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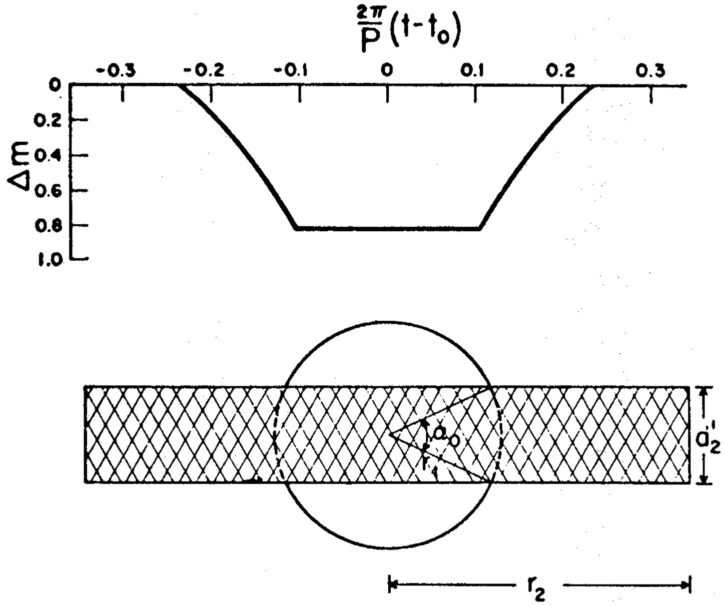
NASA Conference Publication 2384

1982–1984 Eclipse of Epsilon Aurigae



A schematic diagram of our model for ϵ Aurigae and its resulting light-curve during eclipse. It is assumed that we observe this system edge-on. Consequently, the rotating gaseous disk around the secondary component will appear to be a dark rectangle which obscures the primary component during eclipse. The light-curve at the top of the figure is derived by assuming a uniform stellar disk.

Huang 1965 Ap.J. 141

Summary of a working meeting
held in Tucson, Arizona
January 16–17, 1985

NASA

NASA Conference Publication 2384

1982–1984 Eclipse of Epsilon Aurigae

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PREFACE

The bright star epsilon Aurigae underwent a total eclipse that lasted from July 1982 through May 1984. Its last reported eclipse occurred in 1956 and its next eclipse is not until AD 2009. This 27.1 year periodicity has made study of the object difficult. The eclipsing body itself has defied the understanding of generations of astronomers.

Multispectral observations acquired during the recent eclipse of epsilon Aurigae produced an abundance of data. Even this amount of data does not make interpretation of the system any easier. Each data set tells only part of the story; assembling much of it here will give astronomers a comprehensive picture never before possible.

It appears that the extreme ideas that the system contains either a protoplanetary system or a black hole are now ruled out. It is now posited that the system consists of a highly evolved supergiant star and an unusual "companion" -- possibly another pair of stars inside a remnant accretion disk. However, several conundrums are emerging from the study of the recent eclipse.

If epsilon Aurigae is a triple star system, why do we not see more like it, given the moderately frequent occurrence of triple stars? While the binary star inside a disk is an attractive way to get a large mass with low light output (as demanded by the IUE data), why is the exterior of the disk so cold (500 degrees Kelvin per the IRAS data)? Polar jets have been invoked to explain this reduced equatorial heating, and this seems to agree with the mid-eclipse behavior of H-alpha.

The polarization data place severe constraints on the overall geometry of the system. The light variations may be interpreted as a slightly tilted disk occulting the supergiant star (which has a comparably tilted ring of hot gas of its own). The non-flat ultraviolet light curves appear to be consistent with this picture. However, if the disk tilt is sufficient to produce the UV and polarization changes, some suggest we should see directly into the binary star at the center of the disk -- but we do not. And if the disk is vertically thick enough to hide the stars, then the optical eclipse should be deeper and the spectral changes larger.

By providing as complete a data set as possible, some of these problems may now be addressed. Epsilon Aurigae presents a challenge requiring consideration of many types of physical processes. The latest interpretation of the star seems to have a chameleon-like capacity to reflect the "newest" astrophysical concepts (e.g., bipolar jets), and its story continues to reflect the history of the science. Careful study of the new data will lead to improved understanding of this mystery star.

Robert E. Stencel, Editor
15 March 1985, Washington, D.C.

WORKSHOP SUMMARY: Epsilon Aurigae Eclipse Workshop/
16-17 January, 1985

Approximately 50 scientists convened in conjunction with the 165th meeting of the American Astronomical Society to discuss data obtained during the 1982-84 eclipse of the 27.1 year period eclipsing binary epsilon Aurigae. Although the final conclusions about this mysterious object are still to be written, what follows is an approximate consensus developed in the course of the debate:

F Supergiant Star (F0Iap, 100 Ro, 13 Mo, T(eff) 7650K)

Non-radial pulsations, 90 ± 20 days, based on optical, UV and polarization data, axis not aligned with orbit plane; UV continuum variations are Cepheid like (hot secondary?).

On basis of H-alpha profiles during eclipse, possible retrograde rotation of primary, rather than classical direct-rotating H shell around secondary (Ferluga).

Two micron CO bands have C12/C13 ratio = 8, suggesting evolved star.

Some type of extended atmosphere/shell/chromospheric ring/wind with plane tipped 15-25 deg E of orbit plane normal, based on polarization as per Be stars and out-of-eclipse H-alpha variations (Kemp).

System (Wright 1970; Webbink)
27.1 year period (9885 days)

Eccentricity: 0.2 ± 0.03

Separation: 26 A.U. (a(1)sini = 13.37 ± 0.53 A.U.) r(1) = 0.052 a; r(2) = 0.178 a (Huang 1974)

Mass function: 3.25 ± 0.38 Mo

Distance: 600 to 2000 pc (Backman) -- dep. on F* mass, etc.
(B-V) based on 2200A extinction: 0.35 mag (Ake)
System inclination 87 degrees (Kemp); 89 ± 3 degrees (lit.)

Evolutionary status: shell He burning F supergiant or contracting toward white dwarf state (rapid); secondary, a binary supporting a fossil accretion disk is "not implausible" (Webbink).

Possible secular variations in light curve? (Schmidtke).

Epsilon Aurigae Summary: January 1985

Secondary

Photometric and polarization data imply disk as per Huang 1974 aspect ratio 8:1 (2:1 in IR?), tipped 5 deg E of orbit normal; 5 AU dimensions; rotation period (30 km/sec shell lines) = 3 years.
T(outer) = 520K (IR 10 and 20 micron ptm and IRAS 25 and 60 micron).
2-micron CO band imply T(exc) = 1000K (asymmetric toward egress, may imply heated face of disk moving into view).
3-4 micron spectrophotometry implies T(eff) = 700K (Ferluga 1985).
Shell lines imply gaseous envelope , T(shell) = 7000K (").
UV activity appears to increase T(shell); off plane temperature stratification in disk/ring is suggested (Ferluga).
Mid-eclipse brightening observed in 1956, 1983 eclipses imply thinness of disk/ring (non-90 degree inclination).
Enhanced H-alpha absorption at mid-eclipse may imply polar flows.
Ad hoc binary B-star core stabilizes disk with low total luminosity and large mass; supplies too much internal energy to fit T(outer) unless majority escapes in polar flows.
Optical and IR L(bol) approx. 100 L(sun).

Predictions/Necessary Observations:

1. IR effective temperature should rise as secondary minimum nears.
2. F star should show velocity variations per Cepheids.
3. If post mass transfer, H depleted, N enhanced: need better abundance determination, gravity, rotation velocities.
4. Need consistent distance among photometric, astrometric, spectroscopic and orbital solutions.
5. H alpha speckle imaging at next quadrature (1989-90?).
6. Continued photometric and polarimetric monitoring.
7. Velocity curve for secondary through orbit.
8. Eclipse of 2010 A.D. may show even stronger mid-eclipse brightening (Kemp).
9. Confirmation of secular variations (Schmidtke).

Registered Participants, Epsilon Aurigae Eclipse Workshop

16 and 17 January 1985, Tucson

Imad Ahmad	Imad-ad-Dean, Inc.
Thomas Ake	STScI/CSC
Bruce Altner	GSFC/Applied Research Corp.
Dana Backman	Univ. Hawaii
Mary Barsony	CalTech
Robert Burnham	Astronomy/AstroMedia
Andrew Cheng	Steward Obs.
D. Scott Davis	Steward Obs.
Steno Ferluga	Trieste Observatory (Italy)
Robert Fried	Braeside Obs./IAPPP
Wendy Hagen	Univ. New Mexico & Wellesley
Douglas Hall	Vanderbilt Univ.
Walter van Hamme	USC-Coastal Carolina College
Wayne Hanson	USAF/Vandenberg AFB
Cleve Hopkins	IAPPP
Jeffrey Hopkins	Hopkins-Phoenix Obs.
Dick Joyce	KPNO
James Kemp	Univ. Oregon
Wes Lockwood	Lowell Obs.
Barry Lutz	Lowell Obs.
Alan MacRobert	Sky and Telescope
ll-Seong Nha	Yonsei Univ. Obs., Seoul (Korea)
John Roemmelt	Dearborn, Mich.
Paul Schmidtke	Arizona State Univ.
Theodore Simon	Univ. of Hawaii
George Spagna	Renssalaer Polytech. Inst.
Robert Stencel	NASA HQ & JILA
Frank Verbunt	Inst. of Astronomy, Cambridge (UK)
Ronald Webbink	JILA & Univ. Illinois
Robert Wilson	Univ. Florida
F. Brad Wood	Univ. Florida

INVITED PAPERS

EPSILON AURIGAE. HISTORICAL SKETCH.

Frank Bradshaw Wood
University of Florida

If the system Epsilon Aurigae is not unique — at least in our part of our galaxy — it is certainly of an exceedingly rare type. Extreme skeptics have even been known to call it an optical illusion. Approximately every 27 years an F2 supergiant is eclipsed by something. The nature of the eclipsing object has been discussed at great length. Indeed, Struve and Zebergs (1962) have said that the history of studies of Epsilon Aurigae "is in many respects the history of astrophysics since the beginning of the 20th century". Jorge Sahade and I (1978) have given a very brief description of the general nature of the systm inasmuch as it was understood at the time. The purpose of this paper is to give the history up until the beginning of the present observing campaign in order to set the stage for the papers following which will describe in some detail the recent observations.

As far as I am aware, there is no record of its variability being recorded in antiquity. While there are records of a few individual observations in the 1700's, the first mention of its variability which I have been able to find was that by Fritsch (1824) who discussed the minimum of 1821. Since then the star has been recognized as a variable. As a matter of interest, Fritsch was an amateur.

The system was extensively observed by J. Schmidt who made nearly 5000 observations between 1843 and 1884. His observations, plus those of F. Argelander during the 1848 eclipse, gave some indication of the general nature of the light changes.

During the followng years, many observations were made, and these were finally treated by Ludendorff (1903) who found the system to have an Algol type light curve.

Later, Ludendorff (1912) gave a full discussion of observations by Schmidt. The minima of 1847-8 and 1874-5 were clearly shown. However, he felt the eclipse theory was questionable because of disagreement between photometric and spectroscopic data. He was disturbed by the fact that the spectroscopic data gave but one spectrum which was the same as the one seen during totality. This has worried a great many others who have considered the system.

Shapley (1915) included Epsilon Aurigae in his monumental work which applied the newly developed Russell method of solution of light curves to many eclipsing systems. He used 5000 observations by Schmidt and judged the value of the solution to be second grade. He concluded that Wendell's observations showed an outside eclipse variation of 0.3 magnitudes. Much later, Shapley (1928) reviewed observations by Stebbins, McLaughlin, Ludendorff, and Gussow and then reconsidered this conclusion. While he suggested a period of 355 days for the variation, he also thought it "not impossible" that there may have been a seasonal error from the large difference in brightness and some difference in color of Wendell's comparison star (BD $+44^{\circ}1077$, A(2), mg. 7.21).

About this time Miss Payne (1928) analyzed the spectrum using low dispersion and found it "a typical if extreme supergiant".

Also in 1928, Stebbins and Huffer began taking photoelectric observations every two weeks. Beginning in early January they found that until March it grew fainter by about 0.8 mag/month followed by a steady increase from March 30 to April 19.

The preceding is far from a complete listing of all the work done until that time and the reader can find much more in a long monograph published by McLoughlin (1928).

For a number of years after this date the system was followed by a number of observers and the out-of-eclipse brightness observations were well established although by no means well explained. The color changes were also beginning to puzzle some observers. Attempts to find masses sometimes gave results that seemed highly questionable and even cast doubts on the eclipse explanation. One suggestion was that this was a connecting link between Cepheids and Mira stars.

While spectroscopy was not carried out as extensively as the photometry, it was not completely neglected. Struve and Elvey (1930) reported on spectra taken in 1928-30. During the eclipse, many strong lines were strengthened and became unsymmetrical. The radial elocities showed oscillations in a period of about 110 days, but many lines gave discordant velocities. The variations in velocity in a perod of 27.1 years was confirmed. There was no trace of the spectrum of the companion.

The number of observers, both photometric and spectroscopic, at the 1928-30 eclipse was very large although no definite "campaign" was planned or undertaken. On the whole, the agreement between different observers was reasonably satisfactory, although getting the precise duration of the entire eclipse and of the total phases presented some disagreement. In particular, the secondary "wave" of about amplitude 0.15 mag. was recognized by most observers although no clear periodicity could be attached to it, and there was not complete agreement as to its amplitude.

Observations continued after the eclipse ended, and the few observers then in existence who had photoelectric photometers began to make their impact felt, especially in detection of small changes. Of the many, many papers appearing in the 1930's, several deserve special mention. Beyer (1930), Kukarkin (1930), and Jacchia (1931) gave discussions of long lists of visual observations. Huffer (1932) carefully discussed his photoelectric observations. He used three comparison stars to make as certain as possible that observed changes were indeed in the variable. He found irregular fluctuations as large as 0.2 mag and a decrease in the brightness of the system of 0.06 mag. during totality. Gussow (1933) listed photoelectric observation going back to 1926 and noted secondary variations of 0.1 - 0.2 mag. for which she could find no period. She also examined earlier visual estimates and thought they showed similar variations. Krat (1936) made a solution of Gussow's photoelectric curve and suggested pulsations of the secondary component.

Spectrographic studies were not neglected. McLaughlin (1934) tried to explain line residuals and asymmetries by shifting of a strong line across a weaker at mid-eclipse. The measurement of absorption lines suggested strong turbulence to Struve and Elvey (1934). We might finally note a paper by Kuiper, Struve, and Stromgren (1937) which attempted to interpret the photometric and spectrographic observations by non selective opacity concentrated in an outer shell of the cool star and probably due to photoelectric ionization from the F2 star.

It should perhaps be noted that most of the photometric observations were in one color only although a few attempts were made to isolate the different spectral regions, including one by Hall (1938) who measured color excess in the infrared which suggested a difference of magnitude of 2.24 between the components at 9600 A. We might also mention a very good review by Swings (1938).

The 1940's brought slightly less intensive efforts, but the system was by no means forgotten. Hall (1941, 1942) carried out spectrophotometry using a photoelectric cell. Wright and van Dien (1949) measured egress widths from λ 3700 to λ 6700. Turbulent velocities were determined. They found that the line profiles could be produced either by rotational velocity or by large scale turbulent motions. In his book, "Some Famous Stars" published in 1950, W. M. Smart devoted an entire chapter to Epsilon Aurigae.

