V-band Light Curve Analysis of ε Aurigae During the 2009–2011 Eclipse

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Abstract Timings for the eclipse contact points and mid-eclipse, length of ingress and egress, average magnitude during eclipse, and timings for out-of-eclipse variations have been determined in the V band for the long period eclipsing binary ε Aurigae during the 2009–2011 eclipse. This has been done with data from the International Epsilon Aurigae Campaign 2009 and AAVSO. Comparison with data from previous eclipses has also been made.

1. Introduction

The extremely long-period eclipsing binary ε Aurigae (period = ~27.1 years) is still not fully understood. It has been studied by many groups in different wavelengths photometrically, spectroscopically, and interferometrically. The ~2-year eclipse that occurred 2009–2011 presented an opportunity to constrain some parameters for the system. As the system is bright (V = 2.9–3.8) and the duration of the eclipse is long, it is a suitable target for amateur astronomers who can commit a long period of time for this type of project. An international campaign with participants of both advanced amateur and professional astronomers was established (see the campaign website at http://www.hposoft.com/Campaign09.html for further details.) Photometric data from this campaign together with two contributors from the AAVSO, who have covered the whole eclipse, are the basis for this analysis. The campaign produced data in the U, B, V, Rc, Ic, J, and H bands but this analysis only covers the most studied V band.

2. Method

The observers in the campaign used a diversity of equipment and reduction methods (Table 1), from photometers mounted on telescopes, to CCD-cameras with telescopes, or camera-lenses and standard digital single-lens reflex cameras on a tripod. The campaign has published recommended reduction methods and comparison stars to use. But the diversity in equipment and individuality in photometric software and methods used have introduced some differences among the observers. To make the observations comparable to each other the following methods were used.

Prior to the analysis all observations were divided into groups of four-day periods. In each group the mean of magnitude and JD were calculated. Each observer's individual observations were then subtracted from the corresponding means, and the standard deviation of each observer's differences was calculated. Observers with too much spread in their data (SD > 0.04) were then excluded altogether, and some outlying (> 0.08 from the mean) individual points from the remaining observers were also removed. New four-day means and differences were then calculated for the remaining observers. From these new differences an offset for each observer was calculated, showing the difference for each observer's dataset and the mean for all data. This offset was then subtracted from each observer's data and new one- and four-day means were calculated. These corrected means were then used in the further analysis. The individual observations with the offset applied are seen in Figure 1, the 4-day means are in Figure 2 and the 1-day means in Figure 3.

The offset is based on the assumption that each observer used a similar reduction technique during the eclipse, but the choice of reduction techniques and comparison stars differs among the observers, so that each dataset is to a higher degree consistent with itself than with the other datasets. The idea is that by using this method of reconciling the data more fine details in the light curve should be seen.

3. Results

3.1. Eclipse timings and magnitude

The four contact points for a total eclipse between two spherical bodies are defined as beginning of eclipse, beginning of totality, end of totality, and end of eclipse. In the case of ε Aurigae the main star is partially eclipsed by what is supposed to be a dusty disc seen almost edge on (Huang 1965; Kloppenborg *et al.* 2011), giving rise to an elongated and elliptical eclipsing body from our view. Contact 2 and 3 have therefore for this system an ambiguous definition and not the same physical meaning as for a classical eclipsing binary. For this system they could be interpreted as the points where the leading edge of the elongated disc has crossed the whole face of the main star and where the trailing edge of the disc begins to leave the face of the main star.

The contact points (Table 2) were estimated using a linear trend line applied to the ingress/egress from Figure 2 and were decided by where the line crossed the out-of-eclipse mean magnitude of 3.035 (Hopkins 2011) and the mean during the eclipse of 3.728. Some further work may be done to produce a more precise model of the curve and the means before and after the contact points to obtain more accurate times for the contacts. At contact 2 the curve is especially smooth, which makes the contact point hard to define. Contact 3 could have occurred about a week later than the trend line suggests because of the very steep beginning of the egress. Figures 4 and 5 show the graphs used to establish the contact points.

