The International ε Aurigae Campaign 2009 Photometry Report

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Abstract An International Campaign and Web site were started in May of 2006 for the 2009–2011 eclipse of the mysterious star system ε Aurigae. Photometric and spectroscopic observations of the eclipse were coordinated and reported. The eclipse started in the summer of 2009 and lasted until the spring of 2011. During the campaign twenty-four newsletters were published on the web site and made available free as .pdf files to read and download. Twenty-six observers from fourteen different countries submitted photometric data in the UBVRI bands. Over 3,600 high-quality photometric observations were submitted with nearly 2,000 observations in just the V band. This paper discusses the Campaign and report the results.

1. Introduction

Prior to the eclipse, data from previous eclipses and from between eclipses were consolidated in the form of a book (see Hopkins and Stencel 2008). A paper was given at the Society for Astronomical Sciences 2010 Symposium that discussed the ingress of the latest eclipse (Hopkins *et al.* 2010). Most of the photometric data for the 2009–2011 eclipse were obtained in the V band. The largest photometric changes were in the in the shorter wavelengths, however. The U band, which was only observed with the PMT-based systems, provided the largest changes.

Some people thought that during the late spring and early summer the star system went behind the Sun and was not observable. This is not true. The declination of the star system is high above the plane of the solar system and it never goes behind the Sun.The problem is that at lower latitudes it gets very close to the horizon during the dark hours and thus the light passes through very high air mass. Extinction becomes a very significant problem. Those observers at higher latitudes could observe the system at lower air masses, but as one goes farther north the number of dark hours decreases to the point of the midnight Sun. Some of the higher-latitude observers did heroic work during these poor observing times. Even then the data are somewhat confusing and noisy. The mid-eclipse brightening period was at one of these poor times. Some data indicate the brightening and some indicate no brightening. Also, midway during egress was a poor time and something interesting happened then too. There seems to be a knee in the egress photometric plots. Perhaps more and better data during these times can be obtained during the next eclipse in 2036.

A Campaign was formed during the 1982–1984 eclipse and thirteen newsletters published. The current Campaign's web site has some of these newsletters available on line. For the 2009–2011 eclipse there were twenty-four newsletters published by the Hopkins Phoenix Observatory. All of these are available as .pdfs on the Campaign web site along with a great deal of other pertinent data on ε Aur. In addition to the 2009 Campaign's web site at http://www.hposoft.com/Campaign09.html, a Campaign Yahoo forum was started and can be accessed at: http://tech.groups.yahoo.com/EpsilonAurigae/

2. Observations summary

As of December 26, 2011, we had nearly 3,700 total observations reported during the eclipse, with the visual band having by far the most at nearly 2,000 observations. Twenty-six observers from around the world contributed observational data. Table 1 is a summary of the observers contributions.

3. Data quality

ε Aur is bright enough to be visually seen easily even in most light polluted areas. One can even notice the dimming of the eclipse visually. While the use of visual observations for plotting changes in the brightness of stars works well with some stars, the eclipse of ε Aur was not a good project for visual work. To be of value magnitudes estimates must be of a resolution of 0.05 magnitude or better. This is an order of magnitude less than what even experienced visual observers can produce under the best of conditions. For this reason the International Campaign did not use any visual magnitude estimates.

Photometric data submitted to the campaign had average standard deviations for three or more data points of magnitude 0.01. Many observations approached a standard deviation of magnitude 0.001. The standard deviation is used as an indication of the quality of the data by representing a data spread of three or more data points. The photometric plots do not have error bars because the standard deviations, which would be used for the error bars, are too small in relation to the plot scale. Most submitted data have been transformed and corrected for nightly extinction. The Hopkins Phoenix Observatory (HPO) used a high-precision UBV 1P21-based photon counting system. All HPO data were dead time corrected, transformation coefficients determined for each band, and nightly extinction coefficients determined for each band. Data reduction was done using the Hardie equations. Magnitudes were determined for both λ Aur and ε Aur and then differential calculations done and normalized to the standard values for λ Aur's magnitudes. Nightly sessions consisted of three comparison star measurements in each band, three adjacent sky measurements in each band, followed by the same routine for the program star. There were three sets of these measurements made with the program star bracketed by the comparison star. The data were all transformed and extinction corrected. Three magnitudes were determined for each band, a standard deviation calculated, and the magnitude average for each band reported to four places.

