Lessons from DSLR Photometry of b Per "Third Star" Eclipse (February 2018)

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Abstract

Photometry of the "third star" eclipse of b Per was done using an 80mm refractor and Canon EOS/Rebel DSLR. The observing run provided a clear view of the beginning of the "third star" eclipse, and a fair lightcurve of the ellipsoidal variation of the inner binary pair. This project also provided a case study in some well-known considerations for DSLR photometry of bright variable stars: the interplay of exposure duration, de-focus, and camera linear range; selection of the size of the measuring aperture; the risk that the size and shape of the PSF might vary across a relatively wide field-of-view; and the merit of averaging/binning observations to reduce photometric scatter. In this case, everything went very well, and provided excellent internal consistency and photometric precision of 0.01 mag over 10 nights of observing.

Background

AAVSO Alert # 610 requested monitoring of b Per (= HIP 20070 = AUID 000-BBG-774) to detect and characterize the "third star" primary eclipse ,which was predicted for 12 February, 2018. b Per is a three-star system. The inner pair ("A"-"B") has an orbital period of ≈ 1.52 days. These do not eclipse, but do exhibit a continuous periodic brightness variation caused by the ellipsoidal distortion of the stars. The third star ("C") orbits this pair with a period of ≈ 704.5 days, and does display transits/eclipses as it passes across/behind the inner pair. The star is bright (V ≈4.6). The third-star eclipse depth was expected to be about Δmag ≈ 0.25 mag, and the ellipsoidal variation is about Δmag ≈ .07 P-P. Each observer was requested to monitor the star with long observing runs each night, spanning the interval from a week before to a week after the eclipse, in order to characterize offsets between observers, and to ensure that the ellipsoidal-variation could be properly treated in each observer's data

An image of the field, with target, Comp, and Check stars identified, is shown in Figure 1.

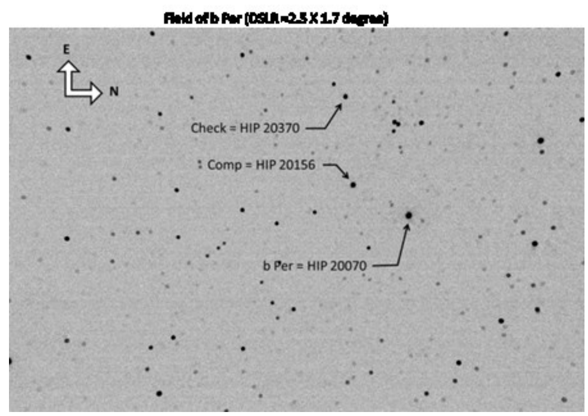


Figure 1: Field of b Per in DSLR

Equipment

I have recently moved to Gold Canyon, AZ, and haven't yet built a permanent observatory. For this project, I cobbled together a simple portable setup: an 80 mm F/6 refractor, an old Canon EOS/Rebel DSLR, and an even older Celestron Polaris mount. The equipment was placed on the roof deck of our house, as shown in Figure 2.

Figure 2: Portable photometry setup

Several cheap accessories were needed to bring this together. As shown in Figure 2, the telescope rings aren't intended for this mount, so a short length of 1X3 Birch lumber was used to balance the assembly and attach it to the Polaris German Equatorial mount. There is no capability for guiding, but the mount tracks well enough for 30 second unguided exposures at this image scale. The telescope's focuser cannot lift the weight of the DSLR without slipping. This was dealt with by rigging a spring arrangement between the camera and the telescope ring that carries about half of the camera's weight. In the Figure, you can barely see this spring arrangement reaching the underside of the camera.

Polar alignment was done "by eye" (and not very well, as it turned out). There is not a "Go-To" mount, so target acquisition was done by offset-pointing and star-hopping each night.

The good results of this project show that scientific astronomical observations can be gathered with surprisingly simple equipment.