The totality phase after mid-eclipse is 0.027 magnitude brighter than before mid-eclipse. The brightest part of the totality is during mid-eclipse, and the dimmest just before mid-eclipse. On average, the dimmest part is in the beginning and end of totality and the brightest in between:

- Mean magnitude during totality:
  3.728 (mean over JD 2455208–2455616)

- Mean magnitude during 1st part of totality:
  3.742 (mean over JD 2455208–2455400)

- Mean magnitude during 2nd part of totality:
  3.715 (mean over JD 2455400–2455616)

- Eclipse depth: 0.693 magnitude

- Length of ingress: 142 ± 10 days
  mean drop of brightness: 0.0049 ± 0.0003 magnitude/day

- Length of egress: 121 ± 14 days
  mean increase of brightness 0.0057 ± 0.0007 magnitude/day

- Mid-eclipse, mean of contact 1 and 4:
  JD 2455401 ± 6 (2010 July 23)

- Midpoint of totality, mean of contact 2 and 3:
  JD 2455411.5 ± 6 (2010 August 03)

- Eclipse duration, contact 4–contact 1: 674 ± 12 days

- Totality duration, contact 3–contact 2: 411 ± 12 days

3.2. Out-of-eclipse (OOE) variations

Besides the eclipse, the system shows a smaller variation of 0.1 to 0.2 magnitude with an irregular period of ~2 months (see, for example, Hopkins and Stencel 2006 for a recent study before start of the 2009 eclipse). The out-of-eclipse variations during totality were calculated by applying a fourth-order polynomial fit to the data points 24 and 27 days around each maxima and minima using the 1-day averages from Figure 3. The mean times and magnitudes from the two sets are shown in Table 3. The error for the specified dates is estimated to be on average within ± 2 days and the magnitude within ± 0.01.

Amplitude is calculated as the difference between the maximum and the mean of the two adjacent minima. The first minimum could be affected by the ingress. The observations made 3–4 weeks before and after solar conjunction that occurred on JD 2455355 (2010 June 07) are contradictory probably because of the difficult observing conditions and differences in extinction calculation among the observers. This gives uncertainty to the data from minimum 2 and maximum 2. During minimum 5 there is a flat part of about 15 days between JD 2455510 and 2455525. The last maximum before start of egress is especially short and low.

The slope of the OOE-variations is between 0.0012 and 0.0029 mag/day with a mean of 0.0022 mag/day, a little less than half of the slope during ingress/egress.

3.3. Ingress and egress characteristics

During ingress there are hints of two OOE variations with maxima about JD 2455080 (2009 September 05) and JD 2455160 (2009 November 24), which can be seen in Figure 4 in the parts of the ingress curve that lie above the linear trend. Another OOE variation just at the end of ingress with a maximum about JD 2455215 (2010 January 18) is also probable and can be seen as a part with low slope at the end of ingress.

The egress started with a high rate of change in magnitude, during JD 2455620 to 2455655 (2011 February 27–2011 April 03). The change was 0.0089 magnitude/day, the highest that was seen during the whole eclipse. Further analysis must be done to tell if a rising OOE variation interacted to generate this high pace. As the last OOE variation just before egress was strangely short and low it is hard to decide by just looking at the light curve if a new OOE variation occurred during this period. During JD 2455655 to 2455670 (2011 April 03–2011 April 18) the slope was lower, at 0.0051 magnitude/day, and then there was a strange standstill or slight decrease of brightness for about 15 days until JD 2455685 (2011 May 03). After that the egress went on at a steady rate of 0.0055 magnitude/day, which is about the same as the mean during the whole egress. The fluctuations that can be seen at the very end of egress are probably caused by the difficult observation conditions during that time near solar conjunction. The big change of slope around JD 2455655 and the later standstill seem too big to be caused by any OOE variation.

3.4 Comparison with previous eclipses

In Figure 6 there is a combined light curve with the 4-day average data from Figure 2 together with two prominent datasets from the previous two eclipses, observations by Gunnar Larsson-Leander 1956–1957 (Larsson-Leander 1959) and Stig Ingvarsson 1982–1984 (Schmidke 1985). The elements from the *General Catalogue of Variable Stars* (GCVS4; Kholopov *et al.* 1984), epoch JD 2435629 and period 9,892 days, were used to phase the data. Table 4 shows data from previous eclipses together with the data from this paper.

Period analyses were made with the light curve and period analysis software PERANSO (Vanmunster 2007) and the ANOVA (analysis of variance) method. The periods calculated (Table 5) are 2–5 days longer than the period from GCVS4.

The trend of decreasing duration of eclipse and egress and increasing duration of totality that was seen during the three or four previous eclipses is broken by the last eclipse. In fact, the 2009–2011 eclipse resembles that of 1955–1957 more than that of 1982–1984, with the more similar length of the different phases, the deep minimum just before mid-eclipse, and the knee half way during the egress. In 1984 the knee was not visible until the system had reached magnitude 3.30–3.25 and the observation season was almost over. The lack of observations at the end of the 1984 eclipse is probably the cause of the very short egress stated, calculated from the slope seen at the first phase of egress.

