

Small Telescope Infrared Photometry of the ϵ Aurigae Eclipse

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Abstract Near-infrared photometry of ϵ Aurigae, in the H- and J-bands, was undertaken during the 2009–2011 eclipse using telescopes of moderate size (8-inch and 14-inch diameter). Instruments of this size successfully collected scientific data in the H- and J-bands. Observations were made from the campus of East Tennessee State University (ETSU), Johnson City, Tennessee, the campus of King College, Bristol, Tennessee, and from the author's home. Signal/Noise ratios of approximately 45 were obtained during times of maximum eclipse. Higher S/N ratios could have been obtained by extending the length of time on target. S/N ratios of almost 100 were obtained outside of eclipse. The infrared light curves produced closely parallel the light curve in the visual range (V), being about 0.5 magnitude brighter in H and 0.7 magnitude brighter in J. The eclipse was easily detected and followed throughout its duration. The rate of ingress was shallower than the rate of egress in both the H- and J-bands. The background variations of the primary star were readily detected.

1. Introduction

The variable star ϵ Aur has been of interest to astronomers for almost two centuries due to its long period (27.1 years) and the long duration (approximately two years) of its eclipses. With such a long eclipse, the occulting object can not be another star, but must be some other type of object. The exact nature of the eclipsing object has been a mystery, although more information becomes available each time an eclipse occurs. This is due to both an increase in the number of observers and also collection of data in additional wavelengths not utilized in previous eclipses. The current model of the occulting object is that of a large, cool disk which contains a central B-type star (Stencel 2011).

Infrared photometry has, until recently, been the province of professional astronomers, using large telescopes, sophisticated infrared detectors, and high-altitude observing sites. UKIRT, SOFIA, IRTF, and Spitzer are a few of the professional instruments that come to mind. It is now possible for the average variable star observer, using a common telescope of modest size, to work in the near-infrared part of the electromagnetic spectrum and to produce high quality, scientifically useful results. The recent eclipse of ϵ Aur provided an excellent opportunity to demonstrate these capabilities; during previous eclipses, infrared studies were restricted to professional observatories since amateur observers did not have the capability.

There are numerous advantages (and some disadvantages) for the observer who works in the near-infrared when compared to visual-band photometry (Templeton 2011a):

- 1) The sky is very dark in the infrared; there is little infrared light pollution. An infrared observer can work under conditions that would make visual-band photometry difficult.
- 2) Atmospheric extinction, while present, is low compared to the visual wavelengths. As the eclipse neared its end, some data were collected at the very high airmass of 5; this high airmass did cause an increase in noise, but the S/N ratio was still adequate.
- 3) Many variable stars are brighter in the infrared than at visual wavelengths (some are much brighter). ϵ Aur was no exception to this; throughout the eclipse, the J-band readings were about 0.5 magnitude brighter than in V, while the H-band readings ran close to 0.7 magnitude brighter than in V. This can be seen in Figure 1.
- 4) There are few infrared observers. While for some stars, visual-band observers (V in particular) will find their data lost in the crowd and so contribute little, this is not the case in the infrared. For the duration of this project (November 2008–present) there were only two observers submitting H- and J-band data to the AAVSO.
- 5) Water is an absorber of infrared radiation. Even though the sky may look clear, there will sometimes be too much water vapor in the air. Some of the noisy data collected early in the eclipse were due to attempts made on poor nights.

2. Equipment

The equipment used during the eclipse consisted of an Optec SSP-4 photoelectric photometer with a manual filter slide holding H- and J-band filters. The H- and J-band filter band-passes are closest to the Mauna Kea Observatory (MKO) and Caltech/Tololo (CIT) systems (Henden 2002). The gallium-arsenide (GaAs) detector in the SSP-4 is one millimeter across (about 100 arc seconds at the focal plane of an 8-inch SCT operating at $f/10$). A version of the photometer is available with a smaller, 0.3-mm detector, but the smaller detector gives less satisfactory results (Hopkins 2006a).

