Photoelectric Photometry of ε Aurigae During the 2009–2011 Eclipse Season

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Abstract A total of 100 V-band photometric observations were made at Holtsville Observatory for the 2009–2011 eclipse of ε Aurigae. A light curve has been plotted using data from these observations which covers the phases before, during, and after the eclipse. The light curve shows precise timing during the first, second, third, and fourth contacts, which mark important parts of the eclipse. The magnitudes and duration of the eclipse in the photometric V band are discussed.

1. Introduction

ε Aurigae is different from other binary star systems. It has been a mysterious star to us since 1821 when it was first noticed that it was a variable, but it was not well known until the early1900s. This star is the longest period eclipsing binary ever studied. What's so mysterious about ε Aur is that we do not know much about its eclipsing object. Even though the eclipsing object has been well identified as existing, it is still unclear what it is made of. With its 27.1-year period, it is a slow eclipse lasting a total of 1.75 years. Regardless of what equipment you use to study this binary system, there is no clear clue about the eclipsing object. Using photometry, spectroscopy, polarimetry, and interferometry, we are beginning to get an indication of its nature. During the time of the eclipse, ε Aur dims about 0.8 magnitude and then returns to a normal brightness.

What is known about this binary star system is that the eclipsing body's orbit is in our line of sight. Every 27.1 years, ε Aur undergoes an eclipse which means the unknown secondary object passes in front of a star as seen from the Earth, causing the light to dim (Hopkins *et al.* 2006). The ε Aur system is so strange that it is unique. With such a rare binary star system, it is difficult to study the eclipse every 27.1 years. Something is orbiting ε Aur, but what is it?

ε Aur is known to be a F0-type star and it is a highly luminous supergiant at V magnitude 3.00. The eclipsing object orbiting this F0-type star doesn't exhibit any spectrum of its own but it is most likely to be a hidden B-type star. The disk must be dark but have transparent regions. But during the eclipse, still it is thick enough to obscure some of the light from the F0 star. The visual light can dim about 0.8 magnitude even though the spectrum does not change. Also, the F0 star itself is a variable and it is perhaps a semiregular type. It is a pulsating star outside of the eclipse with a period of 60 to 65 days. The amplitude can change as much as 0.15 magnitude in addition to the eclipse.

ε Aur has been studied substantially every 27.1 years. The 1982–1984 eclipse was observed by many amateur astronomers, by ground-based professional observatories, and from space. No matter what data were collected, still it was a completely mysterious star. There is so much interest in this binary that all observers are trying to squeeze out as much detail as possible about the secondary. What we really see is only the light of the primary star.

The long awaited ε Aur 2009–2011 eclipse is finally over. Prior to 2009, many organizations and observing campaigns were formed (Hopkins *et al.* 2008). This author is participating in one organization, which is run by Jeffrey Hopkins of Phoenix, Arizona. During the 2009–2011 eclipse, many amateur astronomers were equipped with the most advanced technology, especially in spectroscopy, which plays an important role for ε Aur where the secondary can be detected at certain wavelengths. Also, the Center for High Angular Resolution Astronomy (CHARA) operates an interferometer on Mount Wilson in California (Kloppenborg *et al.* 2010). With up to six telescopes combined together in infrared light, they have successfully imaged ε Aur. They were able to detect an elongated object partially obscure the primary disk. The ε Aur eclipse of 1982–1984 was successful but left us many questions for the 2009–2011 season. Hopefully many amateur and professional astronomers can shed new light on the secondary this time. This author carried out photoelectric photometry in V light during the 2009–2011 eclipse, and it is described here.

2. Method

Photoelectric photometry was the only method this author used to monitor the entire eclipse of ε Aur. The observations provided an excellent coverage in V band. It is a Johnson-type filter with a peak spectral response at 5400nm. The readings were taken photometrically using a SSP3 OPTEC photo counting photometer coupled on a Celestron 8-inch *f*/10 telescope. λ Aur was the comparison star at V magnitude 4.71. It is located just four degrees east-southeast of ε Aur and it was an excellent choice to compare its brightness and to minimize the atmospheric coefficient during the 2009–2011 eclipse season.

