# UBV PHOTOMETRY OF THE 1982-4 ECLIPSE OF EPSILON AURIGAE - A DISCUSSION OF THE OBSERVED LIGHT CURVES

Paul C. Schmidtke
Arizona State University
Tempe, Arizona 85287

## Introduction

At least 29 observers in nine countries have contributed photometric measurements of Epsilon Aurigae during the recent observational campaign. The present discussion is limited to data submitted (and published in various issues of this newsletter) by J. L. Hopkins of the Hopkins Phoenix Observatory (HPO) and S I. Ingvarsson of the Tjornisland Astronomical Observatory (TAO). Both sources are on the UBV system, with no significant systematic differences. Combined, these two sources cover the entire eclipse, from pre-ingress up to the present (April 1985). It should be noted that this eclipse is the first to have complete photometric coverage in all three broad-band filters U, B, and V.

## Observations

Light curves of the HPO and TAO data are shown in Figures 1 through 5. Errorbars for the U, B, and V curves represent the sample standard deviations for multiple observations on individual nights. Errorbars for (B-V) and (U-B), however, are overestimated because they are calculated using the error estimates for the individual bandpasses U, B, and V. For comparison, photoelectric light curves in visual light (transformed to the V filter) from the 1928-30 and 1955-7 eclipses are reproduced (from Gyldenkerne 1970) in Figure 6.

## Light Variations of the Visible Star

Superposed on primary minimum are other light variations usually attributed to Cepheid-like pulsations of the visible star, classified F0Ia. Outside of eclipse, the amplitudes of these variations increase with decreasing wavelength so that the star is bluest at maximum brightness (e.g., as seen during the 1984-5 observing season following fourth contact). Unfortunately, extensive UBV observations have not been published for the observing season preceding first contact. To some extent, the pulsations are present during totality as well as the partial phases. The last statement is qualified because the (B-V) and (U-B) light curves are not well correlated with the V curve during the interval JD 2445250 to JD 2445450. Indeed, an anti-correlation may exist as evidenced by a rise in the (B-V) and (U-B) curves corresponding to a dip in the visual curve just prior to the mid-eclipse brightening. During the latter portion of totality, however, the correlation returns (e.g., the small bump in the V curve around JD 2445725 is accompanied by similar peaks in the (B-V) and (U-B) curves).

Backman and Bell (1982), in a previous newsletter, have commented that the amplitude of the irregular variations is about 0.1 magnitudes outside of eclipse and increases to 0.2-0.3 magnitudes during eclipse. As illustrated in Figure 6, this description is applicable only to the 1955-7 eclipse. Indeed, the reverse behavior (i.e., large variations outside of eclipse and small variations within) is present in the 1928-30 light curve. Except for a large mid-eclipse brightening, the recent eclipse is more reminiscent, in terms of pulsational activity, of the 1928-30 eclipse than the one during 1955-7.

## Mean Light Levels

Adopting simple averages of the data recorded between JD 2445990 and JD 2446167, the mean light levels outside of eclipse are U=3.708, B=3.600, and V=3.048. The levels during totality, calculated as simple averages of the data from JD 2445303 through JD 2445399 and from JD 2445600 through JD 2445725 to avoid the mid-eclipse brightening, are U=4.510, B=4.305, and V=3.734. The depths of eclipse, are then 0.802, 0.705, and 0.686 magnitudes in U, B, and V, respectively. The traditional description of a gray eclipse, therefore, is only applicable to the B and V bandpasses; it is much deeper in the U filter. From ultraviolet data obtained with the IUE, the depth of eclipse is known to increase for decreasing wavelength, down to about 1600A (Ake 1985). Below 1600A the eclipse becomes shallower so that its depth is only 0.2 magnitudes at 1200A.

