Epsilon Aurigae – CCD Photometry Using a Small Telescope

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Introduction

This paper describes methods used to measure photometric magnitudes of the star system Epsilon Aurigae using a CCD camera on a small telescope, in anticipation of the upcoming eclipse of this star in July 2009. Observations were made using a 4" refractor telescope and a CCD camera, equipped with BVRI photometric filters. Observations in the summer and fall of 2008 have been made to establish baseline measurements and to develop observational and data analysis methods that will expedite future observations and may benefit other amateur astronomers.

Epsilon Aurigae is a bright star (magnitude 3.0) which easily saturates a CCD frame. The comparison star Lambda Aurigae (magnitude 4.7) is nearly 5 degrees away from Epsilon, so that it lies outside the field of view of the CCD frame containing Epsilon. To address the first issue, we placed a mask over the telescope objective, effectively blocking out about 95% on the incoming light. To address the second issue, we took images of Lambda and Epsilon in different frames and then corrected for extinction and color response for our particular optical system.

Equipment

Telescope, Camera and Filter Wheel

Our telescope is a Takahashi FSQ-106 apochromatic refractor, operating at f/8. It is mounted on a Paramount ME, which is installed at the Tinyblue Observatory, a private observatory on Whidbey Island in Washington State (Latitude 48° 4' 54", Longitude 122° 36' 0").

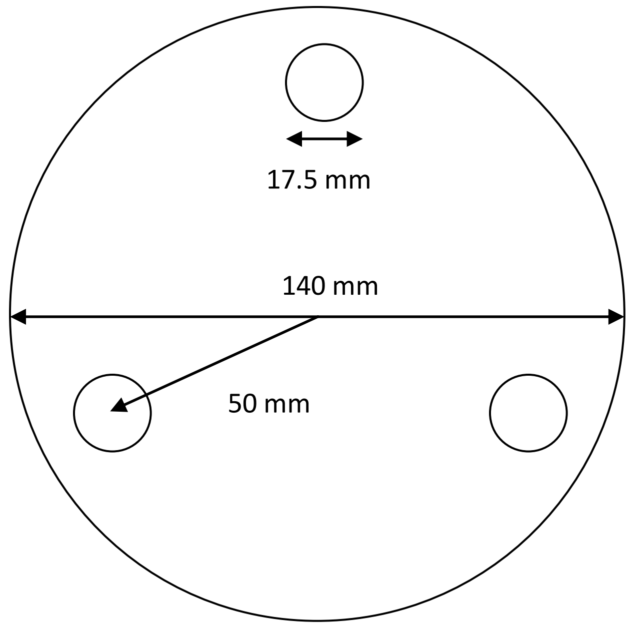
The CCD camera is an SBIG ST-8XME attached to a CFW-9 filter wheel, equipped with Custom Scientific BVRI photometric filters from SBIG.

Objective Mask

To reduce errors caused by scintillation and by variation of exposure time across the frame due to the finite speed of the mechanical shutter (issues that arise with very short exposure times), we aimed to make exposures of 10 seconds or greater. To avoid saturation of images of the target star, Epsilon Aurigae, we constructed a cardboard mask to place over the objective of the telescope. The mask has three holes, equally spaced around the circumference of the circle. Actual exposure times were 15s for

Epsilon Aurigae and 30s for Lambda. Using three holes rather than one allowed us to maintain resolution while reducing incident light.

The holes in the mask are 17.5 mm in diameter, centered at radii 50 mm from the center of the telescope and equally spaced 120 degrees apart from one another.



Using a mask such as this introduces some new issues that should be kept in mind. First, flat frames suddenly become much more complex—every dust grain in the optical path now results in three spots instead of one. It seems especially important to have dust-free filters and a clean window on the camera's CCD chip. Second, if images are slightly out of focus, each star image becomes a little triangular spot rather than a circular spot. These little triangles can actually help establish focus (by minimizing them), but there will invariably be some non-circularity to star images. This has an effect on aperture photometry when the star profile seems to have somewhat more scatter than it would without the mask. Nevertheless, the mask does allow one to use the same telescope/camera/filter combination that one uses for photometry of other less bright stars.

Software

The Sky 6.0

Our Paramount ME is controlled by The Sky 6.0 from Software Bisque. Imaging the target and comparison stars for this project have not required autoguiding.

CCD Soft 5.0

CCD Soft v. 5.0 is used for controlling the ST-8XME camera and the CFW-9 filter wheel, and for FITS image capture. Usually after a night of observation, images are then reduced using CCD Soft. The Reduce Folder feature of Image Reduction is most useful for doing this efficiently.