Planning and Preparation

This project presented challenges that are typical of bright-star photometry, compounded by the limitations of the DSLR camera:

(a) The target, Comp, and Check stars must be well within the linear range of the camera (i.e. unsaturated) on the images. This implies a peak-pixel << 3500 ADU for my old DSLR camera, with 12-bit output, which makes it very important to select appropriate exposure duration to avoid saturation of the star images. (A newer 14-bit camera would be more forgiving, but still a critical step in planning DSLR observations is to select the "right" exposure duration.)

(b) With such a bright target, a small aperture telescope is preferred, to avoid being forced to very short exposures.

(c) Exposures of at least 15 seconds are desired, to minimize the effect of atmospheric scintillation on the photometry.

(d) For DSLR photometry, a low ISO setting (ISO 100) is almost always preferred. The low ISO setting permits longer exposures without saturating the star image, and also increases the dynamic range of the system.

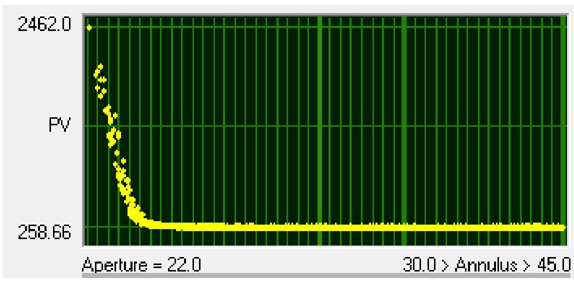
(e) It can be very useful to defocus the imager, for two reasons: First, it is mandatory that the star images be well-sampled (say, ≥4 pixels per FWHM); and a bit of defocus can help meet this criterion. With a DSLR sensor, the sampling requirement must be met after the image is "de-Bayered" to select just the Green channels, which implies a FWHM of at least 8-10 pixels before de-Bayering. Second, the defocus reduces the peak pixel count in the star image (compared to a "best focus" image), which might then permit the use of a longer exposure without saturating. See, for example Mann, et al (2011) and Conti & Gleeson (2017).

(f) With a bright target, a fairly wide field-of-view (FOV) – a degree are larger – is usually needed. Bright stars are widely spaced on the sky, and a narrower FOV won't comfortably encompass the target, a comparably-bright Comparison star ("Comp"), and a good Check star. In the case of b Per, there is only one good comparison star nearby, over 17 arc-min from the target; and the most convenient check star is over half a degree from the target. The setup that I used for this project provided a FOV of 1.7 X 2.5 degrees.

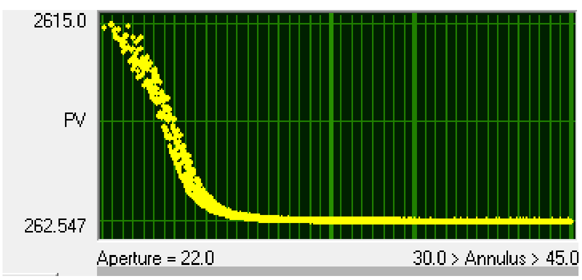
<u>Focus:</u> With the setup I was using, a well-focused image gave a point spread function FWHM ≈ 4 pixels (before de-Bayering). This is "too sharp" to be well-sampled after de-Bayering, and would present the risk of significant artifacts in the

photometry (changing collected light as the star shifts by fractions of a pixel between images). Hence, I spent a fair amount of time learning how to get a fairly-consistent de-focus, to FWHM ≈ 10-14 pixels (before de-Bayering) on each night, before starting the photometry run.

The PSF profile of a star on a tightly-focused image is compared to a de-focused, well-sampled image in Figure 3:



(Top) Tightly focused star image (not well-enough sampled for photometry) FWHM ≈ 4 pixels.



(Bottom) De-focused star image (well-sampled for photometry) FWHM ≈ 12 pixels.