For each set, four readings were taken at ten seconds' integration time for ε Aur, sky readings, and then the comparison star, λ Aur. This author sometimes monitored three to four sets, depending on the weather condition and time. Once the observing night was over, the readings could be calculated. The photometric readings of ε Aur, the sky, and λ Aur were averaged. Then, the sky was subtracted from both stars' readings. That left the ratio brightness between ε Aur and λ Aur. Once the ratio was calculated, ε Aur's brightness could be determined with the known magnitude of λ Aur. Also, the Standard

Deviation (SD) was calculated to analyze how much error was in the readings. Most of the time, the error amount was from 0.012 magnitude to as much as 0.0427 when all the readings were calculated. The altitude was also calculated to determine the air mass during the time of the observations. During the observing run, the higher the stars, the better chance of getting the accurate readings from the photometer.

Many factors had to be also considered: seeing conditions, the winds, periodic clock drive error, polar alignment, and the stability of the photometer, which can all affect the readings. During most nights, the seeing condition was above average with no winds, and the periodic clock drive error was noticeable at times. Being that a portable observatory was used, the polar axis was aligned as close as possible to the celestial north pole. Therefore, in spite of the small drift, the star still stayed inside the reticle circle during the length of time. For the SSP-3 OPTEC photometer itself, the unit was turned on at least an hour before the start of the first counts. This "warm up" routine stayed on until the photometer dark count was stable enough for accurate readings. In fact, the colder the outside air temperature was, the more time the photometer needed to warm up. The unit was running on a 9-volt battery to avoid the power cord tangle-up during the night's run. In the photoelectric photometry method, the accuracy can be little as 0.01 magnitude. This author's readings were close enough to generate the shape of the light curve (see Figure 1 and Table 1).

3. Observations

ε Aur is located in the constellation Aurigae as a third magnitude object and passes nearly overhead most evenings, as seen from the Holtsville Observatory. All photoelectric photometry results were taken from Holtsville Observatory, located under a moderately light-polluted sky fifty miles east of New York City. ε Aur is easily visible to the naked-eye and it is one of the three stars forming the asterism "The Kids," near α Aur (Capella).

This author was gearing up for the first eclipse of the Millennuim. Prior to the start of the eclipse, the first contact was predicted to occur in August 2009 (Hopkins *et al.* 2009). The observations commenced on December 3, 2008, during the 2008–2009 observing season to develop a baseline for the light curve. The photometric readings were taken nightly, weather permitting, until the star reached a conjunction with the sun in June 2009. Within this period, ε Aur was showing a slight variation averaging V magnitude 3.00 out-of-eclipse (OOE). The variation had nothing to do with the eclipsing object. ε Aur itself is a variable and perhaps a semiregular type with amplitude of 0.10 magnitude. The last readings of the observing season in V band showed no indication of the upcoming eclipse.

After the solar conjunction, the observation resumed for the 2009–2010 observing season. The first reading was on August 14, 2009, in the morning sky. Even though the exact start of the eclipse was predicted to be on August 6, 2009, everything looked normal. After several weeks, it got very interesting. Since the start of the new observing season, ε Aur had dimmed considerably. This author didn't know whether or not this was due to ε Aur's variation itself or the start of the eclipse. As ε Aur continued to dim, the partial eclipse had actually begun, but it wasn't confirmed until after mid-September when the magnitude dropped below 3.15 V.

The excitement built up as ε Aur's brightness continued to fall. This author took photometric readings in V band on an average of two nights per week. At certain points of the declining phase, ε Aur's brightness reduction slowed down a bit. This was due to the variation of the star itself. It formed a somewhat wavy pattern as it continued to dim.

At this part of the declining stage, the author was getting ready for the second contact. It wasn't until the end of December 2009 when the brightness decline slowed down a lot at 3.70 V. It still showed a slight dimming until late February 2010 when the light curve reached rock-bottom at 3.78 V—but this was not necessarily the second contact. While ε Aur itself varied within 0.10 magnitude the whole time, this might have interfered with the actual time of the second contact, which should be the beginning of the totality. The second contact was predicted on December 19, 2009, and it looked like it was right on schedule, but the OOE variability caused the light curve to dim even further. After the second contact, ε Aur showed a small variation even in totality. The light curve could be easily identified as a semiregular type with a 65-day period.