## Times of Contact

The times of contact are difficult to assess because of the irregular light variations of the visible star. Not only are these times dependent on the mean light levels inside and outside of eclipse but also on the pulsational activity during partial phases. For example, the determination of first and second contacts is complicated by the shoulder observed in the U, B, and V light curves during the latter portion of ingress, which cannot be accounted for in a simple manner. Observers of the 1955-7 eclipse suggested that variations in (B-V) may be used to rectify the V bandpass light curve. This would be a good technique for the 1982-4 eclipse except that no prominent variation is seen in the (B-V) light curve at the time of the shoulder in the U, B, and V light curves (i.e, the shoulder is grey). Therefore, using the observed data and neglecting rectification, the times of first and second contact are calculated by extrapolating a linear fit of V bandpass data from JD 2445217 through JD 2445282 to the adopted mean light levels inside and outside of eclipse. The resultant times are JD 2445165 and JD 2445302 for first and second contact, respectively.

Although the U, B, and V light curves appear very smooth during egress, the times of third and fourth contact may also be difficult to estimate. This statement is justified by variations seen in the (B-V) and (U-B) curves just prior and also during egress, implying that pulsation-induced light variations may also be present in the U, B, and V curves. Without additional means of separating these effects, however, only a simple fit of the observed data is justified. Extrapolating a linear fit of V bandpass data from JD 2445760 through JD 2445800 to the adopted mean light levels inside and outside of eclipse, the third and fourth contact times are estimated to be JD 2445748 and JD 2445812, respectively. If a pulsation is superposed on the normal brightening during engress, the visual light curve could exhibit an abnormally rapid increase in brightness. Indeed, these calculations yield an extraordinarily short egress time of 64 days. The times of contact are summarized in Table 1, which includes the predicted times based on Gyldenkerne's evaluation of the 1955-7 eclipse.

Table 1

Times of Contact for the 1982-4 Epsilon Aurigae Eclipse

| Contact | Predicted Time Date | JD | Observed Time Date | JD |
|---|---|---|---|---|
| 1st | 82 Jul 29 | 2445180 | 82 Jul 14 | 2445165 |
| 2nd | 82 Dec 11 | 2445315 | 82 Nov 28 | 2445302 |
| 3rd | 84 Jan 09 | 2445709 | 84 Feb 17 | 2445748 |
| 4th | 84 May 29 | 2445850 | 84 Apr 21 | 2445812 |

## Comparison with the 1955-7 Eclipse

Gyldenkerne assigned mean light levels of V=3.002 (outside of eclipse) and V=3.750 (inside) for the 1955-7 eclipse (see Figure 6). All of Gyldenkerne's values, however, must be adjusted by 0.01 magnitudes because he adopted V=4.72 for the comparison star Lambda Aurgiae in contrast to V=4.71 assumed during the recent campaign. As a result, the mean light levels of the 1955-7 eclipse are estimated to be V=2.992 and V=3.740. The change in outside of eclipse magnitude from V=2.992 (1955-7 eclipse) to V=3.048 (1982-4) indicates that long-term variations in the visible star's light may be present. In addition, the depth of eclipse has apparently become smaller, 0.71 versus 0.75 magnitudes. These changes may be insignificant except that Gyldenkerne reported that eclipses prior to 1955-7 had a mean depth of 0.80 magnitudes. Instrumental effects, however, have not been totally ruled out. Both the outside of eclipse level and the depth of eclipse could be underestimated if the deadtime correction applied during recent data reduction is too small.

It should be noted that the determination of the mean inside eclipse light level for the 1955-7 eclipse was complicated by larger pulsations during totality than observed in the 1982-4 eclipse. Gyldenkerne discussed values as faint as V=3.795 for the 1955-7 eclipse, but used V=3.750 for the calculation of times of contact, etc.

The durations of different phases for the 1982-4 as well as past eclipses of Epsilon Aurigae are given in Table 2. Values for the 1955-7 and previous eclipses have been taken from Gyldenkerne. The duration of totality for the recent eclipse is significantly longer than predicted. Indeed, third contact occurred much later than expected, as noted by many observers.