Figure 3: PSF Illustration of de-focused star image

This de-focusing makes rather "ugly" images, with big bloated stars, but defocusing to provide well-sampled star images is important to getting precise and accurate photometry.

It turns out that for the bright target and comp star of this project, the defocusing also was useful for permitting relatively longer exposures. On the "well focused" images, the target star PSF was saturated with an exposure of just 8 seconds. The de-focused image stayed in the camera's linear range for a 30 second exposure (which was my goal).

<u>Linearity and exposure tests</u>: In order to select the exposure to use for the science images, I devoted a night to making a series of images of the target field, at different exposure durations and different ISO settings.

All of these were made with the telescope de-focused by a bit, to FWHM ≈12 pixels. The results using ISO 100 are shown in Figure 4. The combination of low ISO and de-focus permits the use of a 30 second exposure while keeping the peak pixel value in the target star's PSF safely below the linearity limit of the camera (which for this camera is about 3500 ADU).

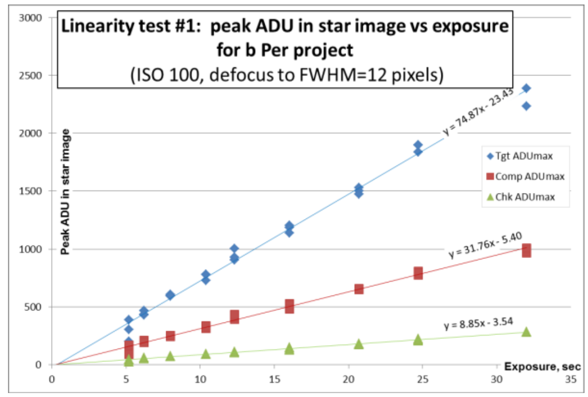


Figure 4: Linearity test (peak ADU vs. exposure duration).

I like to use the "peak pixel" test of linearity, because it is most sensitive to the problem of non-linearity and saturation (despite showing a bit wider scatter in the results, that is driven by small pointing and tracking changes or small seeing changes during the exposure).

An alternate test, using the integrated "star-minus-sky" ADU in the star image, is shown for reference in Figure 5, confirming that a 30 second exposure keeps the target star in the linear range of the camera.

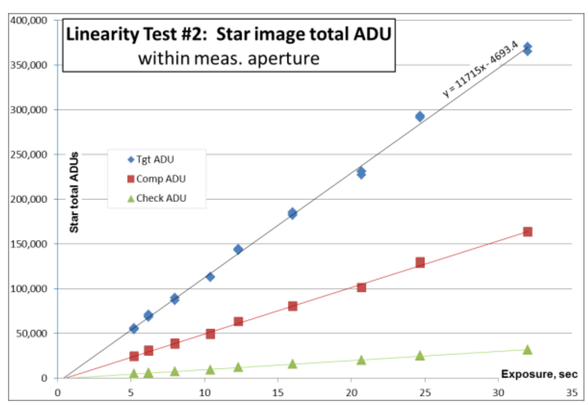


Figure 5: Linearity test (integrated ADU vs exposure duration).

As things worked out, most photometry runs had a bit more de-focus than the night of exposure-testing, which amounted to erring on the safe side: lower peak pixel values, and more protection against saturation.

Size of the Measuring Aperture: The concept of differential, aperture photometry is deceptively simple: Pick a measuring aperture size that encompasses the star PSF, and an annulus that captures the background sky (without any starlight in it). Add up the ADU counts within the measuring aperture ("star plus sky"), and the ADU counts in the annulus ("sky" only) and calculate the "star" (only" ADU counts by subtracting the annulus from the measuring aperture (with appropriate adjustment if, as is usual, the sky annulus contains more or fewer pixels than the star measuring aperture). Do this for both the Target and the Comp star. The intensity ratio of the Target and the Comp star is then

$$\frac{I_{tgt}}{I_{comp}} = \frac{\sum(tgt\ ADU)}{\sum(Comp\ ADU)}$$

so the magnitude difference is

$$M_{tgt} - M_{Comp} = -2.5 * log\left(\frac{I_{tgt}}{I_{Comp}}\right)$$

There are at least three approaches to selecting the size of the measuring aperture for photometry. One is to select it "by eye" – big enough to collect almost all of the star PSF, but not so big that too much sky glow is collected. This works surprisingly well in many situations, despite being poorly characterized (how much is "almost all" of the star PSF? how much is "too much" sky glow?).