AIP4Win 2.2

We use the Single Star Photometry Tool in AIP4Win v. 2.2 to measure instrumental magnitudes. The Photometric Analysis tool is useful for determining the optimum annular radii for a particular night's run. The DataLog window is useful for exporting data to Microsoft Excel.

Excel 2007

We use both Excel 2003 and 2007 for data processing, generally saving worksheets in the "Excel 97-2003 Workbook" format for backward compatibility.

Observation Program

Target Star and Comparison Star

The Target Star, Epsilon Aurigae (SAO 39955, HD 31964) has position (according to TheSky v. 6.0):

Equatorial RA: 05h 02m 40s, Dec: +43°50'20" (current)
Equatorial 2000 RA: 05h 01m 58s, Dec: +43°49'24"

The Comparison Star, Lambda Aurigae (SAO 40233, HD 34411) has position (again, according to TheSky):

Equatorial RA: 05h 19m 48.884s, Dec: +40°06'38.107" (current)
Equatorial 2000 RA: 05h 19m 08.474s, Dec: +40°05'56.585"

Determination of Transformation Coefficients for our Optical System

Since the target star and the comparison star cannot be imaged in the same CCD frame with our telescope system, it was necessary to determine the color response for each photometric filter and determine the corresponding transformation coefficients. Using images of M67 we obtained instrumental magnitudes of a dozen stars whose standard magnitudes are published by the AAVSO and then applied methods adapted from Priscilla Benson and Bruce Gary to compute values for the coefficients. Coefficients have been measured independently in March 2008 and January 2009, resulting in values that differ at most by about 5%.

For details on the methods for deriving, measuring and applying the transformation coefficients, see our Excel spreadsheet, "Transformation Coefficients using M67 2009-01-18.xls"

For details on the methods for deriving, measuring and applying the transformation coefficients, see:

"CCD Transformation Coefficients" by Priscilla J. Benson at

www.aavso.org/observing/programs/ccd/benson.pdf,

"Computing and using CCD Transformation Coefficients" by Lou Cohen at

www.aavso.org/observing/programs/ccd/ccdcoeff.pdf, and

"CCD Transformation Equations for use with Single Image (Differential) Photometry" by Bruce L. Gary at

reductionism.net.seanic.net/CCD_TE/cte.html

Observations for Determining Atmospheric Extinction

In order to determine atmospheric extinction coefficients corresponding to each of the filters BVRI, images of the comparison star, Lambda Aurigae are taken both before and after imaging the program star Epsilon Aurigae. This allows the reference star to pass through sufficiently varying airmass to establish satisfactory extinction values.

Exposures of the reference star and program star are normally 60s and 15s, respectively, unguided. Typically, two series of 3 images are taken of Lambda Aurigae before imaging the target star and one series of 3 images are taken after.

Bias, Dark and Flat Frames

We use CCDSoft v. 5 (SBIG and software Bisque) for capturing and images.

After the camera had been cooled to -10°C and allowed to stabilize for about an hour, a series of 7-10 bias frames are taken, which are later combined into a Master Bias frame using Median Combine.

At the same temperature, three series of dark frame exposures (15s, 30s and 60s) are taken (about 10 frames each) and combined into Master Dark frames corresponding to each exposure time using Median Combine.

Flats are obtained either by covering the telescope with a single layer of cotton cloth from a white T-shirt and aiming the telescope directly overhead at dusk (objective still covered with the 3-hole mask), or aiming the telescope at a plain white sheet of poster board mounted on the inside of the observatory dome and illuminating the poster board with a 100-watt incandescent lamp. A series of five flats are taken with each of the B, V, R and I filters, then reduced using Master Bias and Master Dark frames. The resulting reduced flats were Median Combined into BVRI Master Flats.

Photometric Measurement

The Single Star Photometry Tool in AIP4Win is used to measure instrumental magnitudes of the comparison and target stars. The procedure is as follows:

Using AIP4Win v. 2.2.0, open the set of reduced images corresponding to the night's observations using a particular photometric filter. Select Measure | Photometry | Single Star Tool.

Settings

Radii

The first radius is the size of the aperture to be used for measuring the flux from the star. It should be large enough to include all the obvious bright pixels, but not much larger. The second radius is the inner radius of the annulus that will be used to measure the background sky brightness. The third radius is the outer radius of this annulus.

Use View | Zoom In to see more closely what is being included in the aperture and the annulus.

Use the Single Star Photometry Tool to examine several of your images, taken through your various filters. It's best to settle on a set of three radii that will be fixed across ALL of your images for the evening session. The radii I used for one set of images of Epsilon and Lambda were 12.0, 14,0, 16.0.