Work continued into the 1950's, again too extensive to give in detail. Struve (1951a) gave a discussion of the spectrum and physical nature of the system as it was understood at that time. He also discussed the circumstellar lines of Ca II (Struve 1951 b). Fellgett (1951) found that his far infra-red observation were inconsistent with the absolute magnitude that had been ascribed to the infra-red companion. In general, observers were becomming aware that the next eclipse should start in 1955 and intense observation should begin earlier. An excellent popular discussion was given in Sky and Telescope (Struve 1953). Again the total number of papers is too great to be given in detail here. Some examples follow.

At the National Science Foundation conference on Stellar Atmospheres, O. Struve announced the discovery by Miss H. Pillans of sharp lines of CH^+. These could be interstellar or circumstellar. Strong, sharp lines of Ca II showed a velocity of -28 km/sec at all phases; he suggested this could be from an expanding cloud. At the IAU General Assembley in 1955, K. Glydenkerne announced that he had observed into June 1955 and had noted the beginning of the eclipse.

Wright (1955) described pre-eclipse spectrographic observations in some detail. J. Rives (1955) observed photometrically from April 1954 to April 1955 without noting any certain change. Struve (1956) gave an excellent general summary and a detailed discussion of the older hypotheses and suggested a new one; the essential feature was a cloud around the F star.

A large number of photoelectric observations were made by various observers but for some reason much of this was never published. That which was, however, is much too extensive to be discussed in detail. A few however might be worth mentioning. Struve, Pillans and Zeberg (1958) measured 62 lines on 95 spectra taken from 1928 to 1958. The mean values of different groups of lines showed large departures from the velocity curve. There were also changes in the differential velocity shifts of strong and weak lines. These were similar to those noted in the 1928-30 eclipse.

For this eclipse there had been organized a comparative campaign (at least among the photometrists). This was co-ordinated by F. B. Wood (Trans. I.A.U. X, 625, (1958). The results were discussed by various observers. As one example, see G. Larsson-Leander who published and discussed them (Larsen-Leander 1958) and determined times of contact, or K. Gyldenkerne (1970). Hack (1959) gave a lengthy discussion of the spectra. In the partial phases after the end of totality, she found a doubling of the line similar to the 1929 eclipse with the violet component appearing to originate in a very rarefied shell. This, she felt, surrounded an invisible star. A study of the shell spectrum showed dilution of radiation effects. The second part of her paper dealt with the spectrum out of eclipse and contained a list of observations and detailed discussions.

We might also mention that at about this time an astrometric orbit was presented by Strand (1959). Mach (1961) presented a hypothesis in which the companion was a P. Cygni star surrounded by a shell which was responsible for the eclipse. Huang (1965) presented a somewhat similar model and various other models were suggested along the same general lines (e.g. Wilson 1971).

The history from 1970 on is much the same. Perhaps the chief change observationally was the extension of the observations further and further into the infrared as far as 2.2 microns. Theoretically the possibility of a black hole was suggested, but no compelling evidence for its existence was found. Pfeiffer and Koch (1977) tested for linear polariztion. Genet and Stencel (1981) announced a campaign organization to include all types of observation. Pre-eclipse observations of various sorts were made. Eventually the beginning of ingress was announced and the remaining papers of this working section will now take over.

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OPTICAL PHOTOMETRY OF THE

1982-1984

ECLIPSE OF EPSILON AURIGAE

BY

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16 JANUARY 1985

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ABSTRACT

From slightly before the 1982-1984 eclipse of Epsilon Aurigae to the present observers from around the world have been making photoelectric photometry observations of this star system. Over 2000 UBV observations have been reported as well as observations in the R, I, J, H, K, L, M, N, and Q bandpasses plus the y, b, v, and u bandpasses. Twenty nine observers from 9 countries have submitted photometry data to the campaign. The data have shown many interesting features of the star system including a Cepheid-like pulsation, flare activity, mid-eclipse brightening, post egress brightening, plus other strange activity.

I. INTRODUCTION

The purpose of this paper is to report on the optical photometry obtained during the 1982-1984 eclipse of Epsilon Aurigae. Epsilon Aurigae is a third magnitude star located in the charioteer constellation Auriga and is 1900 light years away (Van de Kamp 1978). It is the northern most star, three degrees southeast of Capella, of the three stars that make up a group known as "The Kids". Epsilon Aurigae is an eclipsing star system that has baffled astronomers for over a century. The variability of the system was first noted in 1821 (Fritsch 1824) and the eclipse has been observed continuously ever since. In 1904 the 27.1 year period and two year duration were determined (Ludendroff 1904).

II. THE CAMPAIGN

F.B. Wood organized and coordinated the campaign to study Epsilon Aurigae during the 1955-1957 eclipse. He also suggested a campaign for the 1982-1984 eclipse. R. E. Stencel (NASA), D.S. Hall (DYER OBSERVATORY), and R.M. Genet (FAIRBORN OBSERVATORY) initiated procedures for organizing the present campaign. A campaign newsletter was started to provide rapid distribution of information and observed data during the eclipse. R.E. Stencel published the first two campaign newsletters. Since then the HOPKINS PHOENIX OBSERVATORY has been publishing the newsletters and coordinating the photoelectric photometry data. R.E. Stencel has been providing editorial comment and coordinating the spectroscopy data. J.C. Kemp (UNIVERSITY of OREGON) has been providing the polarimetry reports. To date there have been 12 newsletters published.
These campaign newsletters were partially supported by two small grants from the National Aeronautics and Space Administration which were administered by the American Astronomical Society.

The present campaign has over 80 members with 29 active photoelectric observers. These observers are located all over the world and have provided over 2500 UBVRI data points from before the eclipse until the present. In addition, several observers have provided J, H, K, L, M, N, and Q data plus narrow band y, b, v, and u data.

I wish to express my appreciation to Bob Stencel (NASA) and Paul Schmidtke (KPNO now at Arizona State University) for their encouragement, help, and guidance with the photometry data of Epsilon Aurigae.

III. THE 1982-1984 PHOTOELECTRIC PHOTOMETRY DATA

Most observers used the recommended comparison star lambda Aurigae, however, BD +42 1170, eta Aurigae, and HD 32655 were also used. Most of the observing was done with small telescopes (6" to 18") using photon counting techniques.

Interesting morphological features can be seen in the UBVRI light curves of Epsilon Aurigae. Figure 1 shows a summary of data on Epsilon Aurigae. Figure 2 is a sample of the UBV data base used in the campaign newsletter. Figure 3 shows a composite plot of all Visual PEP data submitted to the campaign as of the beginning of the summer of 1984. There is considerable scattering of data points. Data from the Tjorn Island Astronomical Observatory (TAO) in Sweden, the Hopkins Phoenix Observatory (HPO) in Arizona and the Grim Observatory (GO) in Utah were combined to form plots of UBV data as can be seen in Figure 4. Figures 4a, 4b, and 4c show the eclipse in ten day intervals in the V, B, and U bandpasses. These data are from the HPO and TAO observatories. All of Figure 4 data were selected because they represent a near complete coverage of the eclipse and are in close agreement. Figure 5 shows the R and I data. Campaign Newsletter number 11 contains a complete set of all photometry data through May 1984.

IV. DATA ANALYSIS

A. CEPHEID - LIKE PULSATIONS

Cepheid like pulsations, of the F super giant primary, with a period of 105 to 120 days, have been observed (Guinan 1982). This pulsation complicates the light curve analysis.

B. FLARE ACTIVITY

Variations of 0.06 magnitudes (using a 3940 Angstrom narrow band filter) with periods on the order of minutes have been reported (Xuefu 1984). Figure 6.

C. COLOR CHANGE

Figure 7a and 7b show the B-V and U-B data from just prior to third contact until past fourth contact. Large color changes can be seen around JD 2,445,625 as well as small changes throughout the eclipse.

D. POST INGRESS BRIGHTENING

About 15 days after second contact a brightening of 0.07 magnitudes in the B bandpass and 0.09 magnitudes in the U bandpass can be seen (Figure 4).

EPSILON AURIGAE ECLIPSE DATA

PRIMARY		SECONDARY
	BS 1605	
Mv 3.0 - 3.8		?
SPEC F0 - F2		I ?
DIA 250 X SUN		DIA 2800 X SUN ?
MASS 15 SUNS		MASS 10 - 20 SUNS

DISTANCE 1900 L.Y.