A second approach is to examine the shape and size of the PSF, and select a measuring aperture that encompasses ≈100% of the PSF, including the faint "wings" that surround the main star image. It is easy to show that in most situations, this approach yields a lower SNR than might otherwise be achieved (because the large measuring aperture is collecting quite a bit of sky glow and dark-noise).

A third approach is to try to pick a measuring aperture that will maximize the Signal-to-Noise ratio (SNR). This may sound like a good thing: all other factors being equal, better SNR is always desirable. In typical situations, the "optimum" measuring aperture size is one that captures about 90% of the starlight (leaving about 10% of the starlight outside of the measuring aperture, because that "signal" in the wings is smaller than the "noise" contribution from the pixels in the wings.

However, all things are not necessarily equal. If you have a near-perfect system (all stars have identical PSFs, pointing and tracking errors are insignificant) or if you have a very faint target, then "optimizing" in terms of maximum SNR might be the right thing to do. But suppose that your system has some field-dependent aberration, so that star images near the edge are different (broader? elliptical?) than images near the center of the field. Further suppose that there is some pointing/tracking drift (polar alignment error?), so that your Target and Comp drift across the field, and their PSFs change (differently) as the night goes on. If one star's PSF broadens, then more of its light falls outside of the measuring aperture; if the other star's PSF remains unchanged, it will appear as if the "broadened" star has grown fainter, simply because more of its light falls outside of the measuring aperture.

Such a situation isn't unusual with small-telescope backyard setups – stars in the center of the image are "tighter" than those at the edges, and both focus and tracking might change over a few-hour observing run. On this particular project, I very nearly fell into this trap.

On several nights' photometry, I saw unusual trends, at the 0.05 mag level, but it wasn't immediately obvious what was happening. One particular night provided the essential clue: UT 2018-02-06. Here's the scenario: polar alignment was several degrees off, so that the stars drifted across the field (going northward), moving roughly half of the field in 2 hours. Then I re-aimed the telescope (to bring the target back to near the center of the FOV), took one set of images to check the pointing, then re-aimed again to move the target star a bit south of the center of the FOV.

The photometric reduction of that night's data is shown in Figure 6. Obviously, the jump in brightness that coincides with re-aiming the telescope is an artifact, not a real change in the star. But it raises the important question, "is the gradual fade in the star over the course of the night real, or is it also an artifact?" The fact that the check star brightness is also changing suggests that these changes in brightness are artifacts, but the check star (HIP 20730) is identified as an RS-type variable in the AAVSO VSX, so it is just barely conceivable that the slow brightness trend in the check star is real (although the "jump" when the telescope is re-aimed must be an artifact).

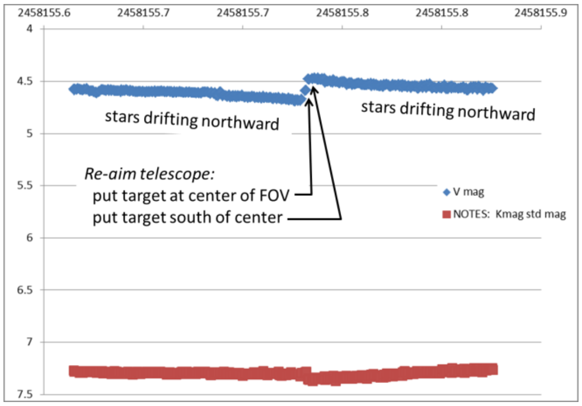


Figure 6: Lightcurve from UT 2018-02-06 (using 15 pixel radius measuring aperture)

What is going on? I first suspected that there might be a problem with the flat frames or with the flat-subtraction algorithm. I made several evaluations of the flat frames, including taking a whole new set of flats, without identifying any issues. I repeated the photometric reduction with and without flats, and the curves were essentially identical. I ran the photometry in Maxim DL instead of AIP4Win, and saw the same effect. So whatever was going on, it wasn't a problem with the flats or with the photometry algorithm.