The SSP-4 photometer is the result of a collaborative program between the AAVSO and Optec, Inc. (West 2007). It contains an eyepiece for centering the target and comparison stars, a flip mirror for sending the image to the detector after centering, and a filter slide containing the H- and J-band filters; the filter slide and flip mirror are operated manually.

The software which Optec provided for use with the photometer was utilized for most of the observations, although an alternate software package,

written by Brian Kloppenborg at the University of Denver, was used on occasion (Kloppenborg 2011). This software gave greater control over the photometer, but the Optec software made a better match with the particular spreadsheet that was in use. Both software packages ran without issue on an older laptop computer running Windows XP Pro. This computer was used for both telescope and photometer control. The computer had 1 GB of RAM and a single-core Celeron processor; it had no problems controlling both instruments at the same time.

Three different telescopes were utilized during the eclipse: an 8-inch Meade LX200, a Celestron C14, and a Meade 8-inch LX90. The two Meade SCTs were fork-mounted on equatorial wedges, while the C14 was mounted on a German-equatorial mount (GEM). All of the telescopes proved adequate to the task, although the C14, due to its larger aperture, gave the best results in the shortest period of time.

3. Observations

When preparations began for the upcoming eclipse during the summer of 2008, an 8-inch Meade LX200 located at ETSU's Powell Observatory was utilized. It is reported that a 10-inch telescope is the minimum useful size for infrared photometry of ϵ Aur due to the faintness of the traditional comparison star, λ Aur (Lucas *et al.* 2006). λ Aur is faint in the infrared ($\text{mag}_h = 3.33$, $\text{mag}_i = 3.62$), making it difficult to use with a smaller telescope. The solution was to use a brighter comparison star—the AAVSO recommendations for telescopes under 0.25 meter (10 inches) are to use Capella as the comparison star and β Tau (el Nath) as the check star (Templeton 2011b).

The two Meade telescopes were controlled with Meade's AUTOSTAR software. Although other control software was tested, the Meade software proved to be very capable and worked well. The C14 was controlled using STARRY NIGHT PRO 5, which also worked well. The goals initially were: 1) collect pre-eclipse data on ϵ Aur, 2) take measurements of standard stars to be used for calibrating the photometer/telescope combination, and 3) measure other variable stars on the AAVSO's IR photometry list.

The first observations of ϵ Aur occurred on November 2, 2008. The star was kept under observation (from the ETSU observatory) from that date until it was lost to the sun in late May 2009. ϵ Aur was re-acquired on the morning of July 24, 2009, and at that point, it became obvious that there would soon be a problem. The author's "day job" is that of a high school chemistry teacher—once school began after the summer break, it would not be possible to make the forty-five-minute drive to ETSU early in the morning, get set up, collect the data, get everything put away, and then get to school in time for the start of classes.

A search for a suitable telescope to use from the author's home was started and a used Meade 8-inch LX90 (UHTC coatings) with an equatorial wedge

was found. It was purchased and set up on a concrete pier at the author's home. The LX90 was not as accurate as the LX200, but its tracking and pointing abilities were more than adequate for use with the 1-mm detector of the photometer. The onset of the eclipse in August 2009 was easily detected.

As the eclipse deepened, it became apparent that a larger telescope would give better results, as the brightness of ϵ Aur was decreasing. A discussion with AAVSO Director Arne Henden, while he was on a speaking engagement at ETSU, led to the advice that longer time on target was one solution (Henden 2009). This worked, but the time involved increased as well.

At this point, about 1.5 hours of collecting data were required for the two data points (one each in H and J). The infrared sky is not transparent over long periods of time (Henden 2002), especially in the Southeastern United States. A larger telescope would allow shortened observation times. King College, in Bristol, Tennessee, offered the use of their Celestron C14 located at the college's Burke Observatory. The college's physics department allowed use of the telescope when it was not being otherwise utilized.

The C14 made a large difference in the S/N ratio. It was used for the remainder of that observing season, although a move back to the ETSU telescope was required in late May (trees became an issue). During the last year of the eclipse, the C14 began to be utilized more often by King College and so observations moved back to the LX90 and the LX200. Currently, the LX90 is the primary instrument used for post-eclipse monitoring.

