai Sehgal, one of the original contributors to MaxIm, wrote a plug-in that installs a standard reference star in the upper left of each image. I can then choose this as the reference star, and measure the stars of each image relative to it and move the data to a spreadsheet. Using the spreadsheet, I can graph the brightness of all the star measurements to look for clouds or other problems, and can compare any star with any other, on the same or on different images.

This system works very well. MaxIm reports the intensities as magnitudes (relative to the reference star) as X.XXX. The time of the measurement is recorded as Julian Day. Note that in the measurement of EY eclipse timings, the ultimate analysis will require the JD to be converted from geo-centric to helio-centric to correct for the light travel time differences as the earth moves around the sun relative to EY.
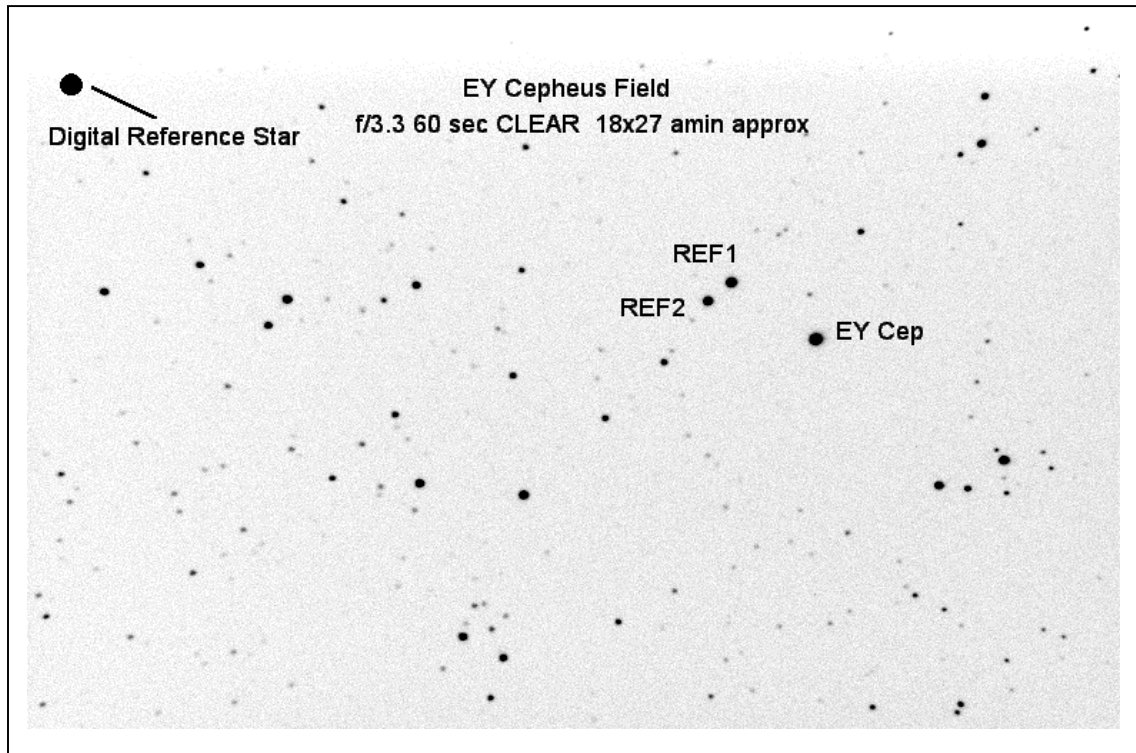
The observatory remote control uses Radmin, a very fast, yet inexpensive, remote control program. Because the dome computer has more RAM and is much faster than my desk computer, I perform the photometric analysis remotely, then download the magnitude data to my desk machine for Excel analysis.

Typical Run

A typical run starts at dusk with remote opening of the observatory. I turn on the scope and camera, move it to a bright star, and calibrate (synchronize) the mount. I usually do a quick look at supernova SN2002 (getting lower in the west), then move to a 5-6 mag star near EY where I focus the scope (usually "manually" or with FocusMax using RoboFocus on the C11 focus knob). I then move to EY, and begin imaging (usually using the autodark for these short exposures). This startup process takes about ten minutes (plus time spent at SN2002!). EY has two nearby stars (about 1.5-2 mag fainter) that I use as the prime reference stars, each about 2-3 amin distant. In addition, there are about 8 additional stars although another 2-3 mag fainter.