Suspect #2 was darks, but after examining the dark frames, and re-running photometry with and without darks, the effect never went away or even changed noticeably.

Suspect #3 was that something in the images themselves was involved – perhaps clouds or hot pixels, or something to do with the de-Bayering algorithm. The FOV is about 2.5 degrees wide, and on partly-cloudy nights I could see the cloud-edge moving across the field over the course of a few minutes, but the drop in instrumental magnitude was obvious and those changes never coincided with re-aiming of the telescope, so it was hard to implicate atmospheric effects.

Visual examination of the images before, during and after re-aiming didn't show any noteworthy issues.

Finally, I thought more carefully about the interplay between star images and the measuring aperture. Recall that I de-focused each night, to a FWHM of about 12-14 pixels. I had selected a measuring aperture radius of 15 pixels as a rough approximation to the size that would maximize SNR. However, that decision came with two bad effects. First, the classic "optimize SNR" concept is usually based on the assumption of a Gaussian-shape PSF (or something similar). But defocused PSFs are not even approximately Gaussian. Indeed, some of my defocused images PSFs are more like a top-hat, which would significantly alter the size of the optimum measuring aperture (although does not, in itself alter the general concept). Second – and more importantly – the size and shape of the de-focused PSF changes a bit across the field of view (and also, occasionally over time, probably because gravity and/or temperature changes shift the focal plane position slightly). It isn't surprising that the size/shape of the PSF may be different at different points in the FOV. Piotrowski et al (2013) discuss the implications of field-dependent aberrations on photometry and ways to correct for them.

Examples of the "curve of growth" (radial integral of the PSF as a function of measuring aperture size) for two stars on the same image are shown in Figure 7. In this example, the Comp star PSF s "broader" than the target star PSF, so the 15-pixel radius measuring aperture contains significantly smaller fraction of the Comp star light than it does of the Target star light. This makes the target star appear brighter than it really is.

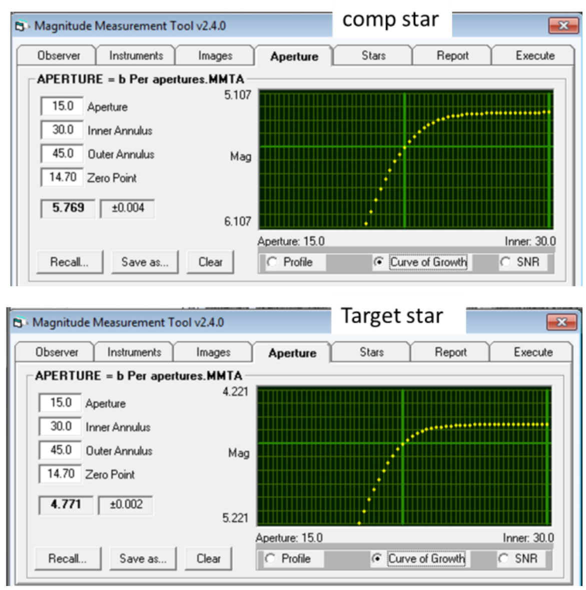


Figure7: Comp star PSF (toward edge of FOV) is noticeably wider than Target PSF (near center of FOV)

If the target star PSF and the Comp star PSF change in different ways or by different amounts, then differential photometry will observe a fictitious brightness change in the target. If the size of the PSF of one star grows, then a slightly larger fraction of light falls outside of the measuring aperture. If the details of the star drift across the image result in a slightly larger fraction of "target star" light falling outside of the measuring aperture, while a slightly lesser fraction of “comp star light” falls outside of its aperture, then it appears as if the target got fainter ... and vice versa.