There has been some concern about the U and B magnitudes from the Hopkins Phoenix Observatory. First, there are no standard U and B magnitudes for ε Aur. The star system varies significantly and randomly out-of-eclipse. The variation is greatest in the U and B bands. If one were to suggest out-of-eclipse magnitudes then the average of several seasons of out-of-eclipse magnitudes could be specified, but a warning would be needed indicating that these are averages. From data taken out-of-eclipse between March 1986 and February 2008, the following are maximum, minimum, and average magnitudes for the UBV bands:

Vavg = 3.04	Vmin = 3.16	Vmax = 2.94
Bavg = 3.61	Bmin = 3.53	Bmax = 3.69
Uavg = 3.73	Umin = 3.60	Umax = 3.92

One of the great things about a campaign like this is that one gets a chance to compare their photometric data taken at approximately the same time against others. Photometric light curves for the campaign were updated and published on the web around once a month. Observers could identify their data and see how well they compared to others. Noisy data are obvious. If the observer was interested, he or she could investigate the differences and improvements in technique and data reduction.

4. Comparison star

There are a vast number of observations of ε Aur covering many decades that use λ Aur as a comparison star. Because during this time λ Aur has been found to be very stable over several decades, no check star is needed. The UBV magnitudes are those used in the previous two eclipses. The longer wavelength magnitudes were obtained from the AAVSO.

The data used for the comparison star are:

Comparison star: λ Aur

Other identification: SAO40233, HR1729, HD34411

Position: R.A. (2000) $05^h\ 19^m\ 08.4^s$, Dec. (2000) +40° 05' 57"

Magnitudes: U = 5.46, B = 5.34, V = 4.71, Ij = 3.88, Ic = 4.00, Rj = 4.19, Rc = 4.30, J = 3.62, H = 3.33

5. Equipment

There were four types of instrumentation used to acquire data for the 2009 Campaign: Digital Single Lens Reflex (DSLR) cameras, CCD cameras, Pin Diode photometers (SSP-3 and SSP-4), and photon counting photometers (PMT-based). The photon counting provided highest quality UBV data followed by the SSP-3 for BV data. Obtaining CCD data was more difficult as the brightness caused problems. CCD provided BVRI data. The last and newest equipment for photometry were the DSLR cameras. The DSLR provided V-band data by using the green channel of the RGB images. With the exception of a couple DSLR observers the data submitted were very noisy. However, DSLR cameras offer an excellent introduction to photometry. Once an observer is confident with doing photometry with a DSLR, an entry level monochrome CCD camera with BVRI photometric filters would be a great way to start doing professional photometry.

6. Results

6.1. Hopkins Phoenix Observatory data

The Hopkins Phoenix Observatory data were taken with a high-precision UBV photon counting system. All data were transformed, dead time corrected, and nightly extinction determined and corrected. Details of the photometric work at the Hopkins Phoenix Observatory is reported in Hopkins *et al.* (2007).

When out-of-eclipse the star system has presented tantalizing data (Figure 1). The light is not constant, but varies at a pseudo-periodic rate in all the photometric bands. The period is not stable, and varies unpredictably between 50 and 70 days. In addition to the period variations the amplitudes vary unpredictably. Period analysis was done using PERANSO period analysis software (Vanmunster 2007), but no period could be determined. Details of this work are reported in Hopkins and Stencel (2007) and Hopkins *et al.* (2008).

While not photometry, in an attempt to shed light on the out-of-eclipse variations high-resolution out-of-eclipse spectroscopy of the star system's Hα region was done at Hopkins Phoenix. The main Hα absorption line is bracketed by emission lines (horns) that go up and down, sometimes together and sometimes completely independently (see Figure 2). They sometimes reach a large peak and at other times disappear completely. This is known as the "Hydrogen Alpha Horn Dance." No connection was found between the out-of eclipse Hα spectroscopic variations and the out-of-eclipse photometric variations. The emission horns did seem to decrease and even go away for a while during the eclipse, however. Details of the spectroscopic observations at Hopkins Phoenix Observatory are reported in Hopkins and Stencel (2009a, 2009b) and Hopkins (2012).