Table 2

Durations of Phases for Epsilon Aurigae Eclipses

| Phase | 1982-4 Eclipse | 1955-7 Eclipse | Prior to 1955-7 Eclipse |
|---|---|---|---|
| Ingress (days) | 137 | 135 | 182 |
| Totality (days) | 446 | 394 | 330 |
| Egress (days) | 64 | 141 | 203 |

Additional Comments on the (B-V) and (U-B) Light Curves

As previously noted, the behavior of (B-V) prior to the mid-eclipse brightening is different than that of the latter half of totality. During the first half, virtually no pulsation-related variations are seen in the (B-V) light curve. For that matter, the eclipse is hardly noticable! The mean value of (B-V) during the interval from JD 2445300 through JD 2445400 is 0.538, compared to 0.548 for outside of eclipse measurements during the 1984-5 observing season. Lack of pre-ingress data complicates the evaluation. After the mid-eclipse brightening, there is a gradual increase in (B-V) (i.e., a reddening of the system), superposed with pulsation-induced variations, up to the time of egress. This phenomenon is probably not unique to the recent eclipse. Gyldenkerne noted systematic changes in (B-V) during totality of the 1955-7 eclipse.

The behavior of the (U-B) light curve is similar to that of (B-V) in that a transition to a redder system occurs at the time of mid-eclipse brightening. There are two notable differences, however. First, the (U-B) data exhibits a definite change during ingress. The mean (U-B) level is about 0.087 magnitudes larger after second contact than observed out of eclipse. The second exception is the unusual variation of (U-B) just prior to fourth contact. Whereas the (B-V) curve shows a Cepheid-like rise followed by a decline, the (U-B) curve monotonically increases, indicating a large ultraviolet excess at fourth contact.

The overall activity of the system, therefore, is characterized by relative quiescence during the first half of totality followed by increasing activity up to fourth contact. The same behavior has been noted in recent spectroscopic studies. Ferluga and Hack (1985) report that the red-shifted 'shell' absorption lines seen at first contact (i.e., evidently, originating from the outer portions of the rotating gaseous disk of the secondary) are significantly less intense than the violet-shifted lines present at fourth contact.

## Comments on the Mid-Eclipse Brightening - A Gravitational Lens?

The mid-eclipse brightening is seen in all three bandpasses. As previously noted, however, the brightening is not present in the (B-V) and (U-B) light curves. The grey nature of this phenomenon argues against a pulsation-induced light variation as the cause. Another suggestion that may account for the brightening phenomenon is gravitational lensing. This explanation is decsribed in the calculations that follow. For a more complete treatment of stellar gravitational lenses, see Liebes (1964).

Let $\ell_D$ be the distance from the observer to the deflector star responsible for the lensing, and let $\ell_{OD}$ be the distance from the deflector star to the object star whose light is being deflected. The mass of the deflector is taken to be $\mathcal{M}$. Then from general relativity, it follows that the maximum deflection is

$$\Theta = (4G\mathcal{M}/\mu\ell_D c^2)^{1/2}, \qquad (2)$$

where $\mu = 1+(\ell_D/\ell_{OD})$, $G$ is the gravitational constant, and $c$ is the speed of light. If the entire disk of the deflecting body falls within the deflection cone, a gravitional lens occurs. Not only is light from the object deflected towards the observer, but also the intensity of the light is amplified. That is, a brightening occurs.

Parameter $\mu$ is important to the possibility of seeing a lens effect in a binary system. For close binaries with small separations, $\mu$ becomes so large that $\Theta$ is very small. Perhaps in wide binaries, such as Epsilon Aurigae, the value of $\mu$ is small enough to permit a lens to occur. Inserting the constants $c$ and $G$ and transforming the units of measurement, equation 1 becomes