PERIOD 27.1 YEARS

DURATION 2 YEARS

FIGURE 1

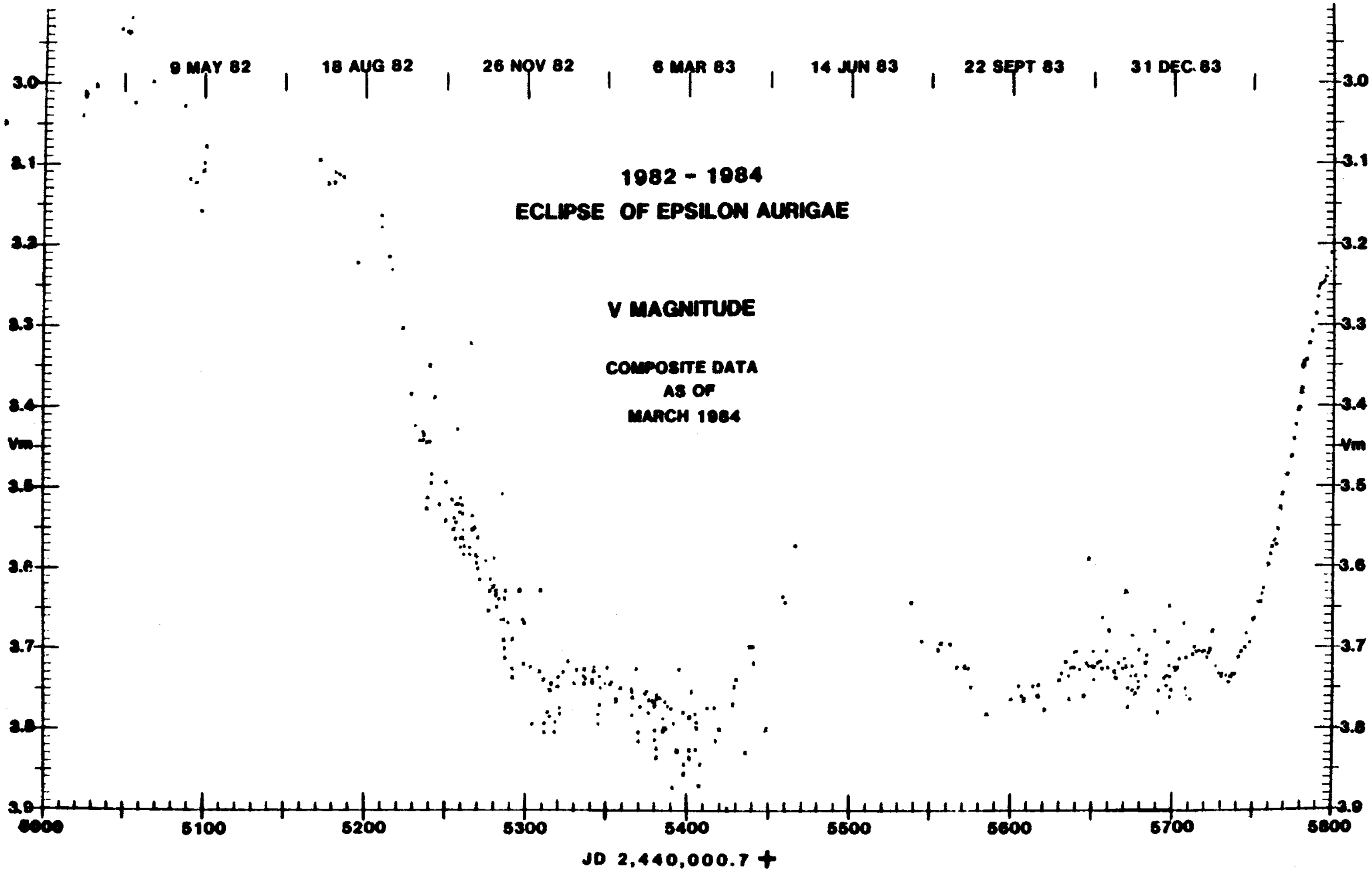
SAMPLE

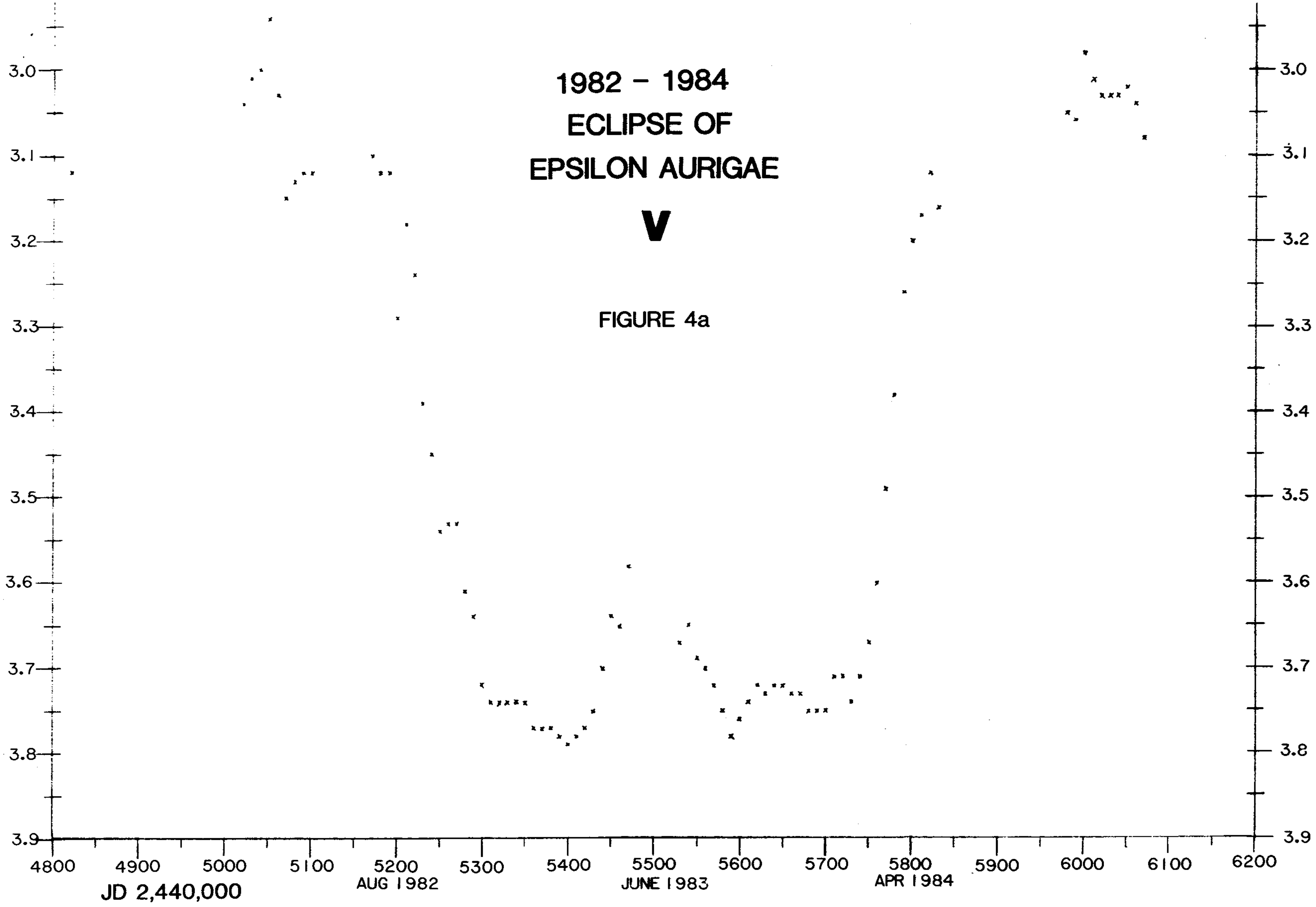
REPORT DATE 13 MAY 1984
EPSILON AURIGAE COMPOSITE
1982-1984 ECLIPSE

		2440000 +	VISUAL			BLUE			ULTRA VIOLET			NOTES/
UT	DATE	HJD	V	N	SD	B	N	SD	U	N	SD	OBSERVER
18	SEPT 80	4501.	3.09	1	----	-----	-	----	-----	-	----	RES IUE *
4	AUG 81	4821.	3.12	1	----	-----	-	----	-----	-	----	RES IUE *
29	AUG 81	4846.	3.11	1	----	-----	-	----	-----	-	----	RES IUE *
	JAN 82											
23	FEB 82	5024.66	3.040	-	.005	-----	-	----	-----	-	----	KK SJC *
3	MAR 82	5032.70	3.005	-	.009	-----	-	----	-----	-	----	KK SJC *
9	MAR 82	5048.71	2.932	1	----	-----	-	----	-----	-	----	ECO ML
22	MAR 82	5051.62	2.937	1	----	-----	-	----	-----	-	----	ECO ML
23	MAR 82	5052.62	2.938	1	----	-----	-	----	-----	-	----	ECO ML
25	MAR 82	5054.38	2.920	1	.030	-----	-	----	-----	-	----	RM MO
28	MAR 82	5057.23	3.025	2	.016	3.508	2	.008	-----	-	----	IED AUO
4	APR 82	5064.	3.07	1	----	-----	-	----	-----	-	----	RES IUE *
8	APR 82	5068.29	3.000	1	----	3.529	1	----	-----	-	----	IED AUO
13	APR 82	5073.	3.15	1	----	-----	-	----	-----	-	----	RES IUE *
19	APR 82	5079.	3.13	1	----	-----	-	----	-----	-	----	RES IUE *
25	APR 82	5085.	3.10	1	----	-----	-	----	-----	-	----	RES IUE *
27	APR 82	5087.46	3.030	2	.040	-----	-	----	-----	-	----	RM MO
30	APR 82	5091.61	3.120	1	----	-----	-	----	-----	-	----	P/E GCO
5	MAY 82	5095.43	3.124	4	.020	3.590	4	.030	3.710	4	.040	RM MO
8	MAY 82	5099.60	3.160	1	----	-----	-	----	-----	-	----	P/E GCO
9	MAY 82	5100.60	3.110	1	----	-----	-	----	-----	-	----	P/E GCO
10	MAY 82	5100.42	3.103	3	.030	-----	-	----	-----	-	----	RM MO
10	MAY 82	5101.58	3.080	1	----	-----	-	----	-----	-	----	P/E GCO
	JUNE 82											
21	JULY 82	5172.47	3.098	9	----	3.649	3	.005	-----	-	----	SII TAO
24	JULY 82	5175.	3.26	1	----	-----	-	----	-----	-	----	RES IUE *
26	JULY 82	5177.50	3.127	6	.003	3.658	3	.014	-----	-	----	SII TAO
29	JULY 82	5181.50	3.126	4	.009	3.702	3	.012	-----	-	----	SII TAO
31	JULY 82	5182.49	3.111	4	.005	3.663	3	.008	3.890	3	.005	SII TAO *
2	AUG 82	5184.48	3.115	3	.007	3.654	3	.017	3.827	3	.014	SII TAO *
4	AUG 82	5186.50	3.119	3	.009	3.679	3	.011	3.828	3	.011	SII TAO *
13	AUG 82	5195.61	3.224	3	.015	3.921	3	.020	-----	-	----	RM MO
14	AUG 82	5196.	3.24	1	----	-----	-	----	-----	-	----	RES IUE *
24	AUG 82	5206.	3.29	1	----	-----	-	----	-----	-	----	RES IUE *
28	AUG 82	5210.46	3.180	3	.006	3.737	3	.003	3.891	3	.012	SII TAO *
28	AUG 82	5210.57	3.168	4	.015	3.849	4	.015	4.001	4	.025	RM MO
2	SEPT 82	5215.63	3.217	5	.015	3.879	5	.015	4.006	5	.020	RM MO
4	SEPT 82	5217.48	3.236	3	.007	3.768	3	.009	3.981	3	.009	SII TAO *
7	SEPT 82	5220.	3.41	1	----	-----	-	----	-----	-	----	RES IUE *
11	SEPT 82	5224.48	3.305	3	.007	3.884	3	.009	4.059	3	.007	SII TAO *
16	SEPT 82	5229.41	3.386	3	.015	3.958	3	.009	4.140	3	.012	SII TAO *
18	SEPT 82	5231.99	3.425	3	.031	3.954	3	.007	4.141	3	.004	JLH HPO
21	SEPT 82	5234.	3.56	1	----	-----	-	----	-----	-	----	RES IUE *
21	SEPT 82	5234.98	3.430	3	.005	3.968	3	.003	4.174	3	.005	JLH HPO
23	SEPT 82	5236.	3.57	1	----	-----	-	----	-----	-	----	RES IUE *
23	SEPT 82	5236.40	3.442	3	.006	3.973	3	.033	4.163	3	.009	SII TAO *
23	SEPT 82	5236.98	3.433	3	.005	3.978	3	.003	4.167	3	.008	JLH HPO
24	SEPT 82	5237.97	3.439	3	.011	3.982	3	.001	4.171	3	.004	JLH HPO
25	SEPT 82	5238.98	3.446	3	.002	3.977	3	.003	4.174	3	.010	JLH HPO
26	SEPT 82	5239.--	3.517	1	----	4.098	1	----	4.304	1	----	O/Y JAP
26	SEPT 82	5239.15	3.529	1	----	4.067	1	----	4.452	1	----	JAPOA
27	SEPT 82	5240.83	3.350	1	----	-----	-	----	-----	-	----	P/E GCO
28	SEPT 82	5241.--	3.487	1	----	-----	-	----	-----	-	----	O/Y JAP

FIGURE 2

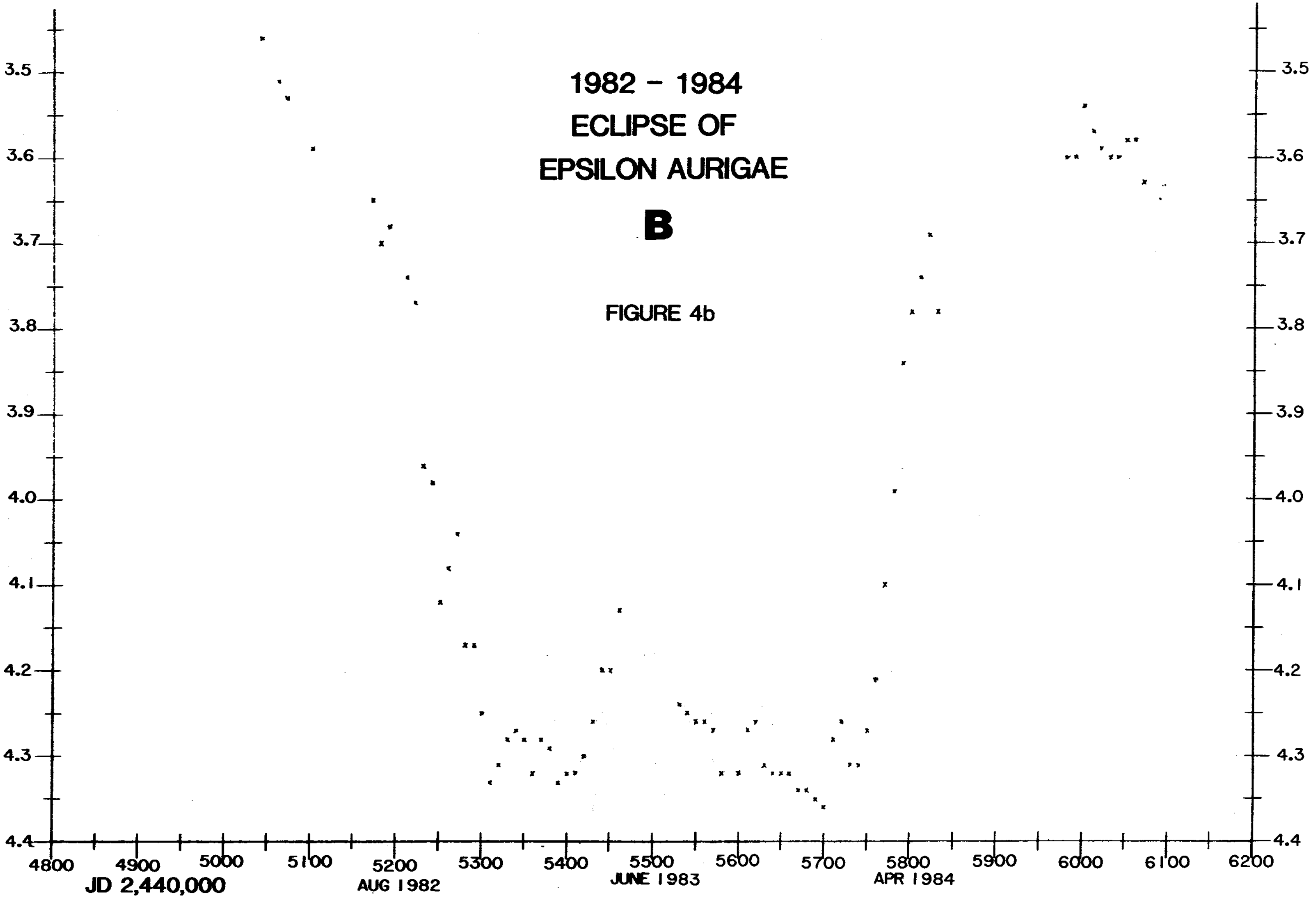
FIGURE 3


1982 - 1984
ECLIPSE OF EPSILON AURIGAE
V MAGNITUDE
COMPOSITE DATA
AS OF
MARCH 1984
9 MAY 82
18 AUG 82
26 NOV 82
6 MAR 83
14 JUN 83
22 SEPT 83
31 DEC 83
3.0
3.1
3.2
3.3
3.4
Vm
3.5
3.6
3.7
3.8
3.9
5000
5100
5200
5300
5400
5500
5600
5700
5800
JD 2,440,000.7 +



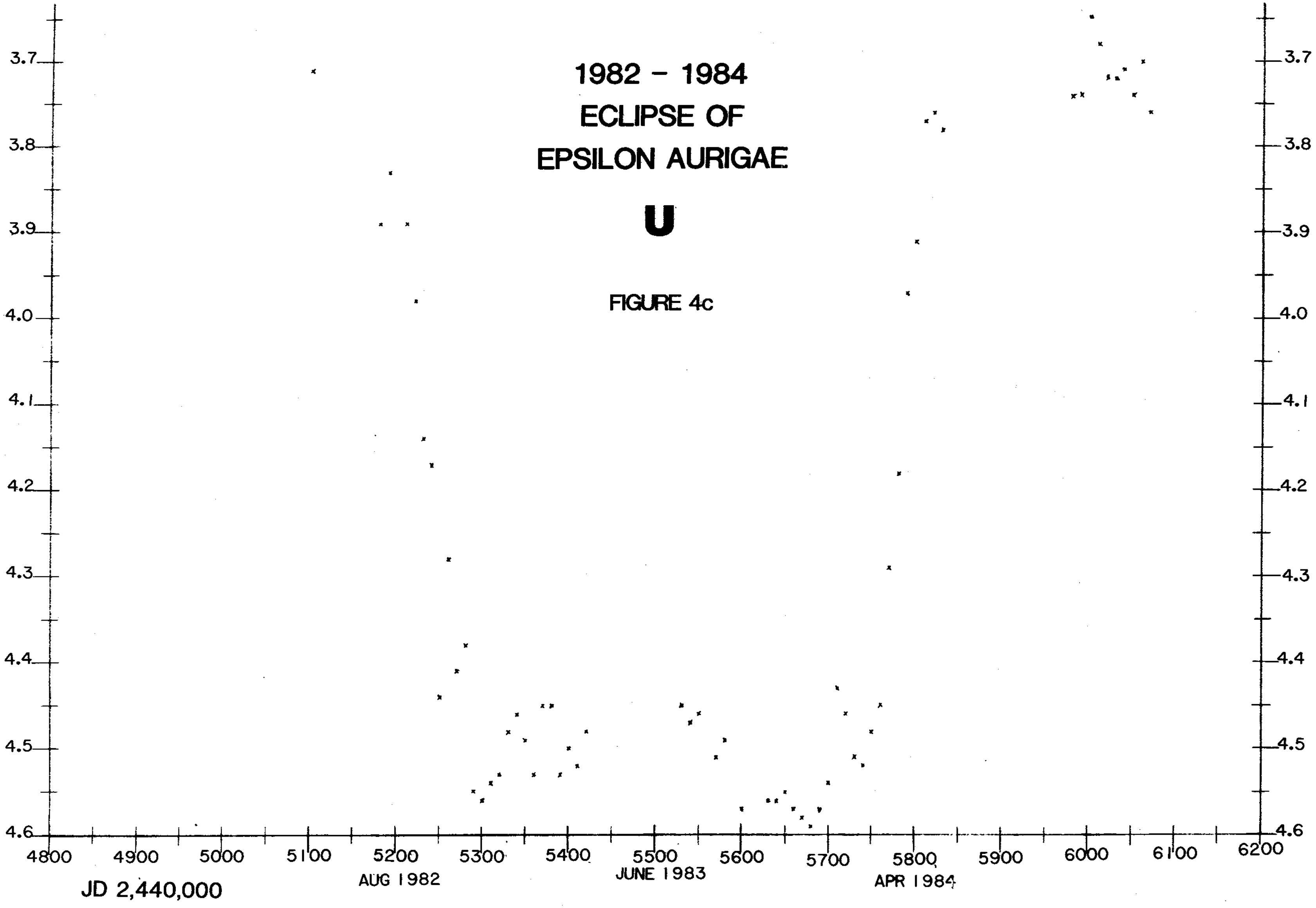
1982 – 1984
ECLIPSE OF
EPSILON AURIGAE
V