6.2. Campaign data

High data producers for the ε Aur campaign were as follows:

DSLR: Des Loughney, Edinburgh, Scotland—238 V-band observations.
CCD: Gerard Samolyk, Greenfield, Wisconsin—721 BVRcIc observations.
SSP: Paul J. Beckmann, Jim Beckmann Observatory, Mendota Heights, Minnesota—89 BVRjIj observations;
Photon counting: Jeff Hopkins, Hopkins Phoenix Observatory, Phoenix, Arizona—565 UBV observations.

Observation techniques varied among observers. Details of each observer are presented on the 2009 Campaign's web site at http://www.hposoft.com/Campaign09.html.

6.3. Campaign light curves

See Figures 3 through 7. UBVRIJH photometric data from 1982 to 2012 are archived and available in multiple formats at http://www.hposoft.com/Eaur09/Data/UBVRIJHData.html.

7. Analysis

There has been some concern expressed by armchair photometrists about the contact times. The following may help understand the complexity of this system and the methodology used to determine the contact points.

The ε Aur star system is very different from most eclipsing binary systems. For the analysis of the contact points the classical method was used. In addition to the non-classical eclipsing body, complicating the analysis are the pseudo-periodic out-of-eclipse (OOE) variations (see Figure 8).

Figure 9 shows the procedure for determining the current eclipse contact points. The average ingress and egress slopes were used to find the intersection with the average totality and out-of-eclipse magnitudes.

An archive of UBVRIJH photometric data is available to the public at http://www.hposoft.com/EAur09/Photometry.html and http://www.hposoft.com/EAur09/Data/UBVRIJHData.html.

A summary of the data is given in Table 2.

8. Predictions for the 2036–2038 eclipse

While I am unlikely to be around for the next eclipse in 2036 it is still interesting to offer photometric predictions about it. Only the V-band contact points are included. There is still controversy about the second and third contact points. These dates were calculated by adding 9,898 days to the first contact, mid-eclipse, and fourth contact of the 2009–2011 contact times.

The V-band predictions are:

first contact: JD 2464964 ± 12 days, September 27, 2036;
mid-eclipse: JD 2465283 ± 9.5 days, August 12, 2037;
fourth contact: JD 2465601± 7 days, June 26, 2038.

9. Conclusion

Each eclipse of ε Aur sees a new breed of equipment and observers. While more was learned from this latest eclipse, the star system is not giving up its secrets easily. It seems to be taunting us. During some of the most interesting times, the system was extremely difficult to observe. The eclipse may be over for another twenty-seven years, but the star system still presents some interesting challenges. Monitoring and understanding the out-of-eclipse variations will be a major objective. This is followed by the strange Hα horn dance. A continued following of the star system with both photometric and spectroscopic observations is suggested. This may provide some additional insights into these mysteries. One of the nice things about observing out-of-eclipse is the times of high air mass can usually be avoided. Observing can be done during favorable times, such as in the early fall, during winter, and in early spring. As indicated earlier, the most active regions for photometry are the shorter wavelengths. U band is a especially important band in which to make observations. The system also offers excellent spectroscopic learning for the hydrogen Balmer lines as well as the sodium D lines.

10. Acknowledgements

I would like to thank all the observers who contributed data to the Campaign. In particular I want to thank Dr. Robert Stencel (“Dr. Bob”) and Brian Kloppenborg for their help, encouragement, and the honor of working with them both with the Campaign and especially with the observing sessions at CHARA on Mount Wilson in California, and the MMT on Mount Hopkins in southern Arizona. Those are treasured experiences and memories.

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Table 1. 2009 ε Aur campaign photometric observer count.