$$\Theta = 0.198\ (\mathcal{M}\ell_{OD}/\ell_D^2)^{1/2}, \qquad (2)$$

where $\Theta$ is measured in milliseconds of arc (mas), $\mathcal{M}$ is in solar masses, $\ell_D$ is in parsecs, and $\ell_{OD}$ in astronomical units. For Epsilon Aurigae the following values are assumed: $\mathcal{M} = 3.5\mathcal{M}_\odot$, $\ell_D$=600pc, and $\ell_{OD}$=25AU, where the deflector is assumed to be two close F0V stars. (Note: the total mass of the secondary may be four to five times larger than the value assigned here, but the additional mass is in the extended disk component of the eclipsing body.) Under these assumptions, the maximum deflection angle is $\Theta$=0.00309mas. However, for amplification to occur, the entire apparent disk of the deflector must fall within this deflection angle. The apparent angular radius of a single F0V star at 578pc is 0.0122mas, or about four times larger than the allowed limit for a gravitational lens to form. Although a stellar lens may not be a viable explanation, two variations of this phenomenon may account for the observed brightening. First, the object responsible for the lensing may not be composed of 'normal' stars, but instead it may consist of a collapsed object (e.g., a black hole has hypothesized by some observers). Second, the extended mass distribution of the eclipsing disk itself may cause the lensing. This situtation would be similar to the lensing seen in the imaging of double quasars by intervening galaxies. For

Epsilon Aurigae, calculations using an extended mass distribution have yet to be attempted.

## References

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Liebes, S. 1964, Physical Review 133, B835.

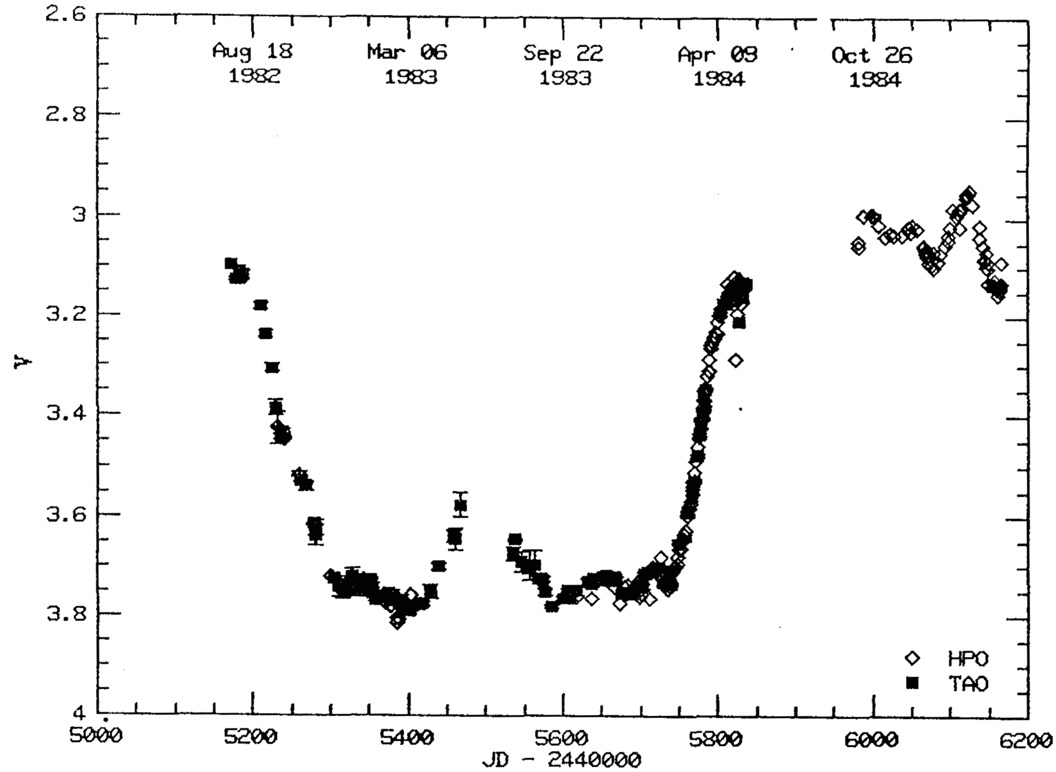


Fig. 1. V light curve of the 1982-4 eclipse of Epsilon Aurigae.