My own images were not perfectly in focus and one consequence of using the 3-hole mask over the telescope objective is that stars appear as little rounded triangles rather than points or disks. This is okay as long as your aperture includes the entire star.

Note: When browsing FITS images, I prefer to use CCD Soft where I can drag and drop images from Windows Explorer. In AIP4Win, drag-and-drop is not supported, so it makes it less convenient for visual inspection of lots of images.

One other unfortunate aspect of AIP4Win is that if you have more than one image open and you want to experiment with different radii on the Settings tab of the Single Star Photometry tool, if you switch from one image to another, trying to apply the same aperture/annulus to different images, the center of the aperture will insist on jumping to the (0,0) position on the image rather than the place you click. You can work around this by clicking on the Details tab and then switch back to the Settings tab before clicking on a new image.

Integration Time

Be sure you set the Integration time (exposure time, in seconds) on the Settings tab and click Save for this information to be reused when you open the next image.

Our value is 30 seconds for Lambda and 15 seconds for Epsilon.

Instrument Parameters

Zero Point

I suggest setting the Zero Point to 0.0, which is arbitrary. This way, the instrumental magnitudes that are computed by the Single Star Photometry tool will be obviously different from standard magnitudes (e.g., an instrumental magnitude of -10.5 for a star with a standard magnitude of 3), thereby reducing the chance of confusing one for the other.

The following values were obtained using the "Basic CCD Testing" procedures in The Handbook of Astronomical Image Processing by Richard Berry and James Burnell, p. 229

Gain [a/edu] ***2.65 electrons/adu***

R.O Noise [e rms] ***20.74***

Dk Curr [e/s/pix] ***0.793 e/s/pix***

Measurement of Instrumental Magnitudes of Comparison Star

The comparison star, Lambda Aurigae was used to determine BVRI extinction coefficients on the night of observations, and its published BVRI standard magnitudes were used as a reference for calculating the magnitudes of the target star, Epsilon Aurigae. To obtain raw instrumental magnitudes, use AIP4Win Single Star photometry tool.

- Open all reduced images in series sharing a particular filter and exposure value. When asked, "Automatically Calibrate Files?", say No – the images have already been reduced using CCDSoft.
- Note: When you use the File Open Image dialog box and select multiple images to open, they will not appear in alphabetical or chronological order in the Window drop-down menu. This can be confusing. It's best to start processing with the first image, which will usually be the SECOND entry in the drop-down menu, not the first. Similarly, each subsequent image will not appear automatically as the window with focus; you need to select each image in sequence from the drop-down menu.
- Select Measure | Photometry | Single Star.
- Click on Settings and confirm desired Radii, Integration Time and Instrument Parameters
- Set the Zero Point = 0.0
- Click on Result tab; Click checkbox Show Analysis. Be sure to Clear the DataLog.
- Bring the first image in the series to the foreground.

- Click on target star. Close the image.
- Click Settings tab and then Result tab
  Note: This is another quirk of AIP4Win; the Single Star Photometry tool will not calculate an instrumental magnitude ("No centroid." Error) when you click on a star in a new image unless you first select a different tab (Details or Settings) before re-selecting the Result tab.
- Select the next image in series, bringing it to the fore, and repeat the procedure for each image.
- After processing all images in the set, open the DataLog to confirm that you have data for each image in sequence. Save this text file as back-up before you begin editing it. It should have blocks of data similar to the following:

```
AIP4Win Single Star Photometry Tool
   AIP4Win Licensed to David Trowbridge
   AIP4Win v.2.2.0
   Image Caption:             [12] EPSILON-
AUR_V_15S.00006268.GCVS_EPS___AUR.REDUCED.FIT
   File Path:                 C:\Documents and Settings\David\My
Documents\Astronomy Observations\2009-01-18 M67, RV-Tau, Epsilon
aurigae\Epsilon Aurigae\V\Reduced
   File Name:
   Date, time, exposure from  FITS header
   FITS Header Date:          2009-01-19
   FITS Header Time:          03:05:38.713
   Exposure Time:             15 seconds
   Filter:                    V
   Star aperture radius:      12
   Sky annulus inner radius:  14
   Sky annulus outer radius:  16
   Star aperture pixels:      452
   Sky annulus pixels:        115
   Integration time:          15.0
   Zero point:                0.0
   Gain [e/ADU]:              2.65
   Readout noise [e rms]:     20.74
   Dark current [e/sec/pix]:  0.793
   Mid-exposure Date:         2009-01-19
   Mid-exposure Time:         03:05:46.213
Star_X   Star_Y    Max_ADU    Sky_ADU   Star_ADU      Mag ±Sigma
654.186  516.095    35287.0   115.1826    538110.  -11.387  0.001
```