FIGURE 4a



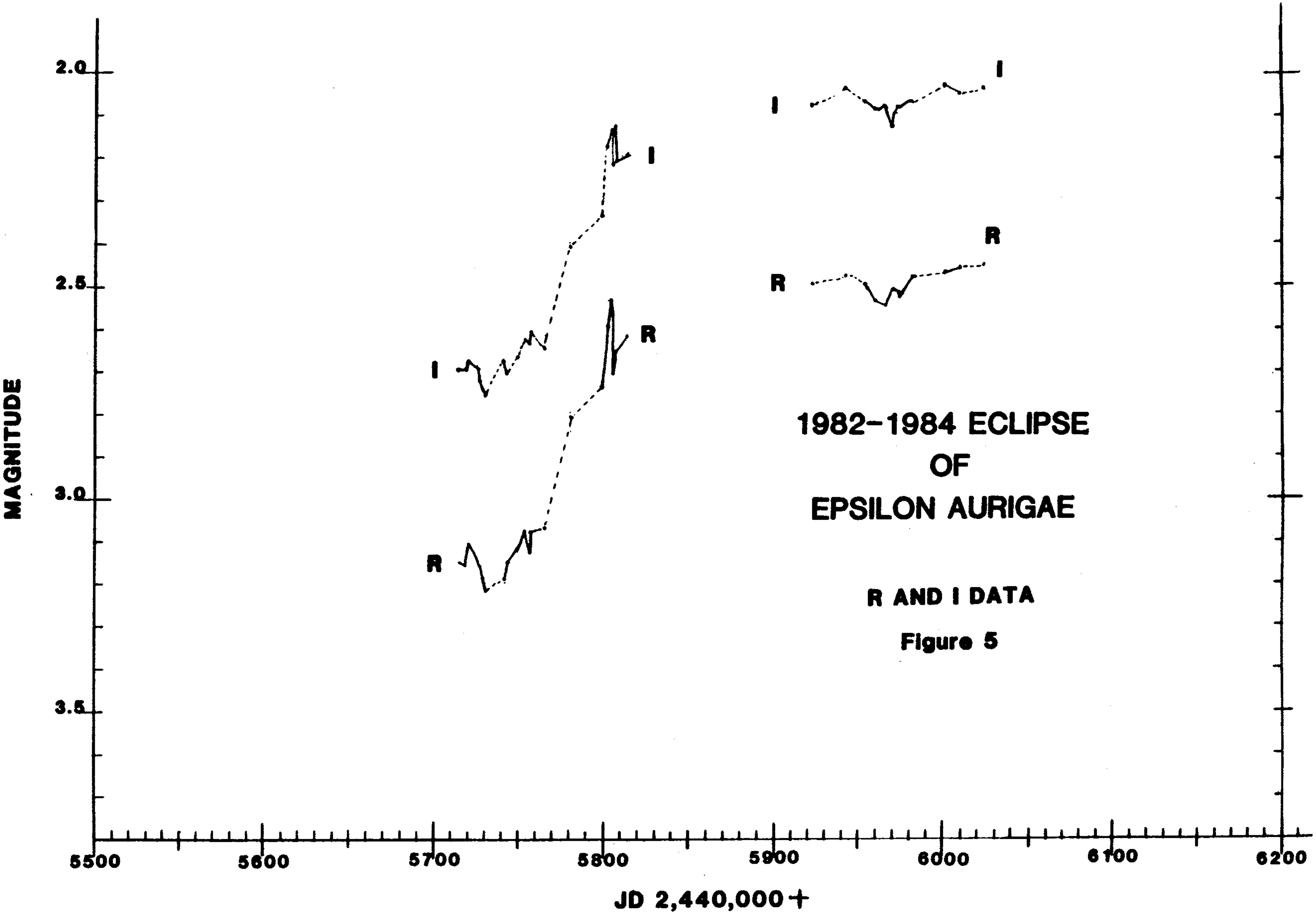
1982 – 1984
ECLIPSE OF
EPSILON AURIGAE
B

FIGURE 4b



1982 – 1984
ECLIPSE OF
EPSILON AURIGAE
U

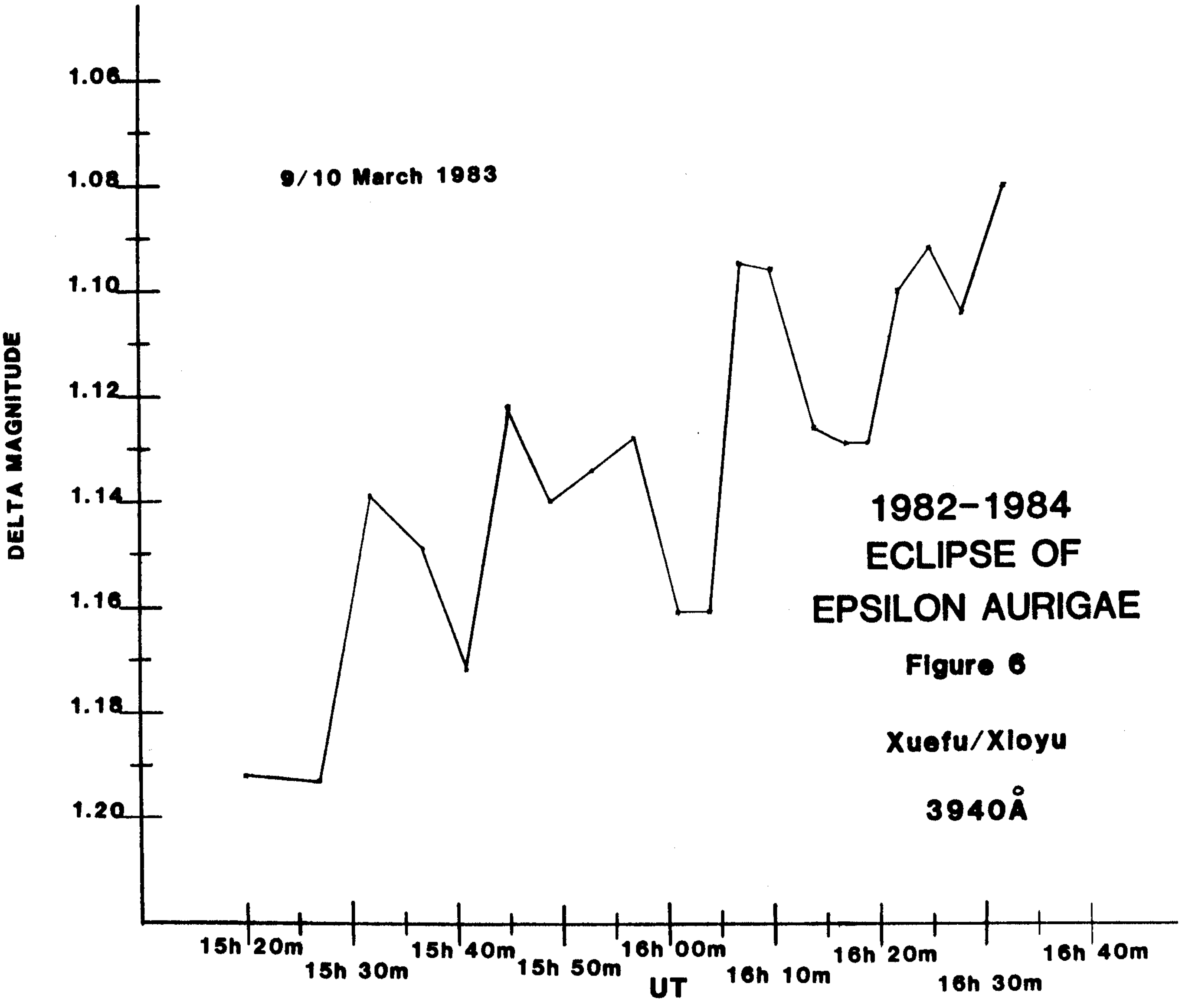
FIGURE 4c



1982–1984 ECLIPSE
OF
EPSILON AURIGAE

R AND I DATA

Figure 5



1982-1984
ECLIPSE OF
EPSILON AURIGAE

Figure 6

FIGURE 7a

1982–1984 ECLIPSE OF EPSILON AURIGAE

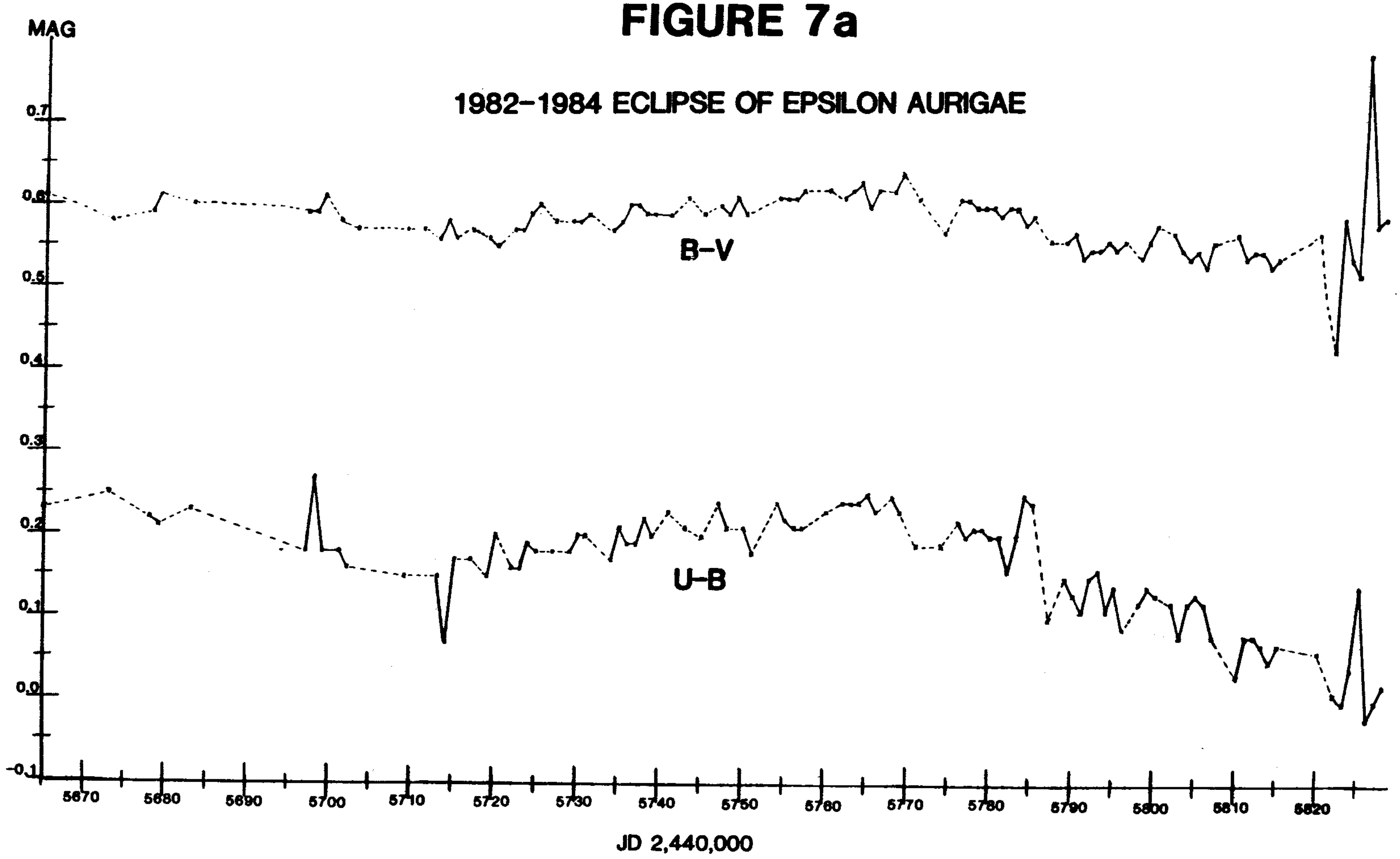
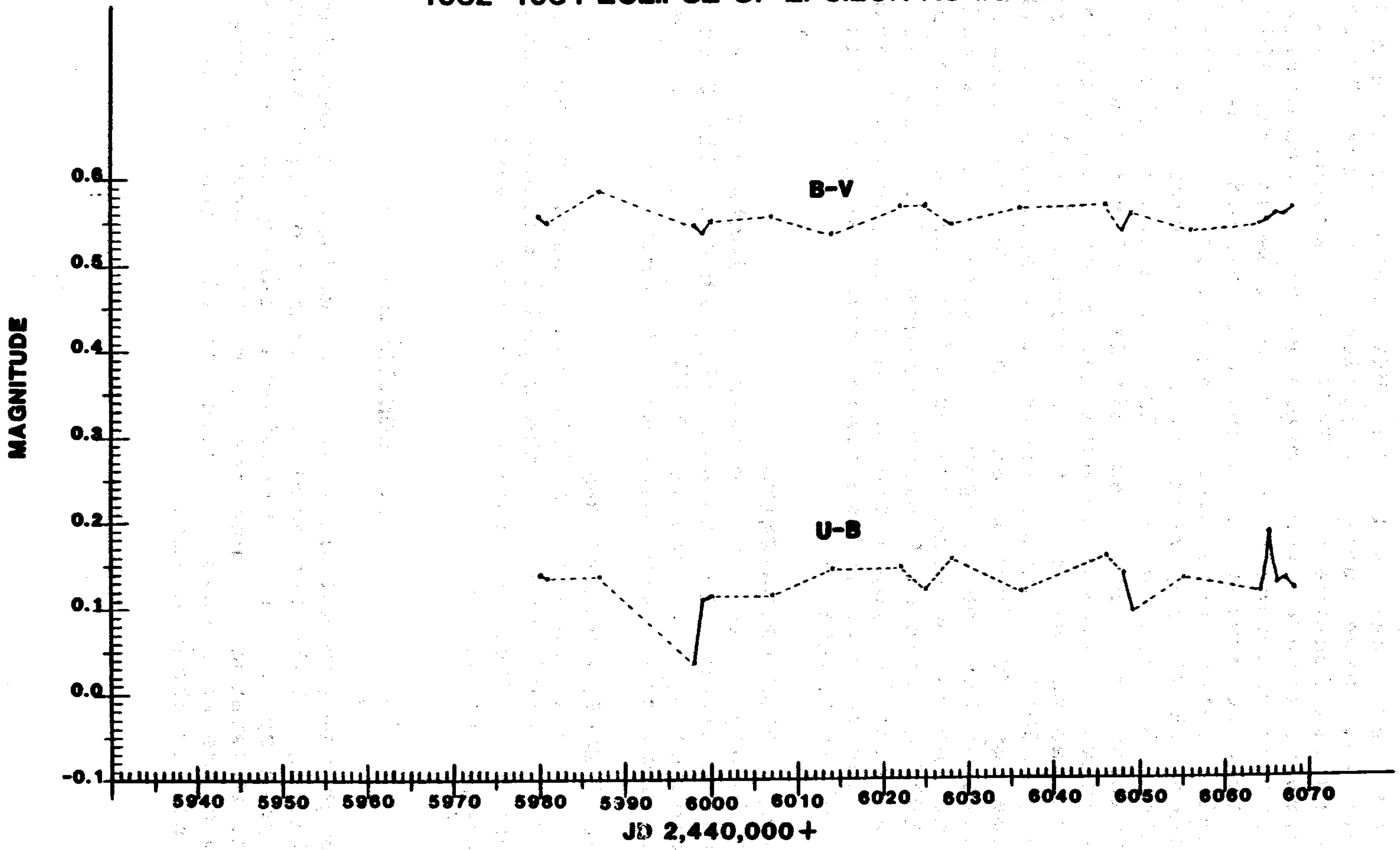


FIGURE 7b

1982-1984 ECLIPSE OF EPSILON AURIGAE



E. MID-ECLIPSE BRIGHTENING

As seen in the UBV plots (Figure 4) there is a mid-eclipse brightening of over 0.2 magnitudes. A similar brightening was seen in the previous eclipse (Webb 1982). It should be pointed out that all the UBV data for this mid-eclipse brightening have been supplied by the Tjorn Island Astronomical Observatory (TAO) in Sweden. Due to the northern latitude (+58 degrees) of the observatory a near year-around observation of the eclipse was possible. Worst case standard deviation during this period was 0.025 with typically better than 0.01 being obtained. Ferluga and Hack (Ferluga 1984) reported their IUE studies in a paper given at the IUE Symposium. They confirmed the mid-eclipse brightening by observing similar ultraviolet continuum variations. A possible explanation of this brightening has been suggested as due to a gravitational lensing effect (Hopkins 1984). Figure 8 shows a comparison of the 1957 eclipse of VV Cephei and the 1928-1930 plus 1955-1957 eclipses of Epsilon Aurigae. A very noticible mid-eclipse brightening can be seen in the VV Cephei eclipse plus the 1955-1957 eclipse of Epsilon Aurigae. The 1928-1930 eclipse has a sizable gap where the mid-eclipse brightening might be. Other long period eclipsing binaries are being examined for similar brightening.