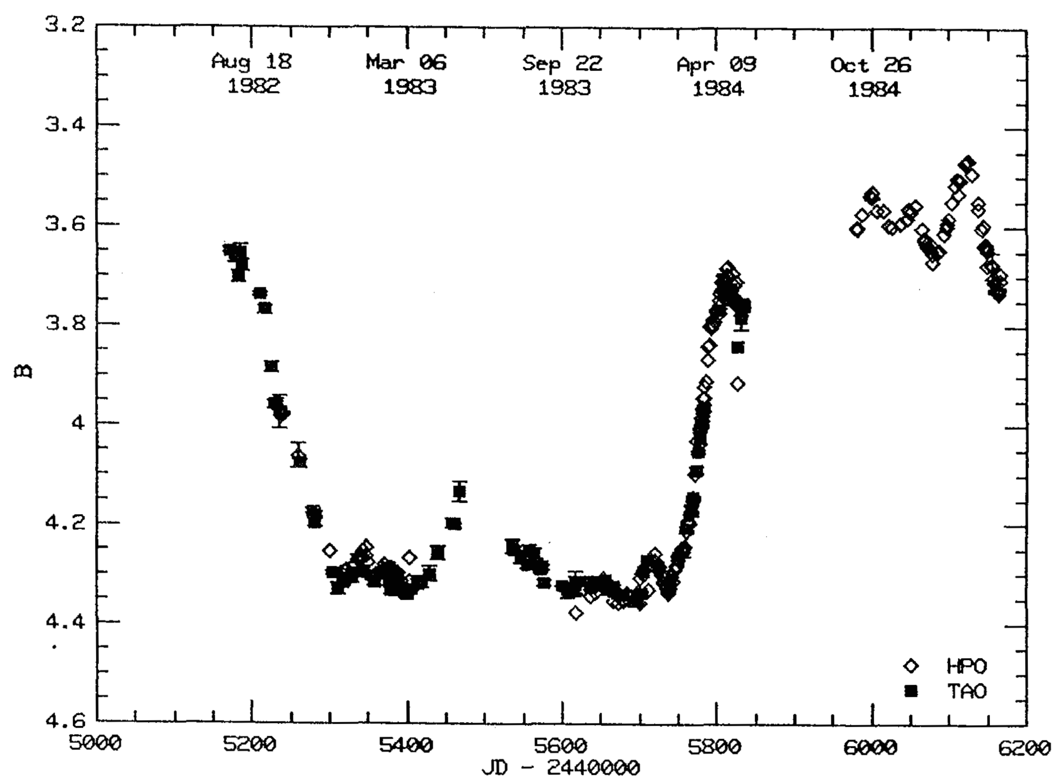


Fig. 2. B light curve of the 1982-4 eclipse of Epsilon Aurigae.