Observer[1]	*V*	*B*	*U*	*Rc*	*Rj*	*Ic*	*Ij*	*Total*	*Equipment*[2]
CH	143	—	—	—	—	—	—	143	DSLR
CO	3	—	—	—	—	—	—	3	CCD
CQJ	100	100	—	—	—	95	—	295	CCD
DES	242	—	—	—	—	—	—	238	DSLR
EAO	68	—	—	—	—	—	—	68	CCD
EGO	81	—	—	—	—	—	—	81	DSLR
EUO	1	39	9	—	40	—	—	89	PMT
FJM	65	—	—	—	—	—	—	65	SSP-3
GHO	165	—	—	—	—	160	—	325	CCD
GO	22	—	—	20	—	—	—	42	CCD
GS	179	178	—	183	—	181	—	721	CCD
GVO	13	8	—	—	13	—	13	47	SSP-3
HPO	147	209	209	—	—	—	—	565	PMT
JBO	16	41	—	—	16	—	16	89	SSP-3
JESO	34	—	—	—	—	—	—	34	CCD
KO	111	—	—	—	—	—	—	111	CCD
LO	87	—	—	—	—	—	—	87	SSP-3
MSO	3	3	—	—	—	—	—	6	CCD
NKO	38	—	—	—	—	—	—	38	DSLR
NPO	—	—	—	—	18	—	18	36	SSP-3
RES	56	—	—	—	—	—	—	56	DSLR
RLO	29	—	—	—	—	—	—	29	DSLR
SGGO	67	17	—	59	—	—	—	143	CCD
TP	86	—	—	—	—	—	—	86	DSLR
VO	193	—	—	—	—	—	—	193	DSLR
WWC	50	42	—	—	—	—	—	92	DSLR
Total	1999	637	218	262	87	436	47	3686	

Table continued on next page

Table 1. 2009 ε Aur campaign photometric observer count, cont.

[1] *Observers (AAVSO observer initials are given in parentheses):*
CH (HEN), Colin Henshaw, Tabuk, Saudi Arabia
CO (OSC), Steve Orlando, Custer Observatory, East Northport, NY
CQJ (CQJ), John Centala, Eastern Iowa
DES (LDS), Des Loughney, Edinburgh, Scotland, UK
EAO (SIAK), Iakovos Marios Strikis, Elizabeth Observatory of Athens, Haldrf (Athens), Greece
EGO, Charles Hofferber, East Greenwood Observatory, East Grand Forks, MN
EUO, Serdar Evren, Ege University Observatory, Izmir, Turkey
FJM (MFR), Frank J. Melillo, Holtsville, NY
GHO (MXL), Richard Miles, Golden Hill Observatory, Dorset, England
GO (CLZ), Laurent Corp, Garden Observatory, Rodez, France
GS (SAH), Gerard Samolyk, Greenfield, WI
GVO (MBE), Brian E. McCandless, Grand View Observatory, Elkton, MD
HPO (HPO), Jeff Hopkins, Hopkins Phoenix Observatory, Phoenix, AZ
JBO (BPJ), Paul J. Beckmann, Jim Beckmann Observatory, Mendota Heights, MN
JESO, Dr. Mukund Kurtadikar, Jalna Education Society Observatory, Maharashtra, India
KO (LHG), Hans-Goran Lindberg, Kaerrbo Observatory, Skultuna, Sweden
LO (GSN), Snaevarr Gudmundsson, Lindarberg Observatory, Hafnarfjordur, Iceland
MSO, Arvind Paranjpye, MVS IUCAA Observatory, Ganeshkhind Pune, India
NKO, Nils Karlsen, Nils Karlsen Observatory, Umea, Sweden
NPO, Gary Frey, North Pines Observatory, Mayer, AZ
RES (SVR), Dr. Robert E. Stencel, University of Denver, Denver, CO
RLO (HHU), Hubert Hautecler, Roosbeek Lake Observatory, Boutersem Brabant, Belgium
SGGO (CTIO), Tiziano Colombo, S. Giovanni Gatano al Observatory, Pisa, Italy
TP, Tom Pearson, Virginia Beach, VA
VO (KTHA), Thomas Karlsson, Varberg Observatory, Varberg, Sweden
WWC (CDK), Donald Collins, Warren Wilson College, Ashville, NC

[2] *Equipment key: CCD, CCD Camera and telescope; DSLR, Digital Single Lens Reflex Camera, unguided; SSP-3, PIN Diode photometer with telescope; PMT, Photomultiplier Tube, photon counting with telescope.*

Table 2. 2009 ε Aur campaign data summary.