Over a ten hour run, the temperature may change by 10F or more at our location. The C11 at f6.3 will show a detectable change in the quality of focus for a 1-2F change, while 10-15F will grossly change the star image size (e.g., from FWHM=4 a-sec to 12 or so). For most runs when I expect the temperature to change more than a few degrees, I operate the RoboFocus using temperature compensation. Although

some of the compensating moves take place during an exposure, the focus moves are normally in the same direction (the non-backlash direction to minimize mirror movement). Even when this movement occurred during an image (approximately 1 in 20 images), the elongated stars could still be used for photometry.

Observing runs normally go all night, terminated only by sunrise or gross weather changes. If clouds came through, I normally continue imaging as less than perfect data are still better than no data!

The next morning, I load the data blocks of 100-125 images into MaxIm. I first blink the images, looking for anything of interest and noting any large blocks of bad images (weather or other problems), taking about 3-4 minutes. I then operate the digital reference star plug-in, which takes about 3-4 minutes to insert the reference star into all the images. I then perform the photometric analysis (also about 3-4 minutes). After evaluating the graphs in Maxim, I save the block of intensity data to a text file for later Excel analysis.
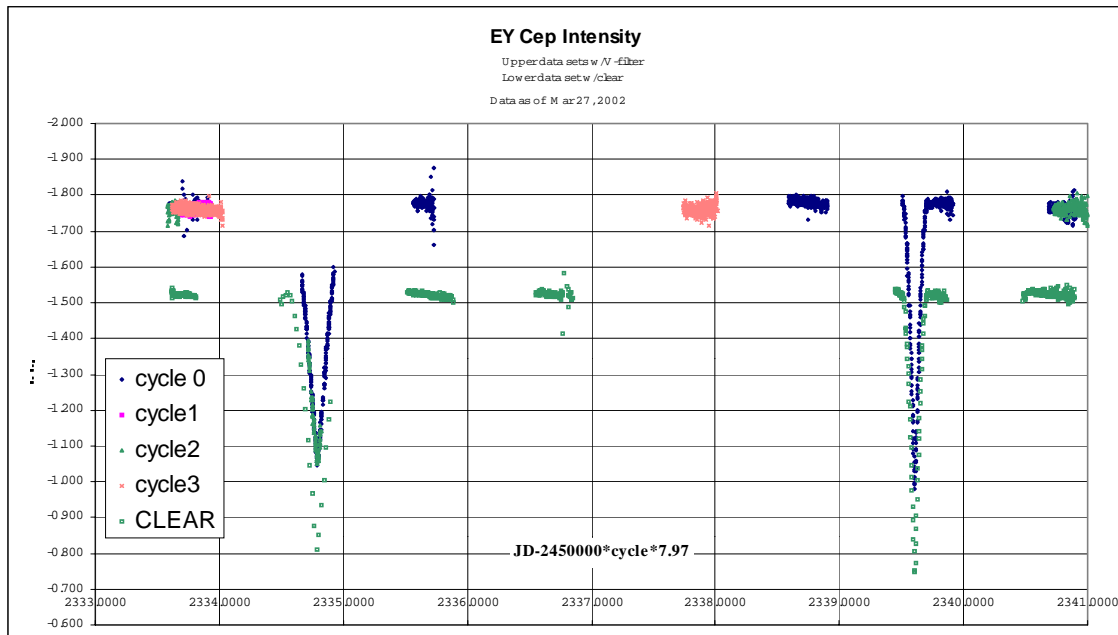
One of the issues in this kind of program is how to keep your data straight! Because these data will be taken over many months and under many conditions, one must be careful to establish standard nomenclature of the data sets. I also normally take a screen shot of the computer monitor as a record of which star was assigned which number.

Data Set Creation

After I analyze a set of images, I move the data into an Excel spreadsheet. I then do a plot of all the data vs. time, which shows the presence of clouds or other problems. I can mix and match data, compare different stars to one another, and generally get a feel for the data. I then plot the EY intensity minus the average of the two reference stars. Taking into account the weather and other data, I delete data points that are clearly inaccurate or suspect. These amount to less than ten percent of the data. I then copy the resulting data onto a Master page in Excel.

On the Master page, I plot all the data sets together, both in a time linear fashion, and with time folding the data according to the 7.97-day period, as shown in the figure. Each group of data includes 100-300 data

points (as listed in Table 1 below). The data on the lower curve ("CLEAR") are from the initial data set before I began using the V-filter. In the discussion below, I will refer to the Day Number during the cycle. The deepest eclipse takes place on Day7, and is known as the M1 eclipse (the other is M2).