Here is the interesting part: ε Aur is known to show a surge of brightness as it nears to mid-totality, which may cause perhaps a small gap in the middle of the eclipsing body to allow the F0 star to shine through. This mystery has not been explained yet, but hopefully it can be solved this time. The mid-totality was scheduled to happen by early August 2010. This author tried to take readings as much as possible while ε Aur was approaching solar conjunction, but, unfortunately, the readings were taken at low altitude in the northwest after sunset. The accuracy of the photometric measurement was not as great, but any attempt to take readings was worthwhile. According to the last two nights in May 2010, this author may have caught a surge of brightness to 3.55 V. The photometric results may not been proven yet because the author did not know whether this was caused by atmospheric turbulence from the low altitude, ε Aur's variation itself, or the F0 star shining through the gap. ε Aur was not in a good position to take further readings and it went through the solar conjunction in June 2010.

The 2010–2011 observing season began when ε Aur was just past the mid-eclipse stage. The observations resumed on August 13, 2010, early in the morning sky. There was no surge of brightness at mid-eclipse that was expected just shortly before the solar conjunction. At this time, the expected surge of brightness may or may not have occurred at exactly mid-eclipse. This is yet to be determined.

The brightness of ε Aur varied within 0.10 magnitude throughout the whole second half of the eclipse, with the magnitude averaging at 3.71 V. Even at totality, ε Aur clearly demonstrated a 65-day variation unrelated to the eclipsing body. The star was monitored on an average of once per week, and the author prepared for the third contact, which was predicted for March 19, 2011. During that month, the star's brightness became a little strange. According to the irregular 65-day pattern, ε Aur was expected to get a little brighter. Instead, it went off track a bit. As this time, we don't know if this was related to the eclipsing body or the result of the star's irregular-type behavior. After March 19, 2011, the brightness began to rise quite rapidly, which indicated the third contact had passed. The total eclipse was over and this was the beginning of the partial phase. It had risen at a faster pace than during the declining stage. The fourth contact was scheduled for May 19, 2011. Earlier that month, the brightness leveled off at 3.25 V. Again, this could be ε Aur's variation itself, but at the same time, the photometric readings were getting difficult to obtain due to the lower altitude in the northwest. The fourth contact, which marks the end of the partial phase, was probably not caught. In late May 2011, ε Aur was approaching solar conjunction and therefore no more readings were taken.

More observations of ε Aur began in September 2011, after solar conjunction. Even though the eclipse ended after the fourth contact around late May or June, this author continued to monitor this star just to confirm that the eclipse was over. The star returned to a normal brightness at an average of 3.00 V, just as before the eclipse. After monitoring the entire eclipse of ε Aur, the photometric observations ceased after two years and nine months.

4. Conclusion

Only the V band at a peak spectral response 5400 nm was used to determine the accurate shape of the light curve. The result may be similar to the 1982–1984 eclipse but a closer look might detect some differences, especially in spectroscopy. However, the mid-eclipse brightening is still a mystery and it wasn't well observed due to the time of the solar conjunction. It is still premature to draw any conclusion whether the mid-eclipse brightness took place in this cycle.

The contact points need further analysis in order to draw any conclusion. It is quite difficult to obtain the data of the contact time just by one person. There are gaps between the observations and probably the actual contact time may be missed even by one day. But the author's light curve was constructed (see Figure 1) and we see two different types of variations. While ε Aur is a semiregular type variable star, the 65-day cycle 0.10 magnitude is clearly seen in the light curve. Secondly, the eclipsing object of a 27.1-year period is obvious—seen at 0.70 magnitude amplitude. With 100 data points, one can show that the eclipse took place but not clearly mark the contact points. The actual time of the contact points may be confused by ε Aur's 65-day cycle, and the 0.10-magnitude variation is enough to bury the actual contact times. Using only the author's data, it would be premature to draw more specific conclusions about the contact times. Data from other observers may fill in the gaps and therefore the contact times may be determined. Also, the results may be compared with eclipses of the past to see whether there is any significant difference. While the photometric data gathered by participants is much more sophisticated than for the past eclipses, the truly new type of data is the spectroscopy. With today's advanced technology, this collective photometric and spectroscopic data set is the best ever obtained. The ε Aur 2009–2011 eclipse is behind us and the results will be studied for many years to come. Still, there will be more questions than answers. Hopefully, we will have more answers by the next eclipse in 2036–2038.