Parameter	*Observed RJD = JD–2400000*	*Error*	*Predicted[1] RJD = JD–2400000*
U band			
OOE Mag.	3.725 Mag. Δ0.230 Mag.		3.73 Mag. (1982–1984)
1st Contact	RJD = 55,062	± 21 days	RJD = 55,065
2nd Contact	RJD = 55,193	± 21 days	RJD = 55,237
Ingress	131 days	± 26.5 days	120 days (1982–1984)
Mid-Eclipse	RJD = 55,377	± 14 days	
Totality			
Average Mag.	4.525 Mag.		4.57 Mag. (1982–1984)
Average Depth	0.800 Mag.		
Duration	438 days	± 10 days	455 days (1982–1984)
3rd Contact	RJD = 55,631	± 09 days	

Table continued on following pages

Table 2. 2009 ε Aur campaign data summary, cont.

Parameter	*Observed* *RJD = JD–2400000*	*Error*	*Predicted*[1] *RJD = JD–2400000*
4th Contact	RJD = 55,693	± 09 days	
Egress	62 days	± 37.5 days	55 days (1982–1984)
Eclipse			
Duration	631 days	± 14 days	630 days (1982–1984)
Average Depth	0.800 Mag.	0.84 Mag.	
Period	9,882 days	± 21 days	9,885 days
B band			
OOE Mag.	3.605 Mag.		3.61 Mag. (1982–1984)
	Δ0.150 Mag.		
1st Contact	RJD = 55,089	± 12 days	RJD = 55,054
2nd Contact	RJD = 55,202	± 12 days	RJD = 55,214
Ingress	113 days	± 12 days	135 days (1982–1984)
Mid-Eclipse	RJD = 55,391	± 19.5 days	
Totality			
Average Mag.	4.325		4.32 Mag. (1982–1984)
Average Depth	0.720 Mag.		
Duration	432 days	± 09.5 days	437 days (1982–1984)
3rd Contact	RJD = 55,634	± 07 days	
4th Contact	RJD = 55,693	± 07 days	
Egress	59 days	± 07 days	71 days (1982–1984)
Eclipse			
Duration	604 days	± 19.5 days	643 days (1982–1984)
Average Depth	0.720 Mag.	0.71 Mag.	
Period	9,919 days	± 12 days	9,884 days
V band[2]			
OOE Mag.	3.035 Mag.		3.03 Mag. (1982–1984)
	Δ0.130 Mag.		
1st Contact	RJD = 55,066	± 12 days	RJD = 55,056
2nd Contact	RJD = 55,199	± 12 days	RJD = 55,213
Ingress	133 days	± 12 days	142 days (1982–1984)
Mid-Eclipse	RJD = 55,384.5	± 09.5 days	
Totality			
Average Mag.	3.710 Mag.		3.73 Mag. (1982–1984)
Average Depth	0.675 Mag.		0.70 Mag. (1982–1984)
Duration	430 days	± 09.5 days	447 days (1982–1984)
3rd Contact	RJD = 55,629	± 07 days	
4th Contact	RJD = 55,703	± 07 days	
Egress	74 days	± 07 days	65 days (1982–1984)
Eclipse			
Duration	637 days	± 09.5 days	654 days (1982–1984)

Table continued on following pages

Table 2. 2009 ε Aur campaign data summary, cont.