Although there are many details of the light curve yet to measure (e.g., apparent structure on Day6 and small peaks preceding each eclipse as hinted in the CLEAR data), the overall shape of the curve is already clear including the timing, amplitude, and shapes of the eclipse events. These data, combined with the spectroscopic data previously obtained, are sufficient to allow calculation of the EY double star system characteristics. These data were sent to Claud Lacy who performed a preliminary EY star system evaluation (See Below).

System Evaluations

As this is my first photometry project using this equipment, I have committed a major effort to develop a detailed understanding of how well the system works. The result is a series of mini-studies (still ongoing) that evaluate different aspects of the system hardware and software, and on the data itself.

Hardware/software studies include
- Uniformity of CCD response across image and evaluation of how and whether to perform flats on the data
- Determination of whether the results depend on various settings in the MaxIm photometry tools

Data studies include
- Noise and consistency in the data
- Color changes during the eclipse (as one star blocks the other)
- Search for variability among reference stars

CCD Uniformity and Flats

Flat fielding is a method used to correct the images to achieve a uniform response across the chip. The flat field calibration of the raw image can reduce the effect of vignetting, dust, CCD pixel to pixel variability, and other sources of error that contribute to getting a different measurement depending on where the image is on the chip. I had previously used dome flats very successfully in imaging; however, I

felt I had to investigate this practice more carefully. Indeed, I quickly discovered that the flats contained a 2-4% gradient across the field. Although the flats were smooth (and could thus correct pixel to pixel variations in sensitivity), such a gradient in a flat calibration could cause a photometric error if the star image moves across the field or if the images are reversed during a run (as a GEM flips).

I investigated a variety of flat production methods including:
- Dome flat with different lighting
- Tee shirt flat
- Sky flat using cloudy night data
- Sunset sky data

The flats usually showed very fine pixel to pixel variations under 1% variations and a few faint (1%) amplitude effects due to dust. More serious, however, I noted that most flats showed gradients as high as 3-4%. Such a gradient could be in the source, i.e. the flat field source is not truly uniform. It could be in the chip itself, i.e. the chip sensitivity varies across the chip. Alternatively, the gradient could be produced in the telescope/filter wheel/camera combination as a result of the light from the flat field source. A flat field floods the scope with light which can reflect within the system, reaching the chip where it can produce a gradient superimposed on the light directly reaching the chip.

I decided to investigate the gradient in two ways.

The first investigation began with imaging a convenient star field having several dozen reasonably bright stars in the field. I then rotated the camera on the scope, so that the star field would be rotated 180 deg. on the chip. I could then measure the same stars relative to one another on the normal and rotated images to determine whether there was any variation in response (after all, such a variation is what the flat is supposed to correct). The result was that there was no measured sensitivity gradient across the chip in any direction that was greater than .014mag (1.4%). This result held for both straight through (no filter) and the V filter.

The second investigation was to take dome flats, which showed approximately a 2% gradient horizontally and vertically on the image (I evaluated the gradients using the MaxIm DL line analysis function). I then rotated the camera 180deg and repeated the images. If the image gradient rotated, then this would show that the gradient was in the source (dome flat or non-rotated telescope). The results showed that 1/3 of the apparent horizontal gradient and none of the vertical gradient was from the flat/scope. The remaining amount of the gradients evidently arose from asymmetric reflections within the scope, filter changer, or camera. The results were the same for the clear or V filter.

The flat data differs from the star measurement data, and shows that a flat source that floods the scope with wide angle rays will not produce a valid map of the sensitivity of this optical system suitable for use in a typical imaging situation. I have decided not to use flat calibration for this initial analysis, as it is likely to introduce more error than it cures in this particular system. The next step will be to conduct tests in which I rotate the scope as well as the camera. I will then reopen the scope and install improved light baffling (and fix the mirror mount), and continue this evaluation.

Evaluation of MaxIm settings

The user has several choices when performing photometry With MaxIm DL. One of the most obvious is the size of the aperture mask used in the software for making the intensity measurements. I investigated this using a typical data set with three choices (R=8,12,16) pixels by measuring the EY intensity vs. the two reference stars. Although changing the aperture radius changed the apparent intensity of any particular star by up to 0.1mag (relative to the digital reference star), the relative photometric readings changed less than .005mag. Aperture choice is clearly not a problem, at least for reference and object stars that are within two mag of one another as in this case.

Noise and consistency

Consistency and noise (image to image variations) can be gauged by comparing the average and standard deviation of a set of measurements that one expects to be uniform (as in portions of the light curve between eclipses). Contributors to reduced signal level such as clouds, filters, shorter exposure times, etc will all cause the apparent noise to increase. Variations in the color transmission of the sky (e.g., as EY descends toward the horizon) are reduced through the use of relative photometry and by using the V-filter.