Differences are the deep minimum, down to 3.85, that was seen at the very end of totality in 1956 but not seen in the two following eclipses. The frequent OOE variations during totality seen during 2010 seem to not occur to the same extent either in 1956 or 1983. Maybe it can be partly explained by the more detailed observations done during the last eclipse.

The pronounced mid-eclipse brightening that was evident in 1983 was not seen to any higher degree in 2010. Although the brightest point during the totality of 2010 occurred at mid-eclipse, it was only 0.02–0.04 magnitude brighter than the two subsequent out-of-eclipse variations. It should also be stated that the mid-eclipse of 1984 coincided with the toughest observation conditions at solar conjunction, and no observations were made at the time of mid-eclipse. If a careful correction for extinction is not done during this period, one could easily obtain values too bright for ε as the most used comparison stars, λ Aur, η Aur, and HR1644, all lie south of ε. This appearance was seen among several observers during May–June 2010.

In Figure 6 one can also notice the placement of the humps from the OOE-variations during the totality phase between the three eclipses. For most part they are not in phase between all three eclipses, with the exception of a brighter phase at mid-eclipse. It contradicts the idea from Ferluga (1990), that the OOE-variations are caused by ring-like structures with Cassini-like divisions in the obscuring disc as it passes the main star. If such a ring structure is stable one should expect that the humps would be in phase between the eclipses.

4. Conclusions

The following conclusions can be drawn from this study:

The OOE variations occur with the same amplitude and periodicity during the eclipse as the period before eclipse and make it much harder to see the features of the eclipse itself.

Ingress and egress have different lengths. In this study egress is about 20 days shorter than ingress. Compared to previous eclipses this relation has varied a great deal. The length of egress, especially, has fluctuated a lot.

The egress has a knee half ways where the slope changes abruptly, a change that is too big to be explained by OOE variations. Further analysis has to be done to see if the geometry of the eclipsing disc can explain the shape of the egress light curve or if some other process is involved.

If the eclipsing body is an homogeneous elliptical disc, then in purely geometrical terms the biggest loss of light by a partial eclipse should occur half ways, and the light curve during totality should be slightly convex. Instead, the average light curve is slightly concave during totality. This means that another mechanism may be involved to explain the shape of the curve, for example, an optically thinner center of the disc or some sort of scattering effect.

There is also a difference in mean magnitude during the first half of totality compared to the second half that could be a real feature if OOE variations are omitted.

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Table 1. The observers whose data were used and their offsets and standard deviation.

Observer, Country	*Affiliation**	*Observer Code*	*Equipment*	*Number of observations*	*Offset*	*SD*
John Centala, USA	AAVSO	CQJ	CCD	96	–0.0042	0.017
Donald Collins, USA	IEAC	WWC	DSLR	74	0.0068	0.020
Laurent Corp, France	IEAC	GO	CCD	19	–0.0045	0.030
Serdar Evren, Turkey	IEAC	EUO	PEP	80	–0.0229	0.016
Snaevarr Gudmundsson, Iceland	IEAC	LO	PEP	125	0.0072	0.016
Hubert Hautecler, Belgium	IEAC	RLO	DSLR	28	0.0177	0.020
Charles Hofferber, USA	IEAC	EGO	DSLR	81	0.0137	0.021
Jeff Hopkins, USA	IEAC	HPO	PEP	148	0.0137	0.010
Thomas Karlsson, Sweden	IEAC /AAVSO	VO/KTHA	DSLR	166	0.0004	0.014
Hans-Gîran Lindberg, Sweden	IEAC	KO	CCD	111	0.0073	0.020
Des Loughney, Great Britain	IEAC	DES	DSLR	206	0.0035	0.020
Brian E. McCandless, USA	IEAC	GVO	PEP	11	–0.0054	0.006
Frank J. Melillo, USA	IEAC	FJM	PEP	95	–0.0119	0.017
Richard Miles, Great Britain	IEAC	GHO	CCD	151	0.0011	0.025
Tom Pearson, USA	IEAC	TP	DSLR	106	0.0143	0.019
Roger Pieri, France	AAVSO	PROC	DSLR	160	–0.0137	0.016
Gerard Samolyk, USA	IEAC	GS	CCD	149	–0.0236	0.022
Iakovos Marios Strikis, Greece	IEAC	EAO	CCD	76	0.0020	0.017
Piotr Wychudzki, Poland	IEAC	PW1	CCD	22	0.0001	0.023
Piotr Wychudzki, Poland	IEAC	PW2	CCD	38	0.0237	0.025

** IEAC, International Epsilon Aurigae Campaign 2009; AAVSO, American Association of Variable Star Observers; PEP, Photoelectric photometric equipment as SSP–3 or PMT; CCD, Charge Coupled Device camera; DSLR, Digital Single–Lens Reflex camera.*

Table 2. Timing of the eclipse contact points.