F. PRE-EGRESS BRIGHTENING

About 40 days prior to egress a brightening (Oki 1984) in all three bands (UBV) is seen (Figure 4). The U band shows a brightening of nearly 0.15 magnitudes, B band 0.07 magnitudes, and V band 0.04 magnitudes.

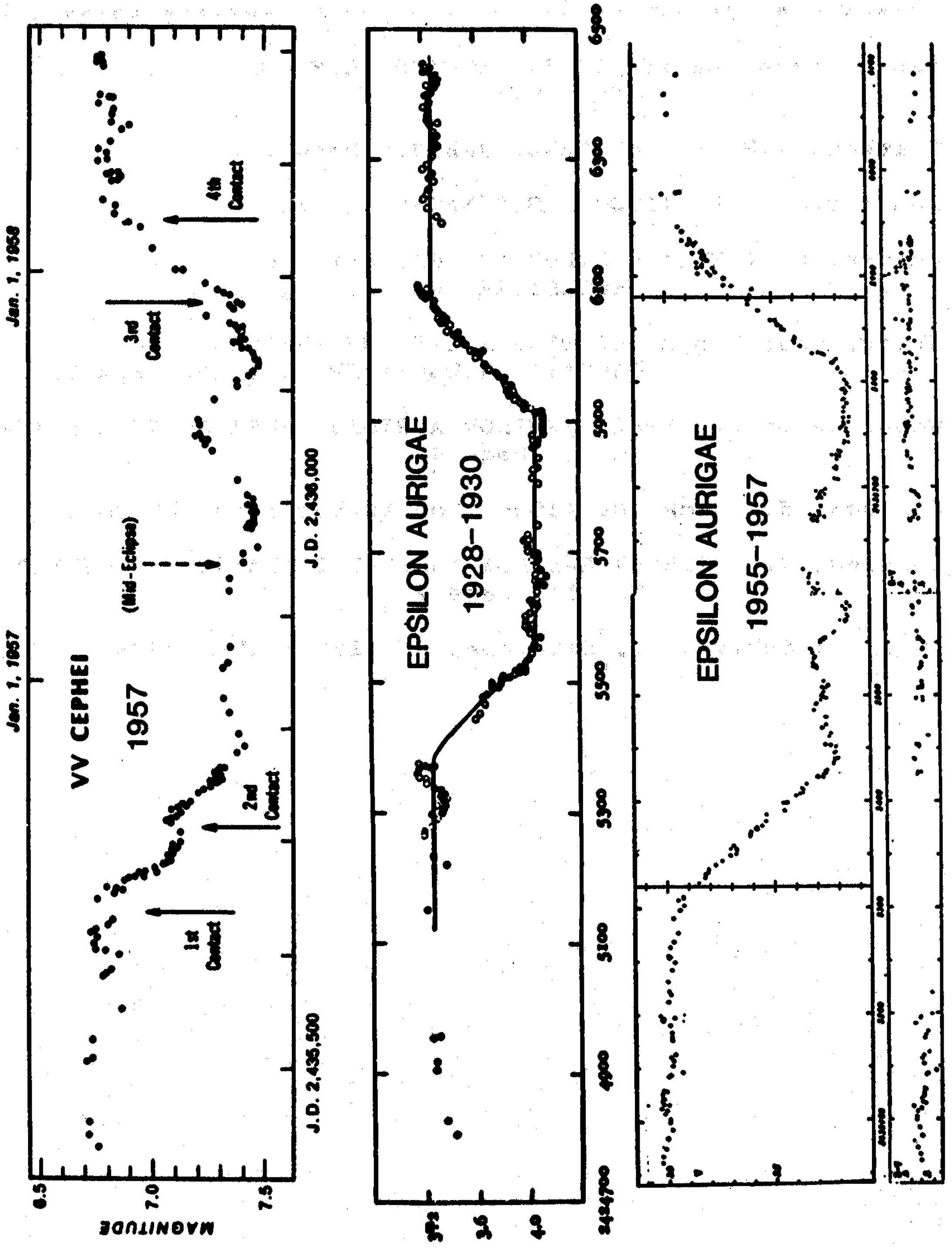
G. POST EGRESS VARIATIONS

Post egress variations of 0.18 magnitudes in the V bandpass, and 0.23 magnitudes in the B and U bandpasses can be seen (Figure 4). These variations are also seen in the R and I bandpases (Figure 5).

V. CONCLUSION

Although the present eclipse has ended, observations are continuing. Data are need to obtain the light variations of the primary so the variations during the eclipse can be better understood. Perhaps for the next eclipse in 2009 astronomers will have a good model with which to test against new observations.

FIGURE 8


VV CEPHEI
1957
Jan. 1, 1957
Jan. 1, 1958
1st Contact
2nd Contact
(Mid-Eclipse)
3rd Contact
4th Contact
J.D. 2,435,500
J.D. 2,436,000
MAGNITUDE
6.5
7.0
7.5
EPSILON AURIGAE
1928–1930
3.2
3.6
4.0
2424700
4900
5100
5300
5500
5700
5900
6100
6300
6500
EPSILON AURIGAE
1955–1957

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INFRARED PHOTOMETRY OF THE 1982-4 ECLIPSE OF EPSILON AURIGAE

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University of Hawaii

The infrared photometry of ϵ Aur performed prior to and during the ingress phase of the recent eclipse allowed the first solid determination of the temperature of the secondary object. The eclipse depth was significantly less at $\lambda > 5$ μm than in the near-infrared. This is explained by a model of the secondary as an opaque and very cool object with a temperature of ~500 K.

During eclipse, the secondary blocks approximately 47% of the near-infrared radiation from the primary star. At the same time, the radiation from the secondary remains completely unobscured, resulting in a shallower light curve at longer wavelengths. This phenomenon is well known in the study of eclipsing binary stars; if the two stars have different colors, then the net color of the system changes during eclipse. In the case of ϵ Aur, the eclipsing object has a "color" deep in the infrared, so the effect is only noticeable there.

The infrared measurements were made by a group of collaborators at the University of Hawaii and Kitt Peak National Observatory of the National Optical Astronomy Observatories†† Figure 1 is a comparison of the shapes of the visual and infrared light curves at three wavelengths during the fall 1982 eclipse ingress. The K band (2.2 μm) is plotted as representative of the entire near infrared; the light curves in the five near infrared bands (J, H, K, L, and M) were identical to within the observational errors. The depth of the infrared eclipse is referred to our pre-eclipse measurements, which were made from 2-1/2 years up until 4 months prior to the predicted date of first contact. The visual points plotted are measurements made by Dietmar Böhme in East Germany, which we received before Hopkins' first compendium (Hopkins and Stencel 1983). We are unable to make a direct comparison between the visual and infrared eclipse depths with the data shown in this figure because Böhme had no pre-eclipse data from dates as far prior to eclipse as ours. The well-known small amplitude pulsations of the primary are one of the reasons why the pre-eclipse baseline magnitudes depend on the epoch of observation; another would be the presence of any gentle "roll-on" of the eclipse in the months prior to first contact. We normalized Böhme's data to ours in this plot using the post-second contact mean magnitudes.

Strictly speaking, our UH/KPNO results come from a comparison of the infrared light curves at $\lambda \leq 5$ μm and $\lambda > 5$ μm. We can only indirectly conclude in addition that the visual and the near-infrared behaviors are identical, by pointing out that the ingress slopes at 2.2 μm and in the visual are the same and that our near-infrared depth for this ingress was similar to the visual depth in the 1955-7 eclipse.

On the basis of our infrared results, we concluded (Backman *et al.* 1984) that the secondary object has a temperature of 500 K. We used two ways to evaluate the amount of infrared radiation coming from the secondary object and thereby determine its temperature. The first method made use only of the dependence of eclipse depth on

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††Operated by the Association of Universities for Research in Astronomy, Inc. under contract with the National Science Foundation.

wavelength in order to separate the relative flux contributions at each wavelength from the primary and the secondary. The second method involved extrapolating the primary star's spectrum from the near-infrared to longer wavelengths and assuming that any excess is due to radiation from the secondary.

The eclipse depth method yielded a temperature of 350 K for the secondary. This method involves the fewest assumptions, so our expectation was that its results would be the most accurate, were it not for the fact that the solution for the secondary's spectrum also gave a solution for the primary's spectrum that we considered unlikely. The implication of this method was that the primary has a continuum beyond 5 μm that is much steeper than a blackbody curve for the star's temperature.

The second method, using the assumption that the primary star's spectrum can be extrapolated using a blackbody function, gave a temperature for the secondary of 650 K. In our paper we pointed out the apparent problem, and reported the temperature as 500 ± 150 K. New information from ground-based infrared observations in the second half of the eclipse plus IRAS spacecraft observations resolve this problem and yield a value of 475 ± 50 K (see below).

An important result from the ingress-phase infrared study regarding the physical nature of the secondary is the conclusion that the secondary object has a very low observed bolometric luminosity for its mass. If the secondary has a uniform temperature of 500 K and a distance of 1200 pc, its total observed flux is only 100 $L_\odot$; inclusion of a possible hot core emitting in the ultraviolet (Parthasarathy and Lambert 1983; Bohme, Ferluga, and Hack 1984) brings this up to only a few hundred $L_\odot$, a factor of 100 less than that expected for a mass of 16 $M_\odot$, which is the secondary's mass if the primary's mass is 20 $M_\odot$. [A much lower mass for the system has recently been proposed (Eggleton and Pringle 1985; Webbink, these proceedings)]. The term "observed" luminosity is used here to indicate the probability that a significant fraction of the radiation from an object embedded in a disk can escape along the polar directions, so the temperature of the rim of the disk may not characterize the total emission. Even so, it is very unlikely that 99% of the flux from the central object could be unobserved. Some possible explanations for the discrepancy between the mass and luminosity of this object are that the secondary's central mass is a black hole (Cameron 1971), or that the mass is split into two stars, a binary embedded in the disk (Lissauer and Backman 1984; Eggleton and Pringle 1985).

Another result from the infrared study comes from reasoning that the luminosity of the primary is capable of heating solid material in the side of the secondary facing it to a temperature of ~1100 K. This would indicate that the secondary must be completely opaque because a much lower temperature is measured for the side facing us during eclipse. The flux from the primary illuminating the secondary is independent of the actual luminosity of the primary because the luminosity scales with the system dimensions in a "standard" geometry in which the secondary does not have a central aperture and its moving edge can be used to measure the diameter of the primary (cf. Wilson 1971).

Infrared photometry of the system was continued by the UH/KPNO group through the rest of the eclipse and into the present post-eclipse phase. Figure 2 is a comparison of the shapes of the full light-curve at 2.2 μm with the combined visual record. The near-infrared and some of the 10 μm observations after mid-eclipse were performed by Dick Joyce and Ron Probst of KPNO as part of a standard star and red-variable photometry program in collaboration with Mike Merrill and Fred Gillett. Again, the normalization used here is the full-eclipse mean at the two wavelengths rather than an out-of-eclipse baseline comparison. Infrared observations were not made during the time when ϵ Aur was in conjunction with the sun. It is clear that the near infrared eclipse follows the visual curve very closely. The last data point is from 1984 December 5.

Figure 3 is the 10.1- and 20-μm data for the complete eclipse plotted for comparison with the 2.2 μm data. The complete eclipse bears out the conclusions made on the basis of the ingress observations. The eclipse was symmetric to first order about its mid-point in the infrared as well as at visual wavelengths.

Table 1 gives the dependence of eclipse depth on wavelength for all the infrared bands using all the available data; the baseline magnitudes are defined using a mean of pre- and post-eclipse observations. On the basis of our ingress measurements, we tentatively concluded that flux from the secondary had been detected at 5 μm at a $\sim 2\sigma$ level. The complete eclipse information now shows evidence of the secondary's presence only at 10 and 20 μm. The mean near-infrared eclipse depth is 0.68 mags, a little shallower than the result from the ingress observations.

The IRAS satellite (Neugebauer *et al.* 1984) made two special (non-survey) observations of ϵ Aur during full eclipse. Table 2 and Figure 4 show the flux from the secondary in the mid- and far-infrared, combining the ground-based and spacecraft results. The IRAS fluxes have been color-corrected. The color temperature of the secondary object from 10 to 60 μm is 475 ± 50 K, close to the results from the ground-based observations alone. The significance of the IRAS data is the extension of the single temperature and low luminosity of the secondary to a wavelength of 60 μm (Backman and Gillett 1985).

The extrapolation of the primary's spectrum beyond 10 μm in Table 2 makes use of a $F_\nu \sim \nu^2$ slope, slightly steeper than a blackbody curve. This model for the primary and a better determination of the out-of-eclipse baseline causes the temperatures estimated for the ϵ Aur secondary by using the two methods described above to approximately converge.

Finally, the combined ground-based and IRAS infrared photometry gives a size for the 475 K secondary of $\sim 9 \times 10^{-16}$ sr. The solid angle subtended by the secondary implies an aspect ratio (length^2 /area) of ~ 2, a surprising result. This result is independent of the distance to the system, again because of the connection between distance and the orbit scale in a "standard" geometry. The small aspect ratio could be due to agitation of the disk material by the embedded object(s), e.g., a rapidly revolving, close, massive binary.

We now know the wavelength region in which the secondary is most easily detected directly. That fact will allow our calculations of the size of the secondary and the amount of heating it receives from the primary to be easily checked as the secondary continues in its 27-year orbit. Infrared observations of ϵ Aur will be continued to further constrain our picture of this unusual system.

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TABLE 1

Infrared Eclipse Depth vs. Wavelength; All data 1980-84

Band	λ (μm)	Mean Eclipse Depth (mag)
J	1.25	0.68 ± .01
H	1.65	0.68 ± .01
K	2.2	0.67 ± .01
L'	3.8	0.67 ± .01
M	4.8	0.68 ± .01
N	10.1	0.58 ± .02
Q	20	0.42 ± .06

TABLE 2

Infrared Flux During 1983 August-September (Full Eclipse)

λ (μm)	Observed Flux Corr. for A_λ[b] (Jy)	Extrapolated Primary (Jy)	Excess ≡ Secondary (Jy)
10.1[a]	9.1 ± .5	7.2 ± .3	1.9 ± .6
12	6.7 ± .3	5.1 ± .2	1.6 ± .4
20[a]	2.7 ± .15	1.8 ± .1	0.9 ± .2
25	2.0 ± .1	1.2 ± .05	0.8 ± .1
60	0.46 ± .03	0.20 ± .01	0.26 ± .03

[a] Ground-based

[b] Corresponding to A_v = 1.1 mag (Ake, these proceedings), scaled using the curve in Figure 1 of Becklin et al. 1978.