The message seemed (to me) to be clear: use a larger measuring aperture – one that captures ≈100% of the PSF plus a little to spare, so that the photometry will be insensitive to field-dependent aberrations and time-dependent aberrations, and will accommodate the PSF shape of a significantly out-of-focus star. Increasing the measuring aperture from 15 pixels to 22 pixels (radius) made the artifact on photometry completely disappear! A 22-pixel radius measuring aperture ensured that essentially 100% of each star’s light was collected, the changes in PSF width (and shape) were always completely contained within the measuring aperture, and hence there were no spurious differences in collected light between the target (or check) and comp stars.

The simple change to a 22-pixel radius measuring aperture resulted in a clean lightcurve, and eliminated evidence of the spurious shift associated with re-aiming the telescope, as shown in Figure 8.

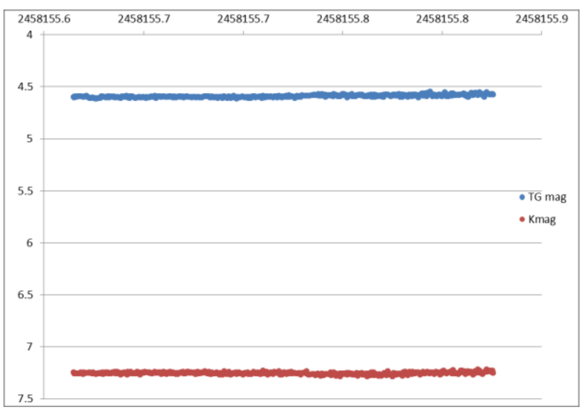


Figure 8: Lightcurve from UT 2018-02-06 (same as Figure 6), but using 22 pixel radius measuring aperture.

This effect can be insidious, and it may not be straightforward to recognize it. The only reason that I double- and triple-checked all of this was because the image drift (caused by my relatively poor polar alignment) made the “jump” show up in the photometry. If the polar alignment had been perfect, then I wouldn’t have seen the mysterious jump in differential photometry when I re-aimed the telescope during a night. But there would still have been a real risk of small night-to-night differences that would have translated into spurious night-to-night photometry shifts, which would have been much more difficult to recognize.

The moral of this story (for me, anyway) is: It is better to err in the direction of a “too large” measuring aperture than having one that is too small. This amounts to striving to “maximize robustness against aberrations”, rather than “maximize SNR”.

<u>DSLR Time</u>: Welty et al (2013) reported that DSLR camera internal clocks may not be stable over long time periods, showing typical drift rates of up to a few seconds per day. I made habit of setting the camera clock to USNO’s web time service (± 1 sec) each evening just before the start of imaging, and checking the camera-time against USNO the following morning. There was always a small difference, with the camera running a bit fast – on average about 2 sec per day.

This is acceptable accuracy for this project, but might not be for some projects. It certainly implies that the camera’s clock should be checked before and after each observing run. (This old Canon EOS Rebel does not have a GPS link. I don’t know if GPS might improve the clock-stability of newer models).

<u>Software and Processing</u>: Photometry was done using the “TG” (Green) pixels only, which gives a reasonable match to V-band.

Image processing, de-Bayering, and aperture photometry were all done with AIP4Win software, with its “MMT” (Magnitude Measurement Tool) that conveniently performs photometric analysis on a large set of images.

AIP4Win will output the results in several different formats. The “AAVSO Report” can be directly uploaded to AAVSO’s WebObs facility. However, I always ran the “Raw Photometry” report also, because it includes the peak ADU count for each star (Target, Comp, Check) on each image. This is a handy check to be sure that no images with saturated stars are used for photometry. It also easily identified times when clouds or contrails passed through the image, so that affected images could be dropped from the photometry.