Contact	*JD*	*Date*
1	2455064 ± 5	2009 August 20
2	2455206 ± 5	2010 January 09
3	2455617 ± 7	2011 February 24
4	2455738 ± 7	2011 June 25

Table 3. Data for out-of-eclipse variations during the eclipse.

		Minima		
Nr.	*JD*	*Date*	*Length*	*V Mag.*
1	2455259	2010 March 03	—	3.77
2	2455311	2010 April 24	52	3.79
3	2455367	2010 June 19	56	3.78
4	2455437	2010 August 28	70	3.72
5	2455520	2010 November 19	83	3.75
6	2455576	2011 January 14	56	3.75
7	2455610	2011 February 17	34	3.77
Avg			58.5	3.761

		Maxima			
Nr.	*JD*	*Date*	*Length*	*V Mag.*	*Amplitude*
1	2455283	2010 March 27		3.72	0.060
2	2455336	2010 May 19	62	3.71	0.075
3	2455407	2010 July 29	60	3.65	0.100
4	2455471	2010 October 01	63	3.67	0.065
5	2455547	2010 December 16	79	3.69	0.060
6	2455590	2011 January 28	43	3.74	0.020
7	—	—	—	—	—
Avg			61.4	3.697	0.063

Table 4. Data from previous eclipses together with the data from this paper.

	Mean of 1901–1903 1928-1930 (1)	*1955–1957 Gyldenkerne (1)*	*1982–1984 Schmidtke*	*2009–2011*
Duration (days)	714	670	647	674
Ingress (days)	182	135	137	142
Totality (days)	330	394	446	411
Egress (days)	203	141	64	121
Depth (mag)	0.80	0.75	0.686 (2)	0.693

[1] *From Hopkins, Schanne, and Stencel (2009).* [2] *Mid-eclipse brightening omitted.*

Table 5. Periods calculated with PERANSO ANOVA.

Comparison	*Period (days)*
1955-57, 1982-84, 2009-11	9897
1955-57, 2009-11	9896
1982-84, 2009-11	9894
GCVS4	9892

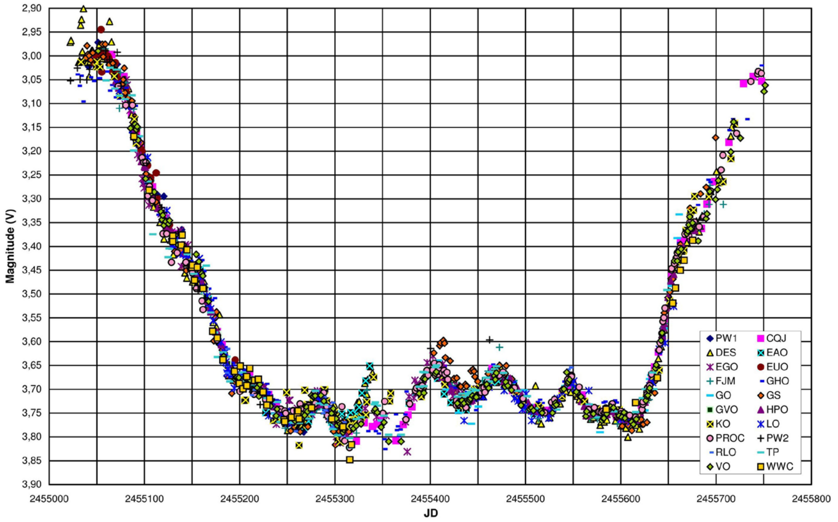

Figure 1. The individual observations, with each dataset corrected with its offset. (The observer PW made observations from two different observatories.)