FIGURE 1

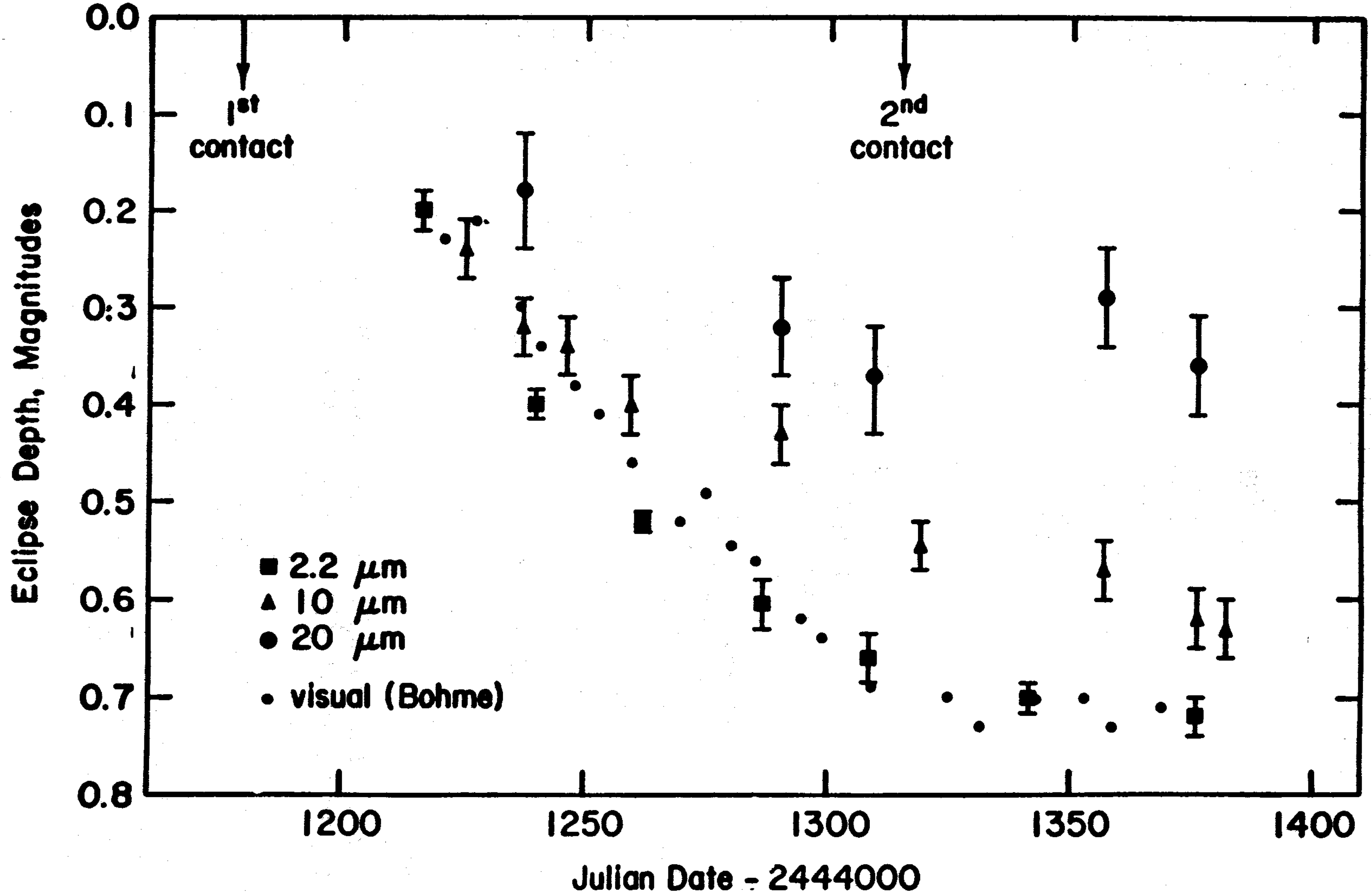

1st contact
2nd contact
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Eclipse Depth, Magnitudes
■ 2.2 μm
▲ 10 μm
● 20 μm
• visual (Bohme)
1200
1250
1300
1350
1400
Julian Date - 2444000

FIGURE 2

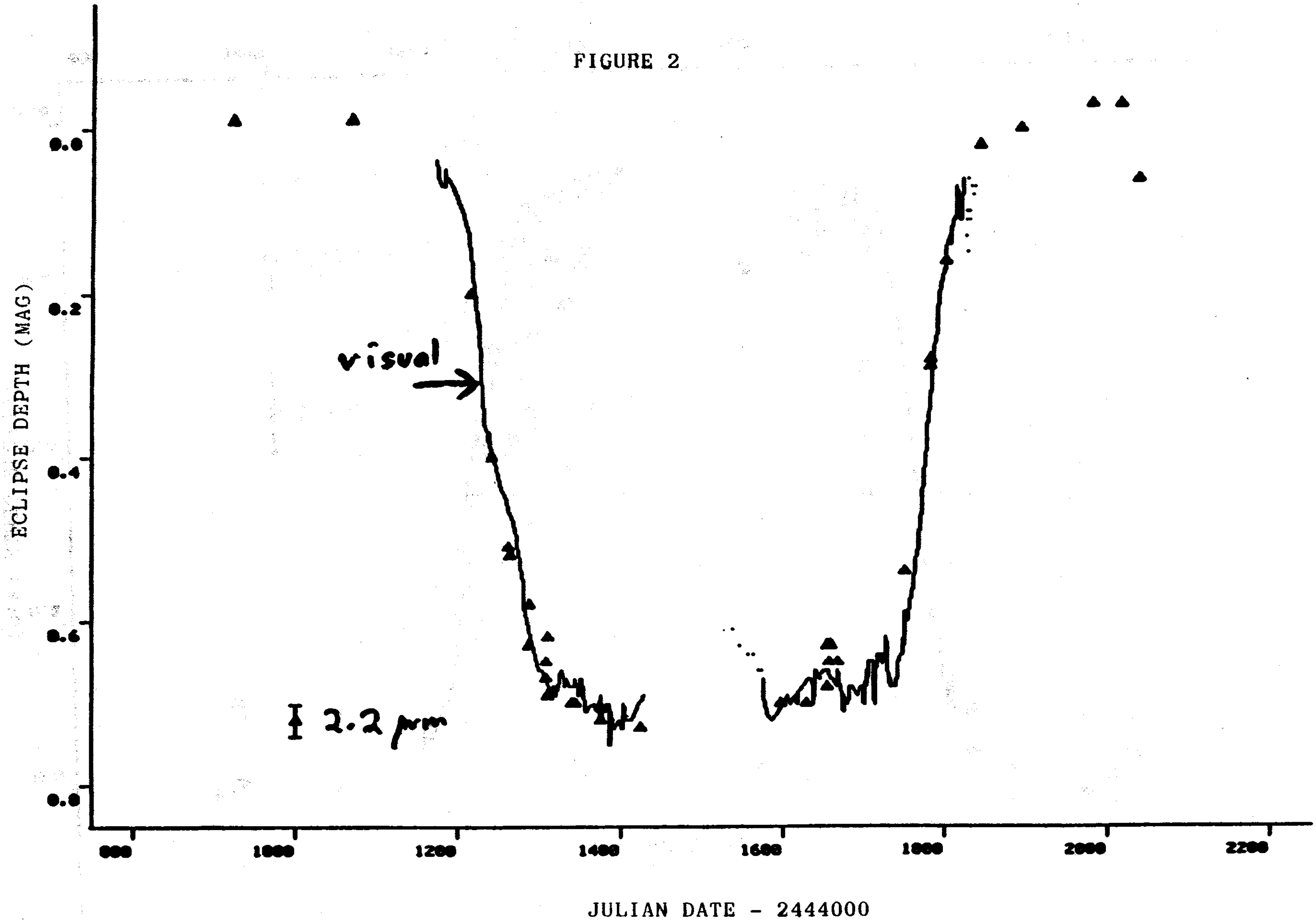

ECLIPSE DEPTH (MAG)
0.0
0.2
0.4
0.6
0.8
JULIAN DATE - 2444000
800
1000
1200
1400
1600
1800
2000
2200
visual
2.2 μm

FIGURE 3

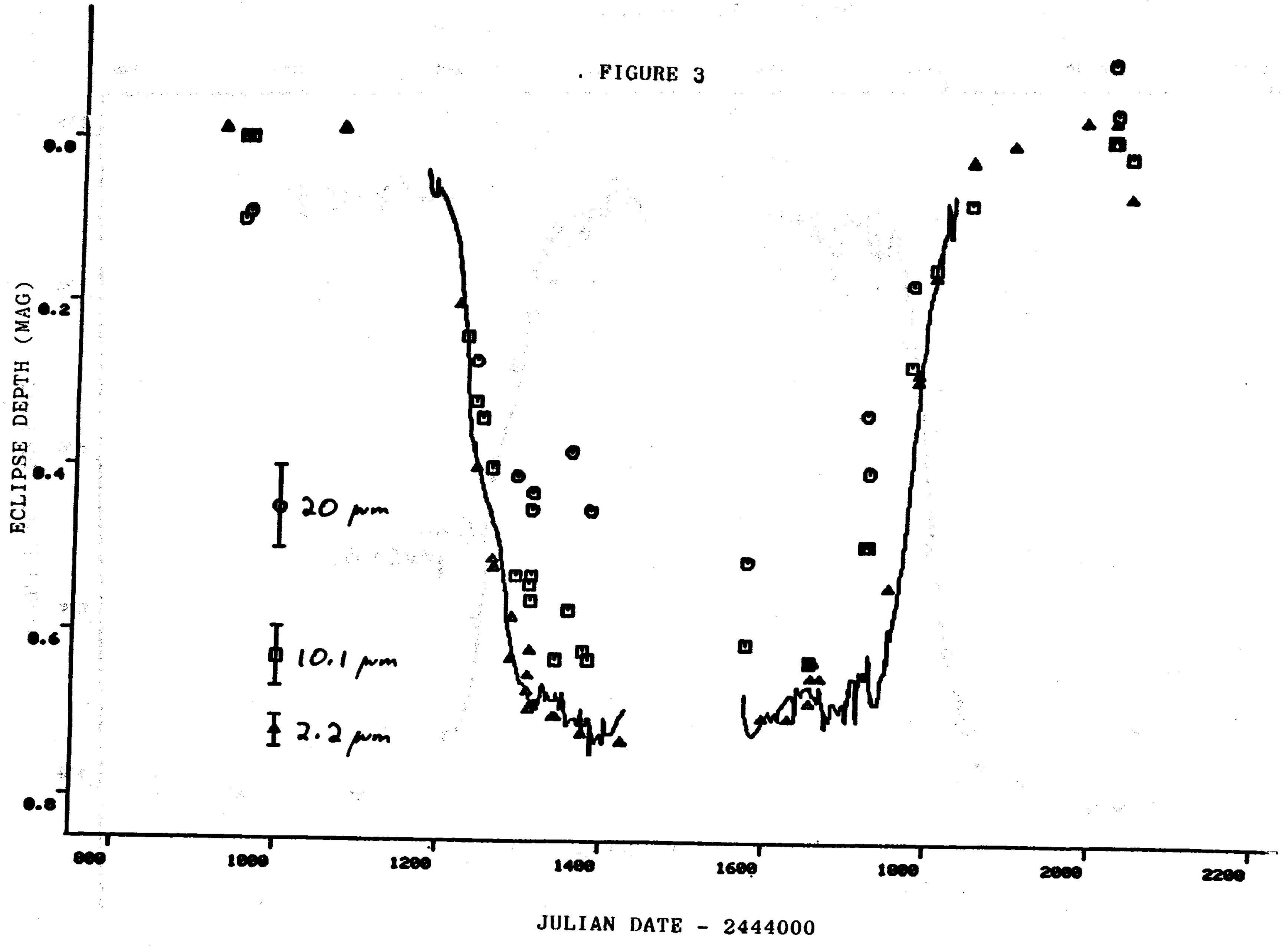
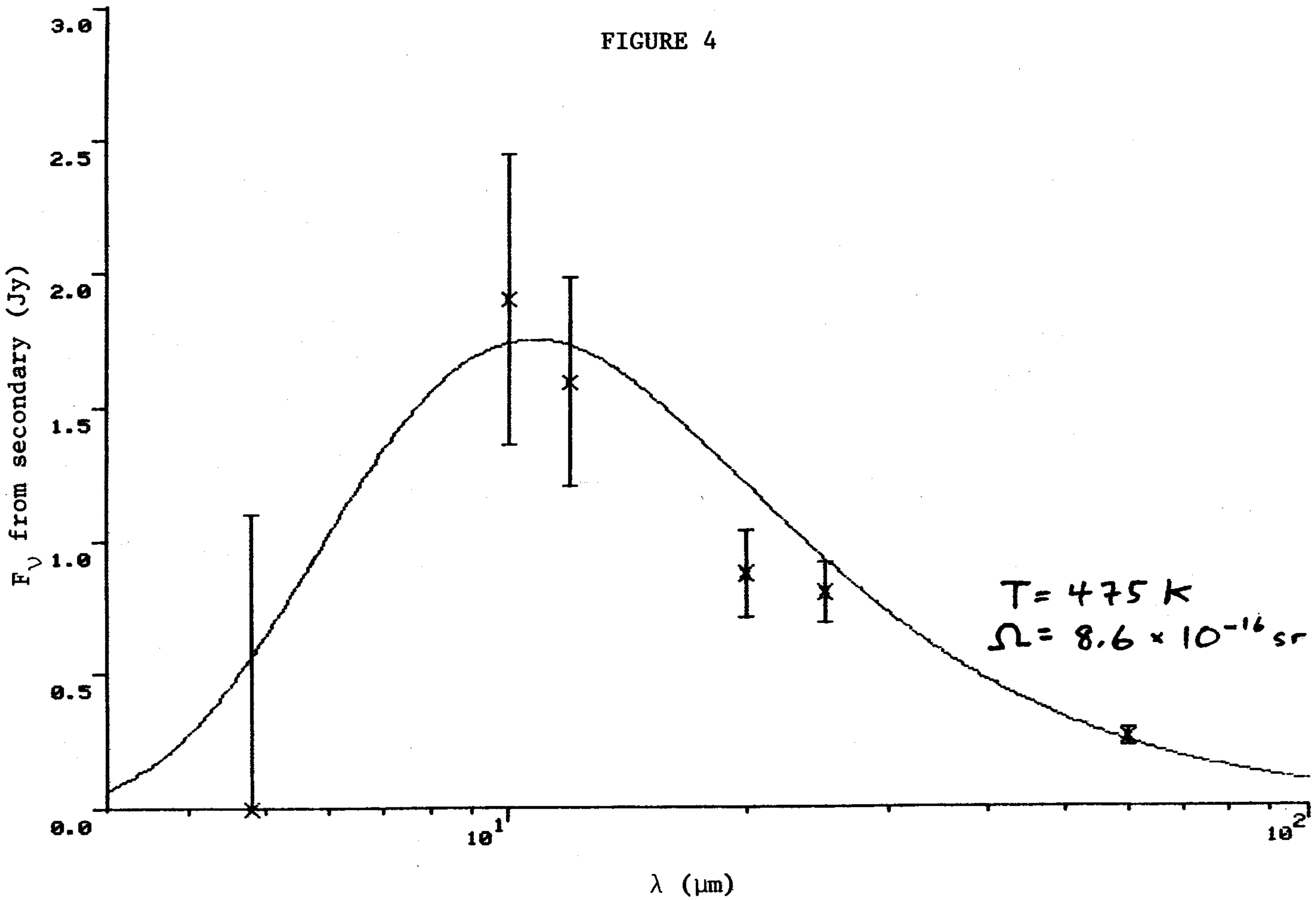

ECLIPSE DEPTH (MAG)
0.0
0.2
0.4
0.6
0.8
800
1000
1200
1400
1600
1800
2000
2200
JULIAN DATE - 2444000
20 μm
10.1 μm
2.2 μm

FIGURE 4


3.0
2.5
2.0
1.5
1.0
0.5
0.0
F_ν from secondary (Jy)
10^1
10^2
λ (μm)
T= 475 K
$\Omega = 8.6 \times 10^{-16}$ sr