Parameter	*Observed RJD = JD–2400000*	*Error*	*Predicted*[1] *RJD = JD–2400000*
Average Depth	0.675 Mag.	0.70 Mag.	
Period	9,898 days	± 12 days	9,908 days
Rc band			
OOE Mag.	2.745 Mag.		
	Δ0.630 Mag.		
1st Contact	RJD = 55,073	± 67 days	
2nd Contact	RJD = 55,217	± 67 days	
Ingress	144 days	± 67 days	
Mid-Eclipse	RJD = 55,333	± 45.5 days	
Totality			
Average Mag.	3.415 Mag.		
Average Depth	0.670 Mag.		
Duration	406 days	± 17.5 days	
3rd Contact	RJD = 55,623	± 34 days	
4th Contact	RJD = 55,695	± 34 days	
Egress	72 days	± 34 days	
Eclipse			
Duration	622 days	± 45.5 days	
Average Depth	0.670 Mag.		
Period	—		
Ic band			
OOE Mag.	2.255 Mag.		
	Δ0.410 Mag.		
1st Contact	RJD = 55,054	± 42 days	
2nd Contact	RJD = 55,202	± 42 days	
Ingress	148 days	± 42 days	
Mid-Eclipse	RJD = 55,414	± 32.5 days	
Totality			
Average Mag.	2.985 Mag.		
Average Depth	0.720 Mag.		
Duration	424 days	± 32.5 days	
3rd Contact	RJD = 55,626	± 23 days	
4th Contact	RJD = 55,707	± 23 days	
Egress	81 days	± 23 days	
Eclipse			
Duration	625.3 days	± 37.5 days	
Average Depth	0.730 Mag.		
Period	—		

Table continued on next page

Table 2. 2009 ε Aur campaign data summary, cont.

Parameter	*Observed RJD = JD–2400000*	*Error*	*Predicted*[1] *RJD = JD–2400000*
J band			
OOE Mag.	1.840 Mag.		
	Δ0.160 Mag.		
1st Contact	RJD = 55,060	± 30 days	
2nd Contact	RJD = 55,210	± 30 days	
Ingress	150 days	± 30 days	
Mid-Eclipse	RJD = 55,391	± 18 days	
Totality			
Average Mag.	2.480 Mag.		
Average Depth	0.640 Mag.		
Duration	404 days	± 18 days	
3rd Contact	RJD = 55,614	± 14 days	
4th Contact	RJD = 55,722	± 14 days	
Egress	108 days	± 14 days	
Eclipse			
Duration	662 days	± 18 days	
Average Depth	0.640 Mag.		
Period	—		
H band			
OOE Mag.	1.605 Mag.		
	Δ0.645 Mag.		
1st Contact	RJD = 55,057	± 15 days	
2nd Contact	RJD = 55,202	± 15 days	
Ingress	145 days	± 15 days	
Mid-Eclipse	RJD = 55,395	± 15.5 days	
Totality			
Average Mag.	2.050 Mag.		
Average Depth	0.645 Mag.		
Duration	388 days	± 15.5 days	
3rd Contact	RJD = 55,590	± 14 days	
4th Contact	RJD = 55,733	± 14 days	
Egress	143 days	± 14 days	
Eclipse			
Duration	676 days	± 09.5 days	
Average Depth	0.645 Mag.		
Period	—		

[1] The predicted times were calculated by adding the previous eclipse times to the previous determined periods. [2] There were no predictions for the longer wavelengths in the V band.

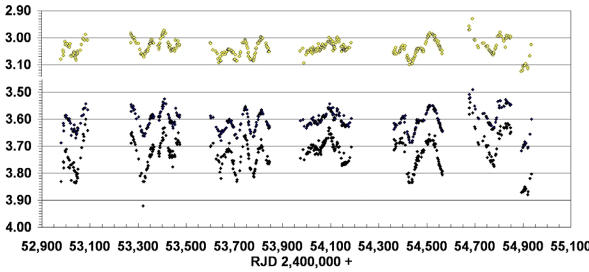

Figure 1. ε Aur out-of-eclipse light curves: top, V magnitude; middle, B magnitude; bottom, U magnitude.

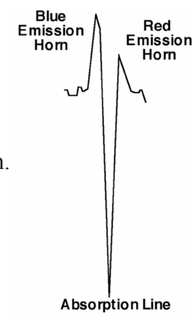

Figure 2. ε Aur Hα spectrum.