4. Data collection

Prior to a night's observations, the photometer was powered up and hooked to the laptop computer. The photometer drew from its own external power supply, but was controlled by software on the laptop through a USB cable. The photometer's temperature control was set to -40° Celsius (below ambient).

When first turned on, the photometer typically produced high dark counts—these decreased as the instrument stabilized (30–60 minutes after power-up). The dark counts would normally drop slowly during the run, but not so far that they became a problem. While the photometer was stabilizing, the telescope was set up, polar-aligned, and placed under control of the laptop (the C14 was permanently mounted, the other two telescopes were not). Prior to starting the data run, the photometer's dark counts were checked and the gain control adjusted to bring them into the range recommended by Hopkins (2006b). The photometer was then set to a gain of 100, with a 10-second exposure.

The comparison star, α Aur (Capella), was measured with both H and J filters. The telescope was then off-set slightly and a reading on the sky was made, once again in both filters; the pattern used was “comp H, comp J, sky J, sky H.” The telescope would then be pointed at the variable star (ϵ Aur) and the same pattern repeated “variable H, variable J, sky J, sky H.” Then back to

α Aur where the pattern was repeated once again. The last measurement of the night was of the check star (β Tau) since it had lowest priority (Schmidke and Hopkins 1990). This procedure produced one data point in each filter. A minimum of three such observations were required so that meaningful statistics could be calculated; more than three observations were necessary due to the small size of the telescopes used.

The photometer software, provided by Optec, allowed the photometer to take one exposure, three sequential exposures, or four sequential exposures. When the project first began, three exposures of ten seconds each were taken, followed by three exposures on the sky and then back to the comparison star where three more exposures were made (according to the above description). These three observations were then averaged. This was repeated at least three times (or five or seven, and so on.). Each group of three readings was averaged down to one reading and then the three (or five or seven, and so on) single readings were averaged to give a single number for the star's brightness for that night's observations. This was then repeated using the other filter. The time involved for this was significant, especially in the beginning.

This method worked well, except when the sky was rapidly changing or for observations made at high airmass—the sky would simply change too quickly between one measurement and the next. It was realized that averaging the data twice did not help in terms of S/N and added a great deal of time to the operation. As the eclipse neared its end, “single shot” readings began to be taken—comp, sky, var, sky, comp, sky—one reading each, not grouped into threes. This produced data that were generally better, if the stars were under changing sky conditions, than the “group of three” method mentioned above. Because of the speed at which the readings could be taken, data could be collected at high airmass and still not be too noisy.

Originally this pattern was repeated three times, but it was found that the total counts were low, (except when using the C14), so it was increased to five sets, then to seven, and finally to nine sets. Nine repetitions were not practical, so eventually seven sets were settled upon—this gave the best trade-off between time involved and S/N ratio.

5. Data reduction

A Microsoft EXCEL spreadsheet was developed, using a format that allowed the observer to simply cut and past the data from the photometer's native output file directly into the spreadsheet.

The data output of the photometer contained columns of data, representing such things as date, time, filters used, gain settings, length of exposure, and numbers which represent the photons detected during the run. It was in an EXCEL-readable format. Several quantities must be calculated from this information:

- 1) The telescope's location—this information, along with the sidereal time, was needed to calculate the local hour angle and from that, atmospheric extinction,
- 2) Time and date of the observation converted into Julian Days—the data run consisted of several readings so the timestamp of the central value of the set was used as the time of observation.
- 3) Filters used—the EXCEL sheet did not utilize these data, but it allowed sorting of the data prior to pasting them into the spreadsheet.
- 4) Gain and exposure times—this information was used to reduce the total counts down to “counts per second” so the brightness of the star at the time of the observation could be determined.