After all images have been processed, open DataLog and edit the data. Place the Mid-Exposure Date and Mid-exposure time on the line just before Star_X and place the File Name on the line immediately after Sigma. Eventually, ignoring columns Star_X, Star_Y, Max_ADU, Sky_ADU and Star_ADU, the data will look something like this:

Mid-Date	Mid-Time	Filter	Mag	±Sigma	FileName
2009-01-19	03:05:46.213	V	-11.387	0.001	EPSILON-AUR_V_15S.00006268.FIT
2009-01-19	03:06:09.476	V	-11.392	0.001	EPSILON-AUR_V_15S.00006269.FIT
2009-01-19	03:06:33.181	V	-11.372	0.001	EPSILON-AUR_V_15S.00006270.FIT
2009-01-19	03:06:56.454	V	-11.389	0.001	EPSILON-AUR_V_15S.00006271.FIT
2009-01-19	03:07:19.687	V	-11.376	0.001	EPSILON-AUR_V_15S.00006272.FIT

In each line above, it is useful to have the Julian Date and Airmass corresponding to each observation. These can be obtained using the online calculators on the AAVSO website, or using the AAVSO Extended Format feature of AIP4Win. On the AAVSO website, the Julian Date calculator is at,

www.aavso.org/observing/aids/jdcalendar.shtml

The airmass calculator is at,

www.aavso.org/observing/programs/ccd/airmass.shtml

The AAVSO Extended Format feature of AIP4Win is a bit unstable and I have found it difficult to use. It can be used successfully if you can avoid certain pitfalls. For details, contact me via e-mail: David (at) Tinyblue (dot) com.

Measurement of Instrumental Magnitudes of Target Star

Use the same procedure for measuring the instrumental magnitudes of the target star. Be sure to set the Integration time to the correct exposure. In our case, this is 15 seconds for Epsilon Aurigae.

Calculation of Standard Magnitudes of Target Star

See our sample spreadsheet, "Observations of Epsilon Aurigae 2008-12-15.xls" for an illustration of the process for calculating standard magnitudes for Epsilon Aurigae. The third sheet, "Extinction" contains instrumental magnitudes for Lambda Aurigae, which are used both for computation of atmospheric extinction and to obtain extinction-corrected magnitudes for the comparison star.

The second sheet, "Target" contains instrumental magnitudes of Epsilon Aurigae and corresponding values corrected for extinction.

The first sheet, "Magnitude" applies the previously measured Transformation Coefficients to the extinction-corrected instrumental magnitudes of target and comparison stars to derive standard magnitudes of the target star, Epsilon Aurigae. This sheet follows the procedure outlined by the paper by Priscilla Benson previously cited.

My procedure for calculating the standard magnitude from a new set of data is to make a copy of the previous "Observations of Epsilon Aurigae YYYY-MM-DD.xls" workbook and then to replace the old data with the new data. By using Copy/Paste Values you can preserve the formatting of dates, times and numbers without having to reapply them.

Instrumental magnitudes obtained using AIP4Win can be imported into Excel via the File Open command for delimited text files. Indicate either Semicolon delimited (for AAVSO Extended Format files) or Tab or Comma delimited for other text files. You may need to open a file twice, once to obtain a satisfactorily formatted header, and again, with a different delimiter, for correctly separated numerical data.

We have found it helpful to retain columns for UT date and time, Julian Day, Air mass and File name, in addition to magnitude and error values. Please see the example spreadsheets.

Discussion of Error

Our images of Lambda (30s) and Epsilon (15s) result in a FWHM of about 3.5 pixels, corresponding to a sigma radius of 1.5 pixels. The S/N ratios are about 640 and 1100, respectively with the V filter. Peak pixel values are 14000 and 35500.

Following the recommendations in The Handbook of Astronomical Image Processing by Richard Berry and James Burnell, we selected an aperture radius roughly five times the sigma radius of the star image (p. 274). The radii of the sky annulus were chosen so that the inner and outer annulus radii averaged to about twice the aperture radius (Berry and Burnell, p. 636). In our most recent observations, our selected radii were: 8.3, 11.7 and 21.7 pixels. Care was taken to use the same radii for all measurements on a given evening.

The extinction-corrected instrumental magnitudes of the comparison star, Lambda Aurigae have standard deviations ranging from 0.004 to 0.011. Extinction-corrected instrumental magnitudes of Epsilon Aurigae had standard deviations of about 0.008.