References

Hopkins. J. L., *et al.* 2006, "Long-Period Eclipsing Binary System ε Aur Eclipse Campaign," Presented at the May 2006 Society for Astronomical Sciences Symposium, Big Bear, California.

Hopkins J. L., *et al.* 2008, "Gearing Up for ε Aur's First Eclipse of the Millennium," Proceedings for the 27th Annual Conference of the Society for Astronomical Sciences.

Hopkins, J. L., *et al.* "2009: The eclipse begins—Observing Campaign Status," Presented at the Society for Astronomical Sciences Symposium.

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Table 1. Differential photometry of ε Aurigae.

UT Date	JD	V Filter	
		Magnitude	Standard Deviation
2008 Dec 03	2454803.73611	2.97	0.02569
2008 Dec 13	2454813.7222	3.04	0.01987
2008 Dec 26	2454826.6875	2.99	0.02654
2009 Jan 04	2454835.70833	2.98	0.02987
2009 Jan 22	2454853.59722	2.98	0.02226
2009 Jan 30	2454861.70833	2.99	0.02321
2009 Feb 09	2454871.625	3.02	0.00754
2009 Feb 21	2454883.70833	3.07	0.01987
2009 Mar 18	2454908.64583	3.08	0.01402
2009 Apr 06	2454927.58333	3.07	0.01954
2009 Apr 13	2454934.61806	3.0	0.01563
2009 May 21	2454972.5625	2.92	0.04598
2009 Aug 15	2455058 +	2.97	0.01548
2009 Aug 23	2455066.79167	3.01	0.02112
2009 Aug 31	2455074.76389	3.02	0.01548
2009 Sep 06	2455080.76042	3.04	0.01289
2009 Sep 14	2455088.73611	3.1	0.01985
2009 Sep 18	2455092.73611	3.13	0.00874
2009 Sep 20	2455094.75	3.16	0.01482
2009 Sep 26	2455100.72625	3.2	0.01365
2009 Sep 28	2455102.72625	3.21	0.01759
2009 Oct 02	2455106.71139	3.25	0.02236
2009 Oct 06	2455110.69819	3.28	0.02
2009 Oct 12	2455116.71146	3.32	0.01913
2009 Oct 20	2455124.66993	3.33	0.01775
2009 Oct 26	2455130.69507	3.37	0.0188
2009 Oct 30	2455134.6559	3.38	0.01999
2009 Nov 04	2455139.70882	3.4	0.02198
2009 Nov 09	2455144.65146	3.41	0.01559
2009 Nov 18	2455153.71319	3.44	0.02646
2009 Nov 21	2455156.70903	3.44	0.02429
2009 Nov 29	2455164.75347	3.48	0.03114
2009 Dec 04	2455169.71424	3.53	0.01975
2009 Dec 11	2455176.71243	3.57	0.0204
2009 Dec 17	2455182.63146	3.62	0.0173
2009 Dec 22	2455187.72181	3.66	0.0124
2009 Dec 28	2455193.6325	3.67	0.01215
2010 Jan 11	2455207.63194	3.68	0.01614
2010 Jan 15	2455211.52264	3.68	0.02811

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Table 1. Differential photometry of ε Aurigae, cont.