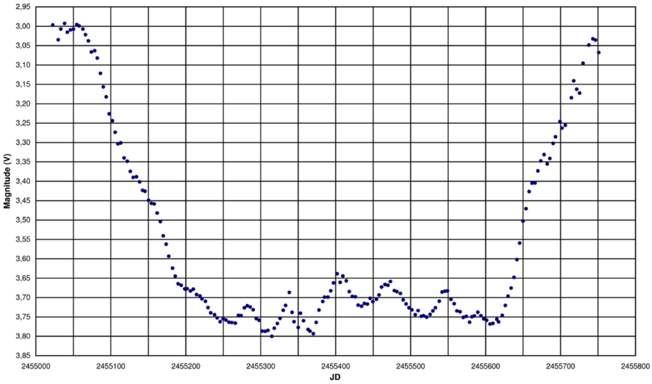

Figure 2. The observations from Figure 1, grouped together as 4-day averages.

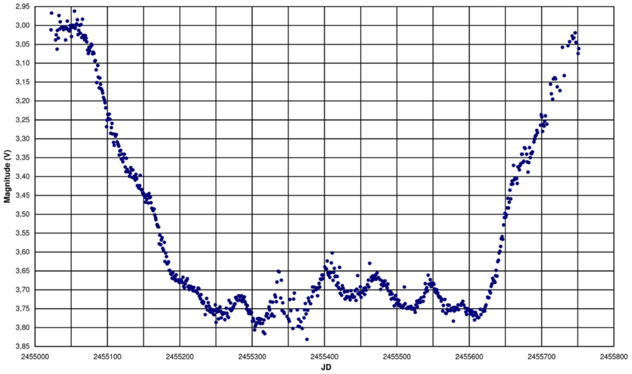

Figure 3. The observations from Figure 1, grouped together as 1 day averages.

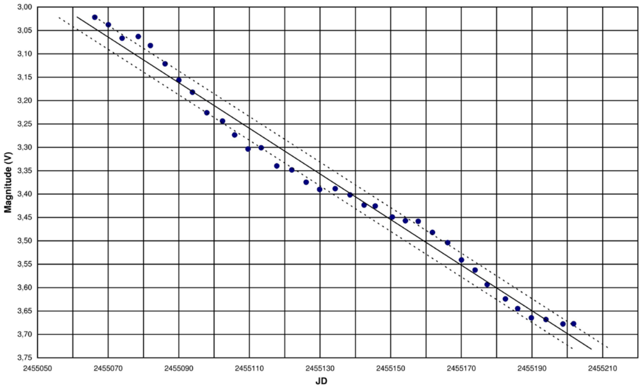

Figure 4. Detail from Figure 2 of the ingress (JD 2455060–22455216) and the linear fit used. The dotted lines show an error of 1 sigma in magnitude.

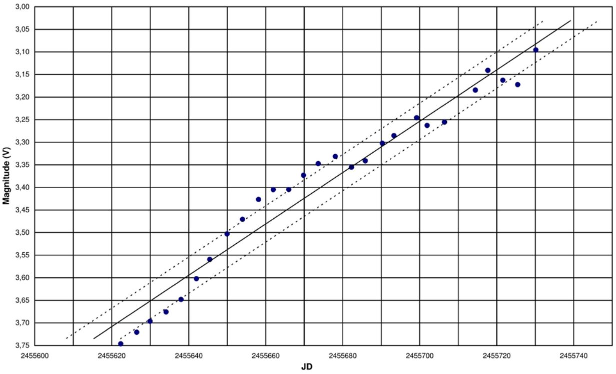

Figure 5. Detail from figure 2 of the egress (JD 2455616–2455740) and the linear fit used. The dotted lines show an error of 1 sigma in magnitude.

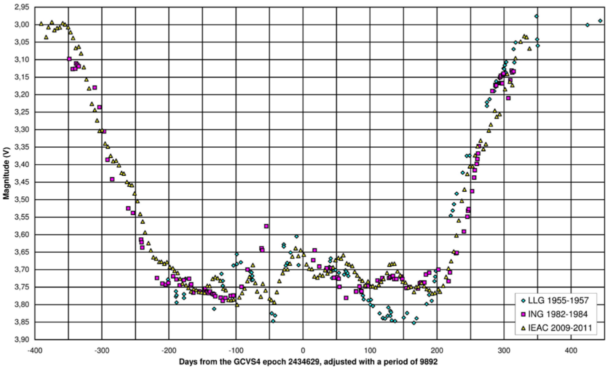

Figure 6. The data from this paper (IEAC) compared with two datasets from the previous two eclipses, Gunnar Larsson-Leander (LLG) from 1955–1957 and Stig Ingvarsson (ING) from 1982–1984.