THE OPTICAL POLARIZATION OF EPSILON AURIGAE THROUGH THE 1982-84 ECLIPSE

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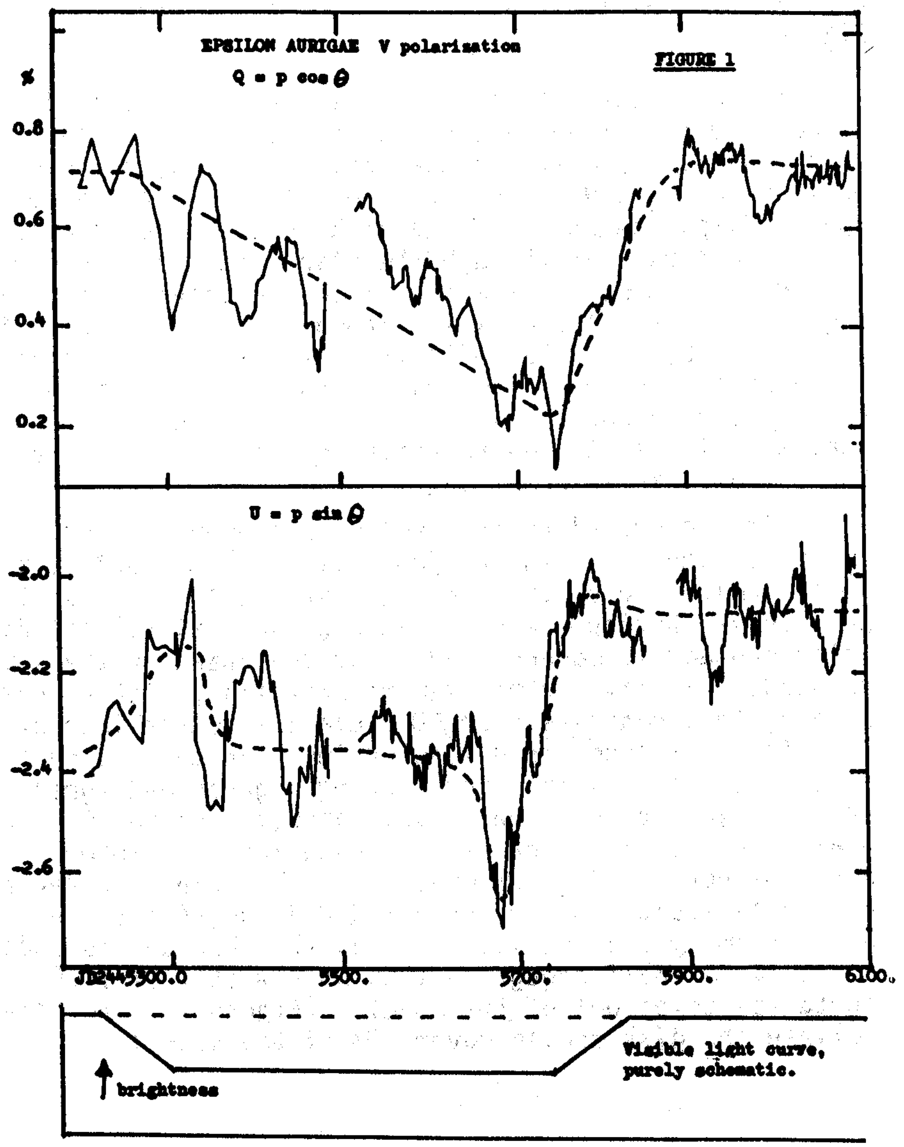
About 350 nights' observations on the 61-cm telescope at Pine Mt. Observatory were made of the variable polarization of Eps. Aurigae during 1982-85, in the U, B, and V color bands. The V data are the most complete and are shown in Figure 1. In terms of the overall features the curves in all three colors are quite similar. The typical errors per nightly point in the V curves are about 0.015% for either of the two normalized, equatorial Stokes parameters Q and U. Note that there is a large background or constant component of some 2.5%, position angle around 135°. This is presumably largely interstellar, and the intrinsic polarization probably does not much exceed the amplitude of the variable component, ~0.5%. We measured a few field-star polarizations but we did not get a very clear pattern in this part of the sky. (The stars closeby in direction, within ~30 arcmin, seemed mostly to be in the foreground, with small polarizations. A deeper study is needed.)

We see two major variation patterns: (1) An overall pattern on the 1-year time scale of the eclipse. Aided by a model, we indicate this by dashed curves in the Figure. And (2) somewhat erratic oscillations on a 100-day time scale.

The "100-day" structure is almost surely connected with the primary star's pulsations --since, for example, these fluctuations continue outside eclipse. The eclipse process evidently interacts in some way with the pulsational polarization structure and we cannot completely separate the two effects. But the 1-year interval between 2nd and 3rd contacts covers about three pulsation cycles, thus the slow, long drop in the Q Stokes parameter, at least, is surely due to the eclipse itself.

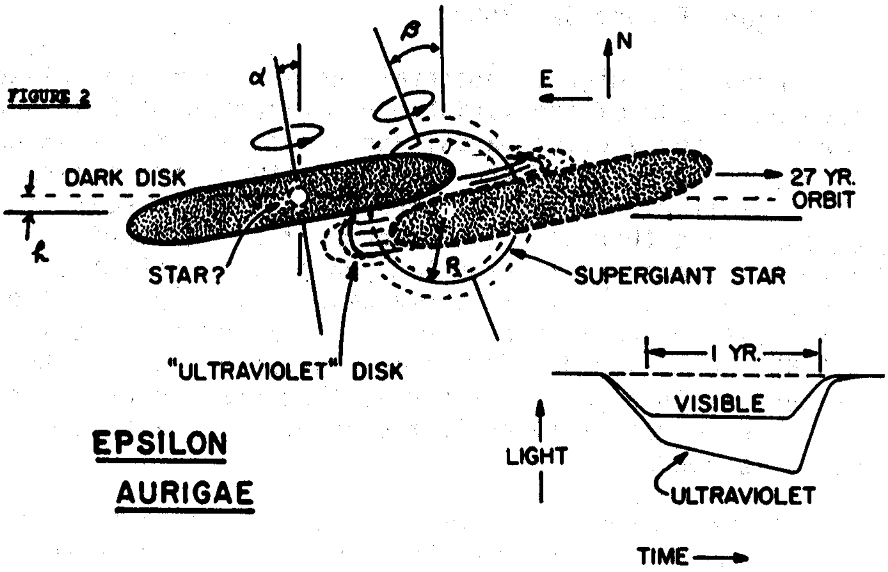
Some rapid changes on time scales of 1-5 days are also seen. While there are a few cases of large errors, this structure is mostly real, and suggests stochastic activity. The minimum time scale seems to be ~ 0.5 day.



On at least 6 nights we followed the object for up to 7 hours and found no changes larger than $\Delta Q \sim \Delta U \sim 0.03\%$ over such time spans.

Models. We model the eclipse polarization in terms of limb polarization in the primary star, modulated by the passing dark cloud. For this we ignore pulsation and consider the star as spherical. See Figure 2. The star is assumed to emit polarized light concentrated strongly on the limb, due to internal scattering, with the E vector parallel to the limb. During partial eclipse this mechanism gives a non-vanishing net polarization (see e.g. Kemp et al 1983, Ap.J., 273, L85).

FIGURE 2



The asymmetrical changes in the observed polarization during the eclipse, especially the slope in the Q parameter, require that the disk must be tilted out of the orbital plane; and the orbit of the system cannot be exactly edge on, i.e. we must have $i < 90^\circ$. In Fig. 2 we indicate the non edge-on inclination by an upward displacement h, of the disk on the sky, relative to a line parallel to the orbit plane passing through the star's center. For our modelling the relevant parameter is h/R, the fractional displacement of the disk (at mid eclipse) from the star center. The disk is tipped by an angle α. The astrometric orbit (van de Kamp 1978, A.J., 83, 975) indicates that the system is oriented on the sky essentially east-west ($\theta \simeq 95^\circ$), and that the disk passes from east to west across the star, as drawn in Fig. 2. Note that some of our qualitative conclusions, mainly that the disk is tilted relative to the orbit and that $i \neq 90^\circ$, do not depend on the astrometric information.

With an upward (northward) displacement h, and a small tilt ($\alpha \lesssim 10^\circ$) in the direction shown in Fig. 2, just after second contact the disk covers mainly the upper hemisphere of the star, giving a relatively small net polarization. (Covering precisely a hemisphere gives zero polarization.) The disk then drifts downward. At third contact it covers, say, a central band on the star, with north and south poles exposed. This gives a maximum polarization, with E vector approximately EW, corresponding to a negative Q or ΔQ (relative to the interstellar value). This effective drifting of the eclipsed zone on the star thus accounts for the simplest feature of the eclipse polarization. During ingress and egress, the transient motions of the eclipsed zone produce relatively abrupt additional structure; positive and negative peaks occur in the U parameter. Assuming a diameter/thickness ratio of 6 for the disk, we generated a few model Q and U curves for several values of h/R and α. The best fits seemed to require $h/R \simeq 0.4$ and $\alpha \simeq 5^\circ$. With an orbit radius of 13 AU and a primary star radius of 1 AU, this h/R corresponds to $i \simeq 88^\circ$. The disk tilt angle α is small enough so that an almost flat light curve (between 2nd and 3rd contacts) comes out of the model. (Figure 2 is not drawn quite to scale. Deep in eclipse the disk should cover 50% of the star.)

Pulsational structure. In the light curve, a ∼100-day "pulsation" pattern is well recognized, both inside and outside eclipse; see e.g. E.F. Guinan's paper at this Workshop. A polarimetric counterpart is not surprising. Because of possibly subtle interaction between the eclipse and the pulsation, we should first look at the outside-eclipse Q and U curves after fourth contact -- after approx. JD 2445850 in Figure 1. Clear ∼100-day variation is seen in the U parameter, and a less-clear and perhaps weaker pattern is seen in Q. Since the U parameter measures polarization in $\pm 45^\circ$ directions (i.e. in NE or NW directions), we must have non-radial pulsations with an eigenaxis which is appreciably tipped from the orbit normal on the sky (approximately NS). We cannot say which direction the eigenaxis is tipped, i.e. toward NE or NW, without a complete model of the pulsation polarization which must include correlation with the photometric pulsation. In Figure 2 we have shown the primary star's spin axis, which we take to be the eigenaxis of the pulsation, as tilted in the NE direction. As will be seen, this choice is influenced by a connection with the IUE light curves.

The mechanism here is that the primary is a rotating pulsator, in which the pulsations produce an expanding and contracting equatorial belt or ring. Light from the star is scattered by this ring, producing the oscillating polarization. The ring is highly ionized with a large free-electron density, giving a high polarizing efficiency and almost color-independent polarization.

Connection with IUE light curves: A chromospheric belt? At this workshop, T. Ake has shown vacuum-ultraviolet light curves of Eps. Aurigae's eclipse, from IUE data. Over about the range 1600-3000 Å, these curves look schematically as we show at lower right in Figure 2. While the visible-light curve is flat (ignoring here the so-called mid-eclipse brightening), the UV curves slope downward. Here is strong evidence, separate from the polarization, for a pronounced asymmetry in the system!

We explain the sloping UV light curves in terms of an inclined, UV-emitting belt, or ring, encircling the primary star's equator -- the same tilted ring which we associate with the pulsational polarization. Because of the tilts of both the secondary disk and the primary star's spin axis, and the slightly non edge-on inclination, the eclipse of the chromospheric belt is somewhat delayed, relative to the eclipse of the star's approximately circular photosphere. The disk's shadow does not fully cover the belt until near third contact.

Epsilon Aurigae: A complex, gyrating system. The polarimetric properties of this system, combined with the asymmetrical IUE light curves, have shown it to be geometrically more complex than anyone had thought, even allowing for the Cepheid-like pulsations of the primary. For example, both the secondary disk and the primary star's spin axis must precess, because they are tilted. A rigid-body estimate for the disk precession time is around 1000 years. Note that the spin and disk directions of course lie in three dimensions, while in Fig. 2 we indicate basically just the projected directions on the sky. Precession would cause successive eclipses to differ, at least slightly. The 1928 eclipse had a quite flat-bottomed light curve, while the recent 1982-84 one had a strong special feature, a mid-eclipse brightening. Guinan (this Workshop) has suggested that the mid-eclipse brightening has to do with a kind of central gap in the secondary disk, which momentarily exposes the primary star. We can think of a precessing doughnut, which in 1928 was almost exactly edge on, so that no hole was exposed. By 1983 the disk may have precessed just enough so that we are beginning to see through the hole. Could we thus predict that in 2010 the eclipse will show an even stronger central brightening?

Continuing observations. We are extending our polarization observations for probably at least another year, with a view to defining the outside-eclipse pulsational structure. This is extremely important, and we issue a nenewed call to photometrists to continue their work as well! There is indication that the polarimetric changes do not reflect a simple "uniaxial" type of pulsation (as with some RV Tauri stars, for example); there may be multimode effects. Apart from the pulsation, in a couple of years the orbital phase will be such that we may be able to detect reflection polarization -- light from the primary scattered by the disk. For one thing that could help to check on the astrometric orientation of the system.

IUE OBSERVATIONS OF THE 1982-84 ECLIPSE OF EPSILON AURIGAE

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INTRODUCTION

We summarize the major characteristics in the ultraviolet of the 1982-84 eclipse of Eps Aur as observed with IUE by various workers. This star can be observed over the entire IUE wavelength range, from 1200 to 3200 A, in low dispersion, allowing eclipse light curves to be obtained in broadband regions, but due to its steep spectral gradient and the sensitivities of IUE cameras, high resolution exposures adequately cover only the regions from 1700-1900 and 2400-3200 A. In many ways, the UV data confirms or expands upon interpretations of the system made from observations in other wavelength regions, but in other respects the system remains as enigmatic as before.

OBSERVATIONS

The flux from an late-A, early-F supergiant like Eps Aur drops over 2 orders of magnitude from 3200 to 1200 A. Thus it is necessary to take multiple exposures of different length to adequately cover all wavelengths. For Eps Aur in low dispersion, typically 2 exposures with each camera are needed, ranging from 7 sec to 20 minutes. In high dispersion, two LWR images with an exposure ratio of 4 are needed to optimize exposure levels in the continuum and at Mg II; for the SWP, a full shift exposure only extends to about 1700 A. Unfortunately this precludes studying astrophysically interesting high temperature lines such as C IV and Si IV if they are present.

The characteristics in low dispersion can be summarized as follows:

1. The eclipse light curve in the near UV generally follows that found in the optical region. During totality, the eclipse depth slowly increases up to third contact. The minor fluctuations in light seen optically are increasingly exaggerated in the UV from 3200 A down to about 1500 A. Shortward of this, the fluctuations become smaller in amplitude. The fluctuations occur predominantly prior to mid-totality.
2. The eclipse depth is dependent upon wavelength, increasing somewhat in depth from 3200 A to 1600 A then becoming shallower such that at 1200 A it is only 0.2 mag. deep.

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[1] Guest Observer, International Ultraviolet Explorer

3. Two extraordinary brightenings were seen in the UV near first and third contacts. The occurrance at first contact has caused various IUE observers to find different depths of eclipse because different reference spectra were used. The brightening seen optically at mid-totality is also visible in the UV, the degree being in the same ratio as the optical/UV depth.

4. The 2200 A depression characteristic of interstellar grain absorption is consistent with published values of E(B-V) $\simeq$0.35. There is no detectable change in the dip during the eclipse.

5. Compared to other A-F supergiants, there is a UV excess shortward of 1400 A. The line spectrum, however, does not match that of a middle-B type star, and subtracting a hot continuum does not adequately explain the shallowness of the eclipse from 1400 to 1500 A.

6. The only strong emission line seen is that of O I 1304. It fluctuates by a factor of 2 during the eclipse, but too little out-of-eclipse data is available to say if this behavior is eclipse dependent.

The observations at high dispersion are more difficult to study because of the wealth of overlapping lines at IUE's resolution. Some early results are:

1. P-Cyg profiles in the Mg II doublet were revealed in the central core as the continuum faded. The profile remained essentially unaltered throughout the eclipse, the absorption core being shifted -13 km/s. During ingress, the Mg II line wings dropped more rapidly than the continuum and during egress recovered more slowly.