UT Date	JD	V Filter Magnitude	V Filter Standard Deviation
2010 Jan 19	2455215.52937	3.68	0.0363
2010 Jan 23	2455219.75847	3.69	0.02937
2010 Jan 28	2455224.51042	3.7	0.01443
2010 Feb 01	2455228.70486	3.7	0.02712
2010 Feb 08	2455235.62917	3.72	0.01923
2010 Feb 13	2455240.71597	3.73	0.02232
2010 Feb 20	2455247.71347	3.77	0.01564
2010 Mar 03	2455256.63194	3.76	0.02179
2010 Mar 07	2455262.52986	3.76	0.0174
2010 Mar 17	2455272.64306	3.74	0.01712
2010 Mar 25	2455280.64938	3.73	0.02301
2010 Apr 02	2455288.65486	3.74	0.02851
2010 Apr 15	2455301.56736	3.78	0.01706
2010 Apr 20	2455306.62931	3.76	0.02374
2010 Apr 24	2455310.62778	3.76	0.03999
2010 Apr 29	2455315.60361	3.76	0.04549
2010 May 06	2455322.56451	3.78	0.02002
2010 May 16	2455332.5711	3.71	0.03709
2010 May 17	2455333.57111	3.69	0.03997
2010 May 27	2455343.55278	3.56	0.02828
2010 Aug 14	2455422.82389	3.68	0.01155
2010 Aug 21	2455429.81597	3.68	0.02243
2010 Aug 28	2455436.79354	3.7	0.01768
2010 Sep 05	2455444.77292	3.7	0.02137
2010 Sep 15	2455454.73403	3.67	0.02348
2010 Sep 21	2455460.73056	3.65	0.03312
2010 Oct 03	2455472.72431	3.65	0.01199
2010 Oct 09	2455478.71007	3.68	0.03198
2010 Oct 18	2455487.65347	3.67	0.0159
2010 Oct 23	2455492.68597	3.7	0.0128
2010 Nov 01	2455501.64625	3.73	0.02182
2010 Nov 06	2455506.68056	3.73	0.02324
2010 Nov 13	2455513.72514	3.75	0.0194
2010 Nov 20	2455520.72222	3.74	0.01928
2010 Nov 29	2455529.64236	3.72	0.03263
2010 Dec 08	2455538.71181	3.7	0.01633
2010 Dec 18	2455548.71042	3.68	0.01852
2010 Dec 30	2455560.63889	3.71	0.03079
2011 Jan 06	2455567.52431	3.75	0.03577

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Table 1. Differential photometry of ε Aurigae, cont.

UT Date	*JD*	*V Filter*	
		Magnitude	*Standard Deviation*
2011 Jan 14	2455575.52694	3.75	0.01603
2011 Jan 31	2455592.63472	3.74	0.02098
2011 Feb 04	2455596.52847	3.76	0.02623
2011 Feb 11	2455603.53104	3.75	0.01365
2011 Feb 23	2455615.52639	3.76	0.02029
2011 Mar 02	2455622.69104	3.73	0.03067
2011 Mar 09	2455629.69313	3.71	0.03032
2011 Mar 14	2455634.59722	3.67	0.02517
2011 Mar 20	2455640.69722	3.59	0.04129
2011 Mar 25	2455645.69604	3.55	0.02363
2011 Mar 29	2455649.70271	3.5	0.03054
2011 Apr 06	2455657.65646	3.42	0.02266
2011 Apr 22	2455673.65542	3.31	0.03364
2011 May 01	2455682.58889	3.35	0.3777
2011 May 06	2455687.57313	3.32	0.03628
2011 May 11	2455692.57201	3.3	0.01258
2011 May 12	2455693.56646	3.26	0.02463
2011 May 26	2455707.55549	3.3	0.05566

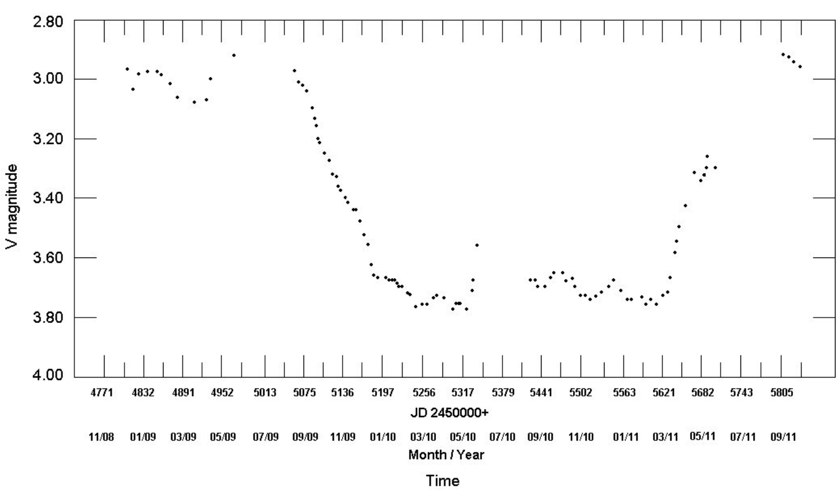

Figure 1. Light curve of ε Aur, 2008–2011. V magnitude is with respect to λ Aur comparison star at V magnitude 4.71.