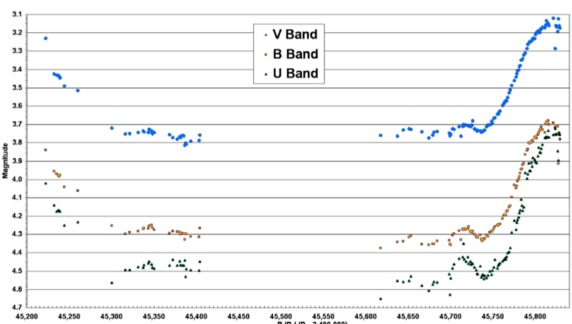

Figure 3. ε Aur light curve, September 1982–May 1984: top, V band; middle, B band; bottom, U band. Hopkins Phoenix Observatory data.

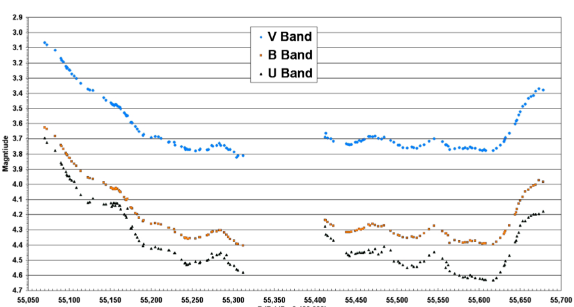

Figure 4. ε Aur light curve, August 2009–April 2009: top, V band; middle, B band; bottom, U band. Hopkins Phoenix Observatory data.

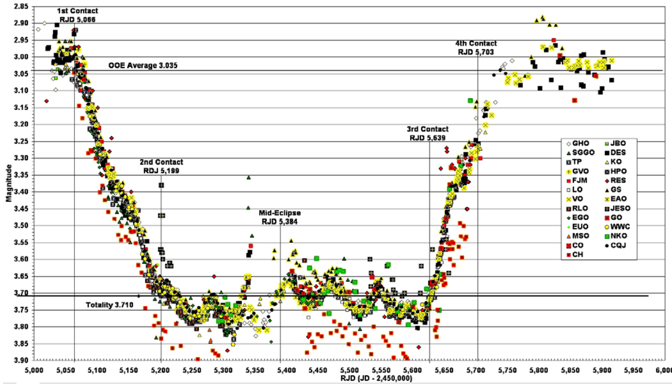

Figure 5. ε Aur campaign V data. See Table 1 for key to observer identification.

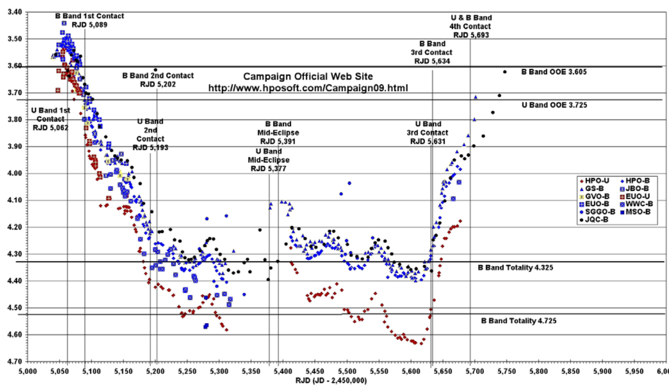

Figure 6. ε Aur campaign U and B data. See Table 1 for key to observer identification.