Because my imaging sequence created a wealth of data point (several hundred each night), I exported the AAVSO report into Excel, and did two processes in Excel. First, there were almost always some time intervals where thin clouds obscured the stars. Those time intervals are easily recognized by plotting Comp and Check star instrumental magnitudes vs time. Intervals where the instrumental magnitudes were noticeably faint were eliminated from the data set. Second, the data was grouped into sets of 9 consecutive images, and the 9-point average was calculated (time, target standard magnitude, comp and check instrumental magnitudes, air mass). This 9-point average yields a noticeable reduction in random "noise" in the photometry report. For each group of 9 images, I also calculated the time span (from first to ninth image), and if it was longer than 15 minutes, I simply dropped that group from the report (e.g. when the 9 images spanned an interval of poor sky transparency).

The censored, 9-point averages were reported to AAVSO.

Results

I was pleased – and a bit surprised – by the quality of photometry that was achieved with a small telescope, a low-end DSLR, and a primitive setup.

Censoring of data was done only to deal with poor sky transparency, and obviously-flawed images (poor tracking or saturated images caused by temperature-induced focus shift). Figure 8 (above) shows a single-night run, spanning almost 5 hours and built up from roughly 400 images, each a 30-sec exposure. This was a perfectly clear night. On other nights, when variable sky transparency was seen to be affecting the photometric results, periods of poor transparency were deleted from the data.

The complete record of my observations is plotted in Figure 9.

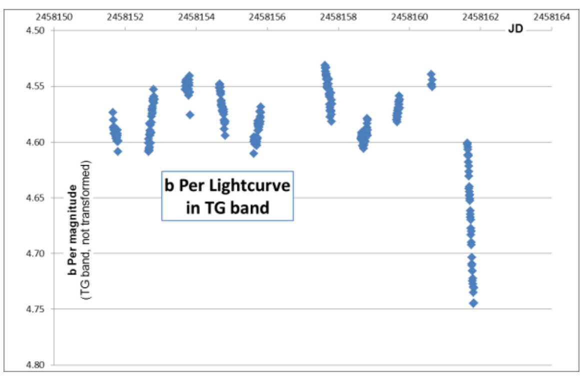


Figure 9: 10-night lightcurve of b Per

The nightly variations reflect the ellipsoidal variation, and the strong, consistent fall in brightness on the final night marks the beginning of the third-star eclipse. Alas, the next two weeks were cloudy at my location, so the start of the eclipse marked the end of my observations. Happily, quite a few other people scattered around the world were able to continue observing throughout the duration of the third-star eclipse.

The 9-point-averaged data had quite good precision and internal consistency. Taking the "out-of-eclipse nights, and phasing the photometry to the 1.5273643 hr period of the inner pair, the ellipsoidal variation in brightness (≈0.07 mag, P-P) is clearly visible, as shown in Figure 10. The scatter amounts to about ±0.02 mag over 9 nights, which seems quite good.

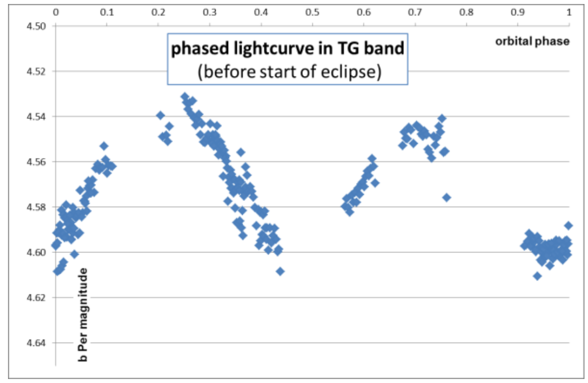


Figure 10: Phased lightcurve of ellipsoidal variation of b Per

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