The averaged photometer readings mentioned previously represented the number of photons that arrived from the target star during each exposure. Several additional corrections to these raw counts were necessary in order to get the star's true magnitude in each filter. A summary of the procedures are listed below. The full procedures and equations used may be found in Henden and Kaitchuck (1982), Hall (1988), and Schmidke and Hopkins (1990):

- 1) Convert the raw counts into instrumental magnitudes.
- 2) Calculate the difference in brightness between the target star (ϵ Aur) and the comparison star (α Aur). The value used for α Aur was the average of the readings taken just before and just after the reading on ϵ Aur.
- 3) Apply an extinction correction to the differential magnitude of the target star. This extinction correction is necessary due to the difference in airmasses between the comp and target stars. In the case of the α Aur- ϵ Aur pair, the difference was slight while the stars were rising in the east (late summer), but increased as they traveled westward, reaching a maximum in late spring.
- 4) Apply a correction for the instrumental color response for the system—this final correction adjusts the magnitudes to the standard system.

There are other, additional corrections that could have been performed on the data. However, the impact of those corrections is very slight in the infrared (Henden 1982) and so those corrections were not made.

6. Results

Although this project was primarily instrumental in nature and not analytical, some conclusions about the eclipse can be drawn from the data:

- 1) ϵ Aur is fainter in the J band than in the H band, both in and out of eclipse (see Figure 1).
- 2) The background variations of the primary are evident, both in and out of eclipse (Figure 1).
- 3) The second half of the eclipse is not as deep as the first half—perhaps the trailing side of the disk is thinner than the leading side or it might not cover the primary to as great an extent.
- 4) A comparison of the rates of change during ingress and egress in both filters show that the eclipse ended at a greater rate than it began. This can be seen in Figures 2 and 3. The slopes of the ingress stages were 0.0045 mag./JD in H and 0.0048 mag./JD in J, while those of the egress portions were 0.0060 mag./JD in H and 0.0067 mag./JD in J.

These slopes are very shallow due to the long duration of the eclipse. Data points for making slope determinations were chosen from when both the ingress and egress stages were well underway.

- 5) By taking the slopes of the pre- and post-eclipse stages and overlaying them on the slopes of the ingress and egress stages, it is possible to determine the dates of the eclipse's onset and ending in the H and J bands.

An examination of Figure 2 and Figure 3 shows that the eclipse began around JD 2455046 in H and JD 2455057 in J (3 August 2009 in H and 14 August 2009 in J). There is a large amount of scatter in the pre-eclipse J band data points and this might explain the variation in the starting dates between the two filters. The eclipse appeared to end on JD 2455707 in both the H and J bands (26 May 2011).

7. Conclusions

Near-infrared photometry in the H and J bands can be successfully undertaken using a telescope of modest size, such as an 8-inch Schmidt-Cassegrain. Care should be taken in the choice of comparison, target, and check stars in order to keep signal/noise ratios as high as possible. The ϵ Aur eclipse did fall within the reach of this type of setup, but at its deepest, the drop in the S/N ratio was very apparent. Target stars for such a setup should be brighter than about magnitude 2 in the chosen filters, if possible. Fainter stars can be monitored, but require long data collection times in order to keep the signal at acceptable levels.

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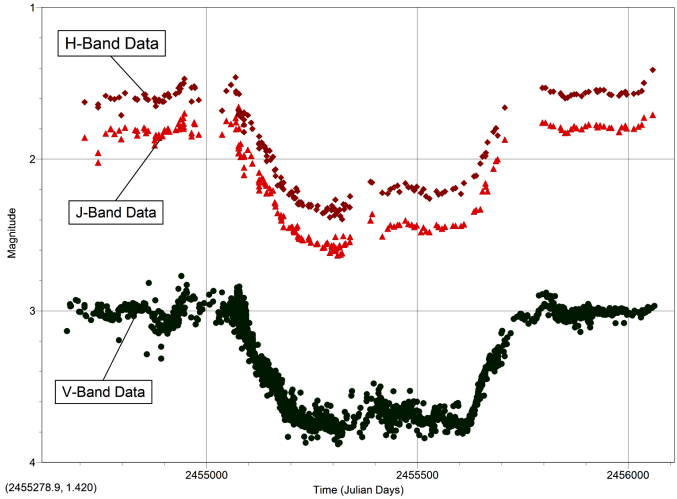


Figure 1. The ϵ Aur eclipse (2009–2011) in V, H, and J. ϵ Aur is brighter in both the H and J bands than in the V band in both the in- and out-of-eclipse phases. The background variations of the primary star can also be seen. (Data courtesy AAVSO).