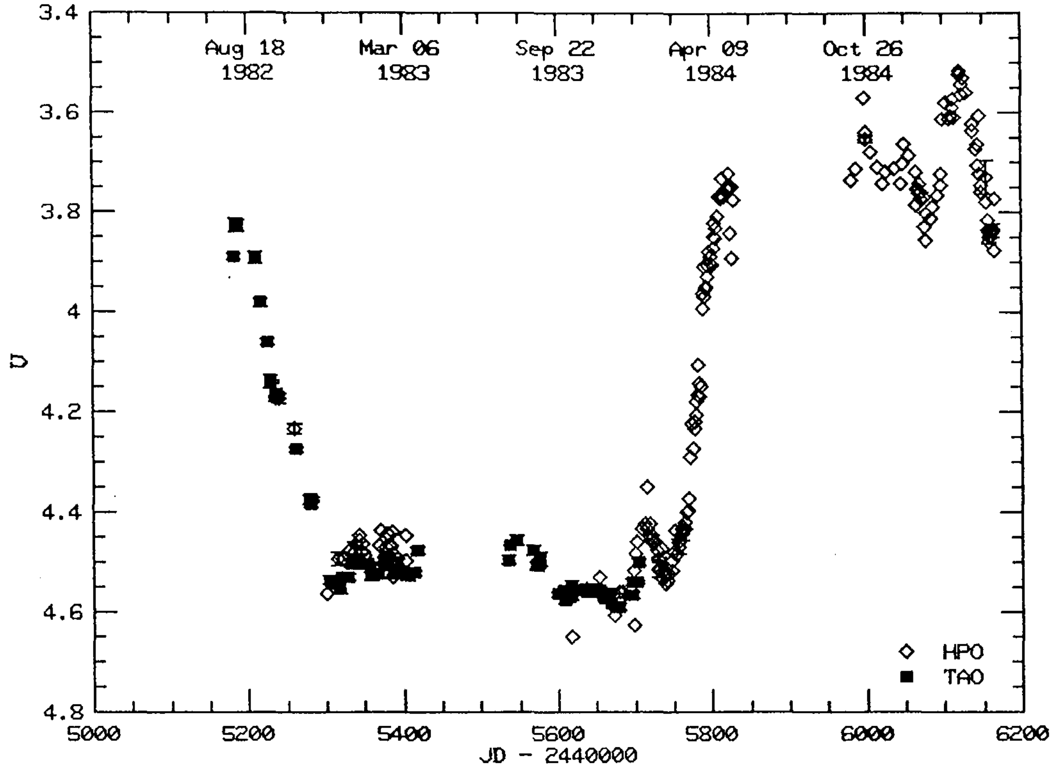


Fig. 3. U light curve of the 1982-4 eclipse of Epsilon Aurigae.

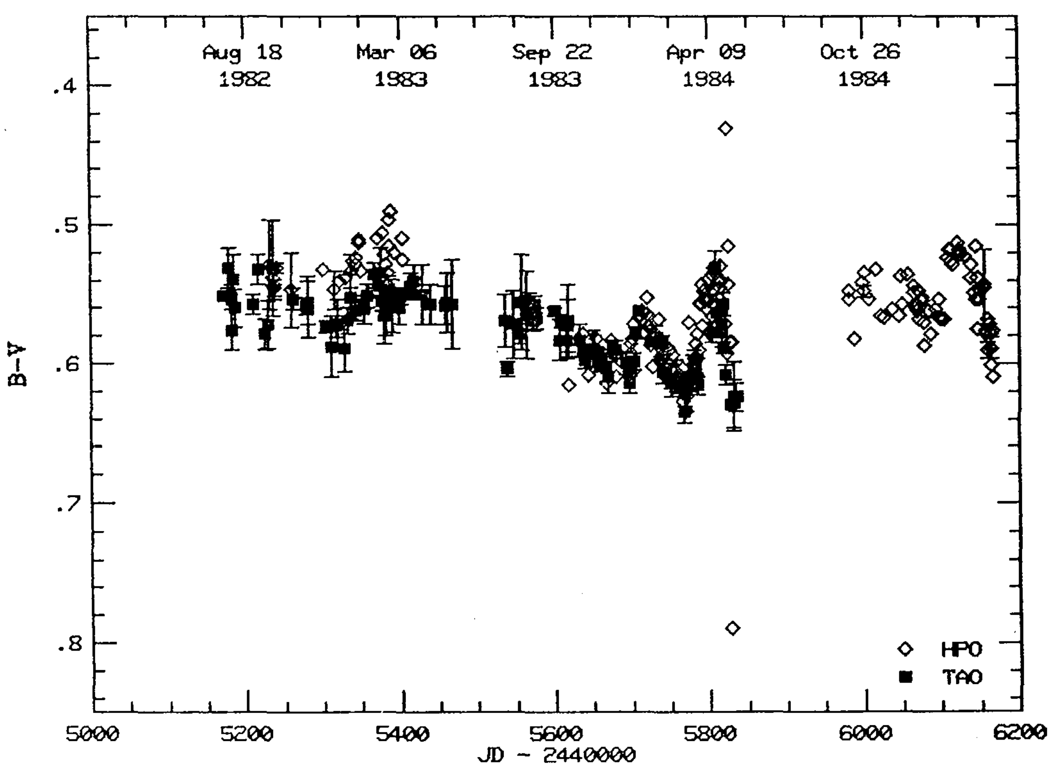


Fig. 4. (B-V) light curve of the 1982-4 eclipse of Epsilon Aurigae.