Table 1 is a summary of the data to date. The columns are as follows
Col 1. Relative day during the eclipse cycle
Col 2. Note re data
Col 3. Calendar date in 2002 of start of data set (e.g., evening of 2/27/02)
Col 4. Julian Day (less 2452300)
Col 5. Cycle number after start of project (8 days per cycle)
Col 6,7. Average mag of EY rel to the digital reference star and Std. Dev.
Col 8,9 Difference in mag of two reference stars, and Std. Dev.
Col 10. Number data points in data subset

Table 1- Data Sets (to Mar.27, 2002)

Eclipse Day Phase	Note	MM/DD	JD	Cycle	EY	Std Dev	REF STARS DIF	Std Dev	# pts
1		02/27	33.9	0	-1.766	.011	-.860	.018	
		03/07	41.9	1	-1.760	.008	-.849	.014	
		03/15	49.6	2	-1.760	.016	-.847	.022	
		03/23	57.9	3	-1.761	.009	-.852	.016	
2	Eclipse	02/28	34.6	0	NA	NA	-.865	.016	
	Eclipse	03/16	50.6	2	NA	NA			
3		03/01	35.7	0	-1.776	.014	-.867	.022	
4	No Data								
5		03/27	61.9	3	-1.759	.015	-.848	.031	
6		03/04	38.7	0	-1.780	.008	-.865	.015	
7	Eclipse	03/05	39.6	0	NA	NA	-.864	.014	
8		03/06	40.9	0	-1.760	.013	-.846	.021	
		03/22	56.9	2	-1.762	.013	-.851	.025	
	AVE/SD				-1.765	.008	-.856	.008	

Color Changes During Eclipse

It is interesting to measure the relative colors of EY compared to the reference stars, and to measure whether there are color changes in EY during an eclipse (as one star blocks the other). As a first attempt, I measured the various stars using the Blue and Red photometric filters and evaluated the differences. The measurements showed that during the eclipse the color as measured by B-R changed less than .01mag. This is consistent with the spectroscopic data that show the two stars of EY as being of the same class.

Search for Variability among reference stars

EY has two convenient reference stars nearby that I have used for all the photometric measurements. However, it is still possible that these stars themselves may be variable. Although the main concern is to show that the reference stars are stable over the 8-day cycle of EY, because data will be taken over many months, one would also like to know the stability of the reference stars over that time as well. I have also measured additional stars on the images as additional checks (though not all stars are on all images).

The data in Table 1 show the variability as measured by the average and the standard deviation of the difference of the reference stars in each data set. The standard deviations are in the range of .014-.031 mag, and the standard deviation of the set of averages is about 0.008 mag. There is no indication in the data of variability in the reference stars over the time measured.

Preliminary Results

The purpose of the intensity data is to combine it with the spectroscopic data to permit computation of the EY Cep characteristics. Although I will not have the full intensity curve until next year, the present data allowed preliminary calculation of the system characteristics. Based on these data, the results reported back to me by Claud Lacy are as follows:

> From the light curve model you get the relative radii (relative to the semi-major axis), the orbital inclination, the relative surface brightness of the secondary (relative to the primary), and the eccentricity factors (e cos w) and (e sin w), hence the eccentricity and the longitude of periastron. From the RV curve model you get the mass factors (m sin^3 i), the projected semi-major axis (a sin i), and the eccentricity and longitude of periastron. The combination of the two sets of results produces the absolute dimensions and masses. The sharp bottoms of the eclipses are due to the facts that the orbital plane is almost exactly edge-on and both stars are essentially identical.

> The data you have already gathered is sufficient to fix the major geometric and radiative parameters of the model to an accuracy of about 1%! The eclipsing binary consists of a pair of essentially identical F2 stars with masses of 1.51 solar masses each, and radii of 1.43 solar radii, indicating they are very young main-sequence stars. The semi-major axis of the orbit is 24 solar radii and the orbital eccentricity is 0.45, quite eccentric and another indication of the youth of the system (they tend to circularize pretty quickly due to tidal forces). The orbital plane (as seen by us) is almost exactly edge-on. The standard error of the observations is about 0.013 mag, quite reasonable. Thanks for your research efforts so far. They bode well for the future of the project.

Conclusion

Even with little experience, with the proper equipment and software, and "a little help from your friends", one can do "real science". Of course, this particular project will require many more months of data taking for a complete data set, and many more internal and external data comparisons to assure that the data are as reliable as possible. Even this work is just a "toe in the water", as there is always the goal to do more accurate measurements, and to take on ever more challenging projects.