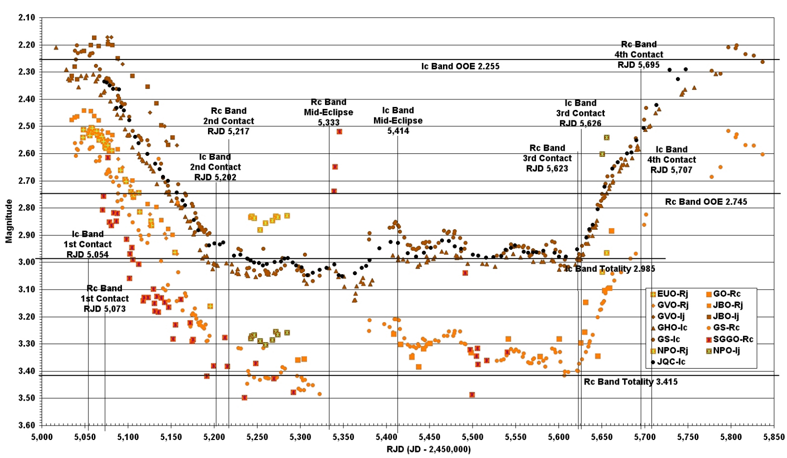

Figure 7. ε Aur campaign R and I data. See Table 1 for key to observer identification.

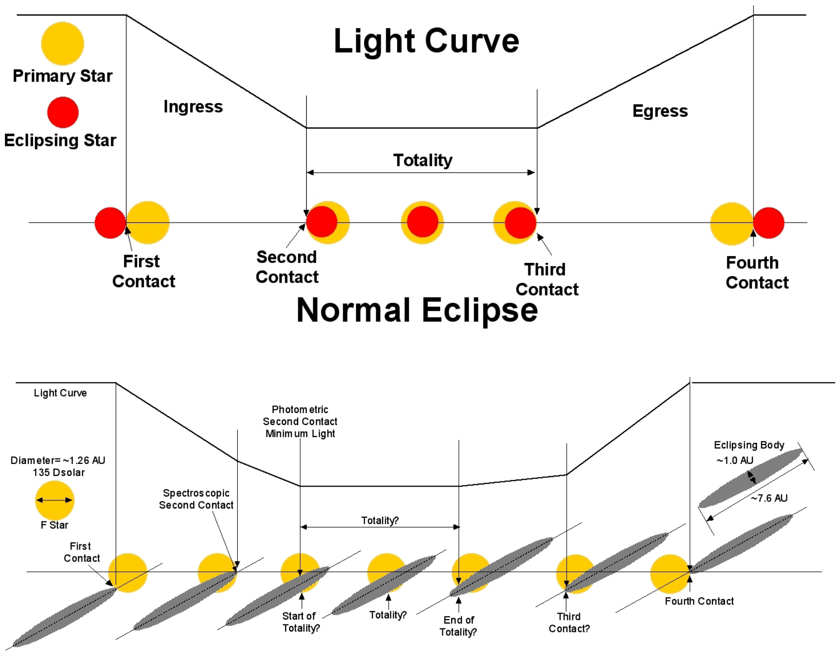

Figure 8. Classical contact points (top) and ε Aur new contact points (bottom).

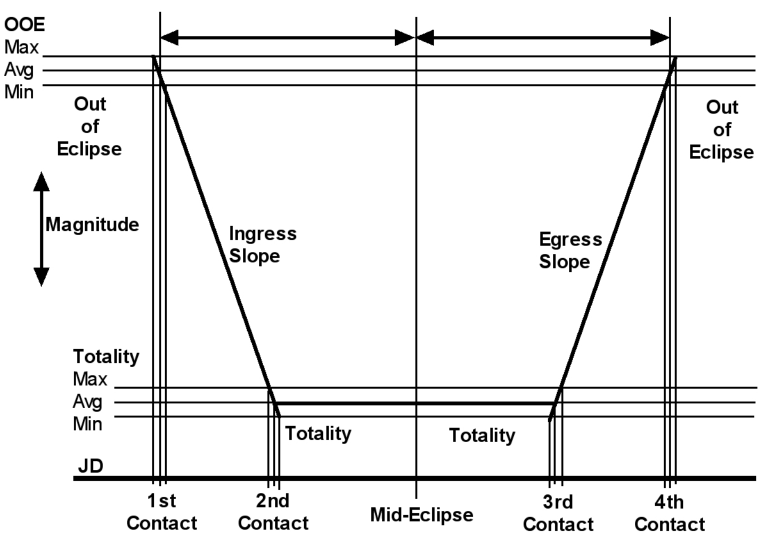

Figure 9. Contact point determination methodology.