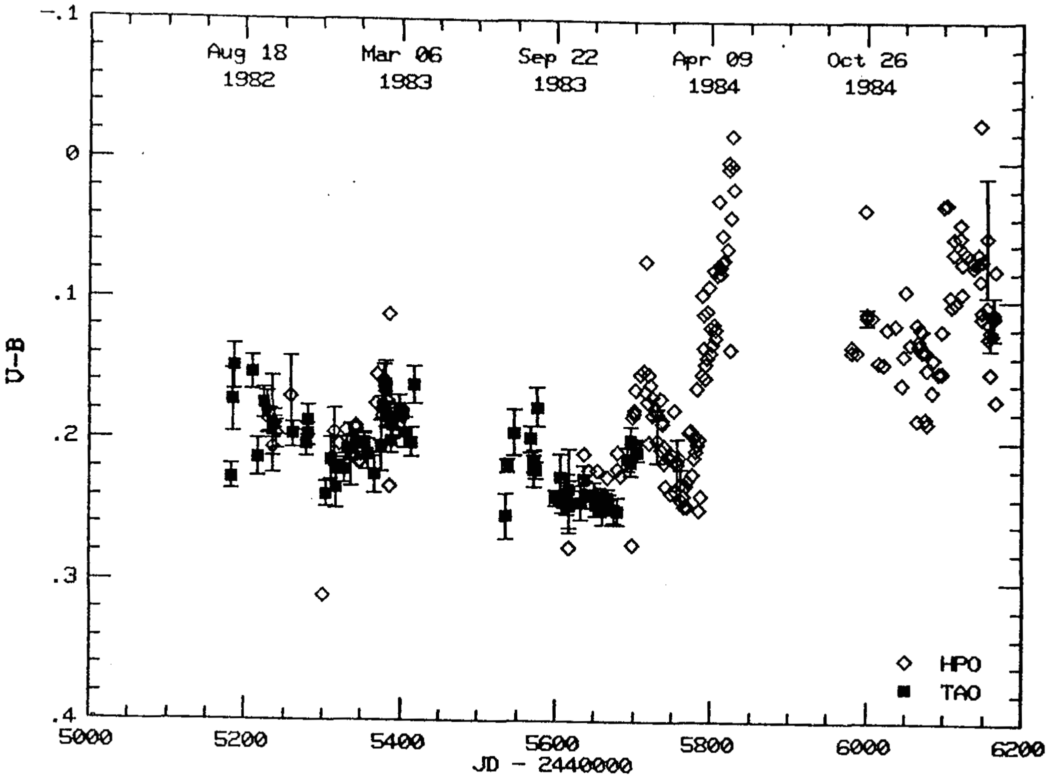


Fig. 5. (U-B) light curve of the 1982-4 eclipse of Epsilon Aurigae.

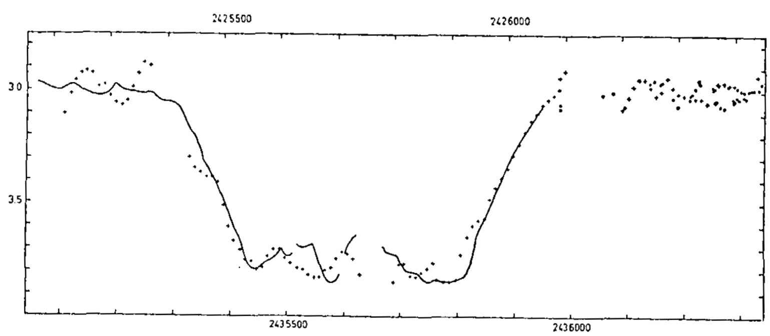


Fig. 6. The 1928-30 light-curve (plus signs, upper abscissa scale) superposed upon the 1955-57 light-curve (smooth curve, dots in post-eclipse phases; lower abscissa scale). The ordinate scale represents V for the 1955-57 eclipse. From Gyldenkerne (1970).