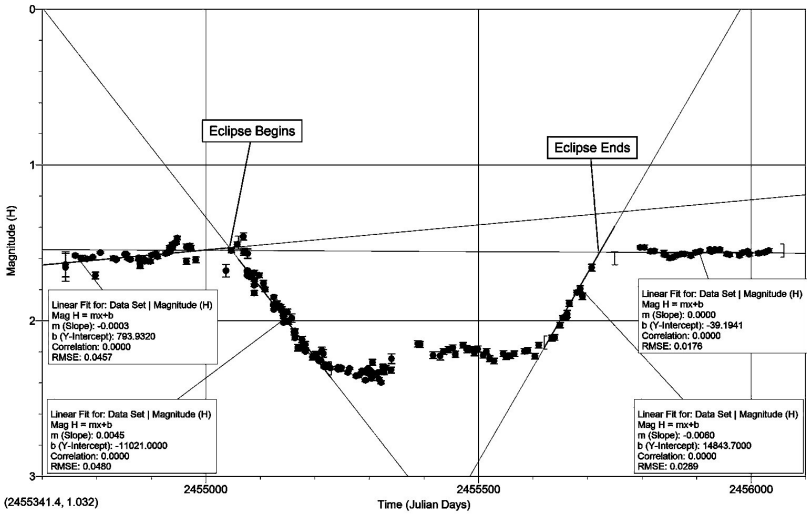


Figure 2. The ϵ Aur eclipse (H). Once the ingress stage was well underway, the eclipse proceeded at the rate of 0.0045 mag./JD in H. Once egress had begun, ϵ Aur began to brighten at the rate of 0.0060 mag./Julian Day in H. The dates of eclipse onset and eclipse end can be seen by determining where the pre-and post-eclipse slopes cross the ingress and egress slopes.

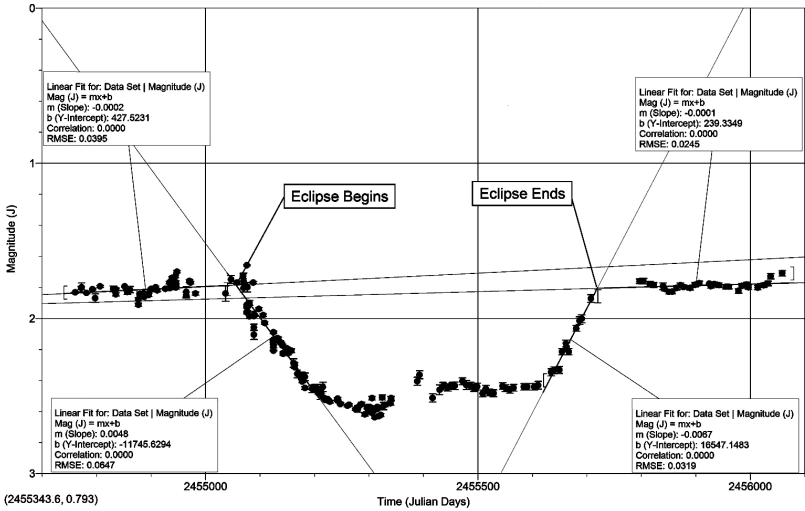


Figure 3. The ϵ Aur eclipse (J). The ingress phase (J band) of ϵ Aur proceeded at the rate of 0.0048 mag./JD. As egress occurred, it proceeded at the rate of 0.0067 mag./JD. The dates of eclipse onset and eclipse end can be seen by determining where the pre-and post-eclipse slopes cross the ingress and egress slopes.