2. It is difficult to distinguish multiple velocity components in the UV, but some structure is reported. The radial velocity curve of the photospheric lines is nearly constant up to mid-totality, becomes more negative by about 45 km/s up to third contact, then returns to the velocity value expected from the orbital motion of the primary at the end of the eclipse.

3. The low-excitation lines of Fe II, Mn II and Cr II have stationary components that appear to be the tops of emission lines filling in the absorption cores of the stellar lines. At the constant velocity phases, they are appear on the redward side of the corresponding absorption lines.

DISCUSSION

As would be expected from the pre-eclipse observations that the UV energy distribution is still mainly dominated by the primary, the eclipse data mimics in many ways the behavior seen in the optical region. The downward slope of the light curve during totality, the superimposed light fluctuations, and the radial velocity curve are consistent with previous observations; the Mg II emission has counterparts in other regions, such as in H alpha, and is consistent with Ca II measurements. The IUE observations, however, do shed some light when interpreting this behavior.

The UV fluctuations have been interpreted as being due to aperiodic Cepheid-like pulsation of the primary (Ake and Simon 1984) or as structure in the occulting body (holes or tunnels, Parthasarathy and Lambert 1983, Boehm et al 1984). We feel the fact that variations are enhanced with decreasing wavelength down to 1500 A favors the pulsation explanation. Schimdt and Parsons (1982) find that in Cepheids a 0.5 mag. amplitude in V translates to amplitudes up to 5 mag. at 1600 A because of the extreme temperature sensitivity of the UV continuum and ionization edges in F supergiants. The strength of the O I emission in Eps Aur is also consistent with the shock-induced O I emission in Cepheids.

The opacity of the occulting body is mainly continuous (Chapman et al 1983) as most of the absorption lines in high dispersion do not change in depth nor do different lines appear during the eclipse. Some lines, however, are reported to show some structure taken to be evidence of multiple components (Ferluga and Hack 1984) and others seem to be filled in by emission peaks (Castelli et al 1982). Furthermore interstellar or circumstellar components are seen in low-excitation lines of Mg I, Mg II, Fe II, etc.

The radial velocity curve in the UV derived from the photospheric lines is somewhat consistent with that reported in the past with other eclipses. The lines are found to be blueshifted after mid-totality, but prior to mid-totality no corresponding large redshift is seen (Ake and Simon 1985).

The constancy of the Mg II emission (Altner et al 1984) and deduced emission of other low-excitation lines is characteristic of the Zeta Aur systems where a hot secondary interacts with the wind from the cooler primary and excites the circumsystem material. In these systems, when the continuum from the hot star is reduced during an eclipse, the emission lines appear with redshifted peaks due to scattering of the hot star photons off the receding gas in the wind from the primary. In Eps Aur, the "emission peaks", which remain constant as the overlying absorption deepens during the eclipse, are found on the redward side of the corresponding absorption components much as in the Zeta Aur systems.

Perhaps the most intriguing aspect of the IUE observations is the shape of the far UV energy distribution and the eclipse light curve since they provide new insight into the nature of the system. The 2200A depression does not change during the eclipse indicating that the occulting body is not composed of the types of grains typically found in the interstellar medium (Boehm et al 1984, Ake and Simon 1984). Moreover, the absence of additional line absorption implies that the occulting body is also devoid of a significant amount of gaseous material. Finally we note that the UV excess shortward of 1400 A, as reported by Hack and Sevelli (1979), is suggestive that a hot secondary has been detected, but it cannot be definitively stated to be that of a hot star (Parthasarathy and Lambert 1983, Ake and Simon 1984). The final test of the location of this added UV source will be observations at the predicted time of the next secondary eclipse.

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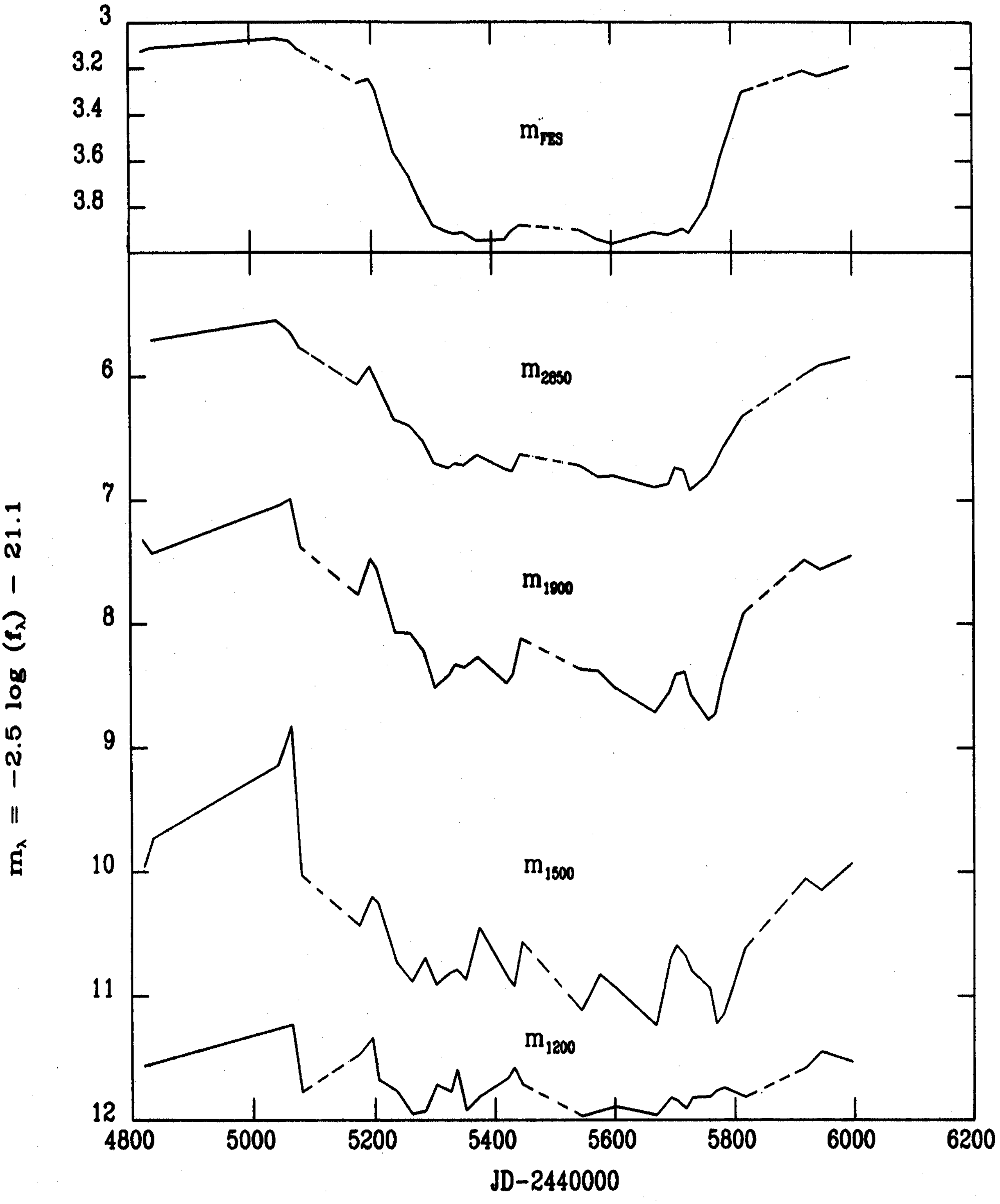

Figure 1. (Ake) Eclipse light curves for ϵ Aur as measured by IUE's Fine Error Sensor (transformed to V magnitudes) and ultraviolet regions centered at 2850, 1900, 1500 and 1260 A (converted to magnitudes on an energy scale where m_λ=0 is 3.64 x 10^{-9} ergs/cm^2/sec/A). Dotted lines indicate unobserved dates due to ϵ Aur's proximity to the Sun.

THE ECLIPSE OF EPSILON AURIGAE
VISIBLE SPECTROSCOPY AND ULTRAVIOLET ACTIVITY

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We report the preliminary results of the study of several high-resolution spectrograms ($\lambda 3500$ - $\lambda 7000$ Å), obtained at the Haute Provence Observatory (OHP) in France, at different epochs before, during and after the eclipse. We also compare some of these spectrograms with corresponding IUE high-resolution observations, in order to study the effects of the intrinsic UV activity, towards the longer wavelengths.

1. The Visible Spectrum

As during the previous eclipses, we have observed the appearance of sharp absorption components on the red side of the strong low-excitation lines and of the Balmer lines during the ingress phase, and on the violet side during the egress phase (Ferluga and Hack, 1985: Paper I). This additional spectrum, which we call "shell spectrum", appears only during the eclipses and is very well observable during the partial phases of the eclipse. During totality it is observable as a strong deepening of the absorption cores of the strongest lines, especially the Balmer lines. The shell spectrum is explained by a gaseous envelope surrounding the eclipsing body and rotating in the same sense as the orbital motion. Since the shell spectrum appears before the beginning and disappears after the end of the photometric eclipse, the gaseous envelope must be more extended than the occulting body (a dusty disk, as suggested by the IR observations by Backman et al. 1984). The shell has about the same excitation temperature of the photosphere of the FOIa primary, but a much lower density. This is indicated by the fact that the quantum number of the last resolved Balmer line is $n = 31$ in the photospheric spectrum and $n \gtrsim 50$ in the shell spectrum; moreover,the high excitation lines and all the faint lines do not present the shell component. (Fig.1)

The shell responsible for the additional spectrum has an absolute value of the rotational velocity lower before totality than after it (e.g., 277 days before mid eclipse the shell RV is +15 km/s and, 269 days after it, it is -35 km/s; 227 days before it, it is +17 km/s, and 221 days after it, it is -37 km/s). that is, the part of the shell which follows in the orbital motion rotates faster than the preceeding one. Moreover, both parts of the shell show a rotational velocity which increases from the outer part to the inner one, reaches a maximum and then decreases again (Fig. 2). The general behaviour and the values of the RV are the same as observed by Struve et al. (1958) during the 1955-57 eclipse.

At the epoch of the brightening on Jan. 1984 near the end of totality (Ôki et al., 1984) the shell has the maximum negative RV and also maximum intensity. Weak low-excitation lines which generally do not show the shell components show it in the spectrum (GB 8177) taken at the OHP on Jan 24, 1984 (*) . This fact could indicate that in correspondence of a diminution of the density of the dusty disk we observe the absorption of the FO Ia

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(*) Note. The same behaviour is shown in the UV by the spectrum LWP 2673, obtained with the IUE at high resolution on Jan 20, 1984.

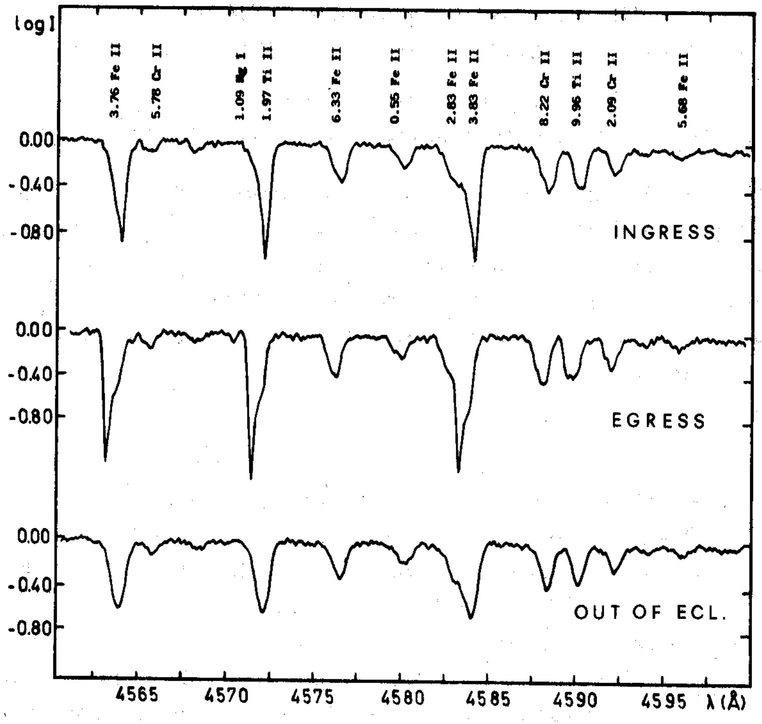

Fig. 1 - The shell spectrum. An additional component is superimposed over the stronger low-excitation lines. This component is red-shifted on ingress (Nov 19, 1982) and violet-shifted on egress (March 29, 1984). The spectrum taken out of eclipse (Jan 4, 1981) is reported for comparison.

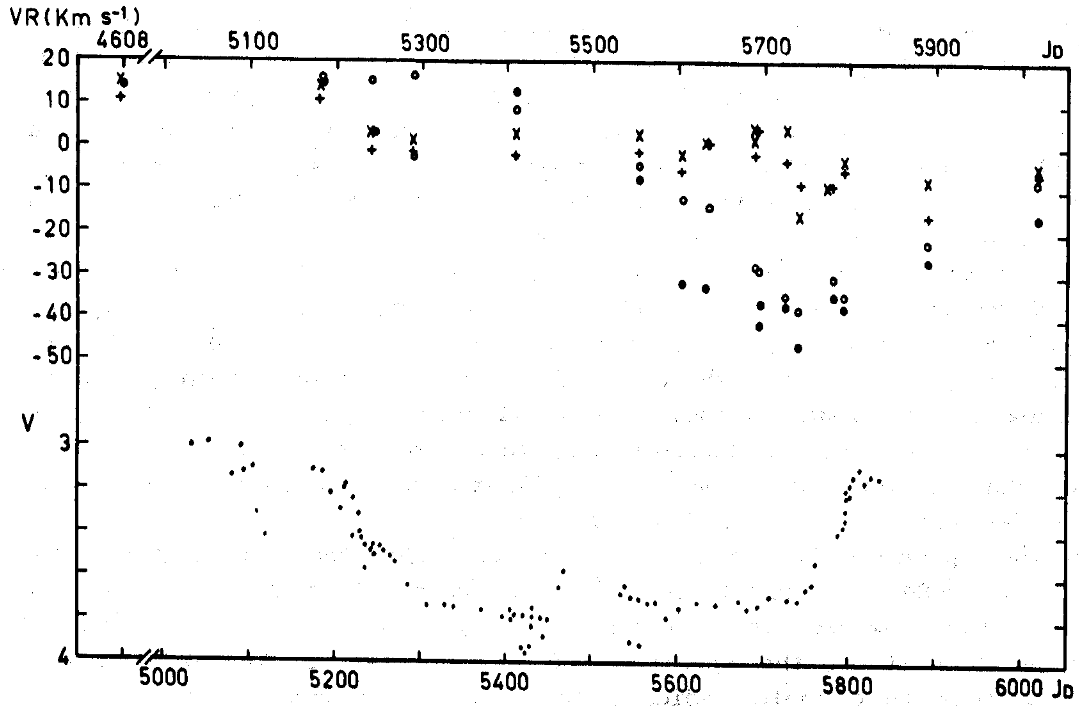

Fig. 2 - The radial velocity curve during the eclipse (together with the V light-curve reported at the bottom for comparison [ε Aur Newsl. 11, 32]). The shell components of Hα, Hβ, Hγ, (●), and of other lines (o), have radial velocities wich are positive on ingress and negative on egress. At the same time the stellar line Mg II λ 4481 (+), and the other lines with dominant stellar component (x), show a remarkably slower variation, due to the orbital motion.

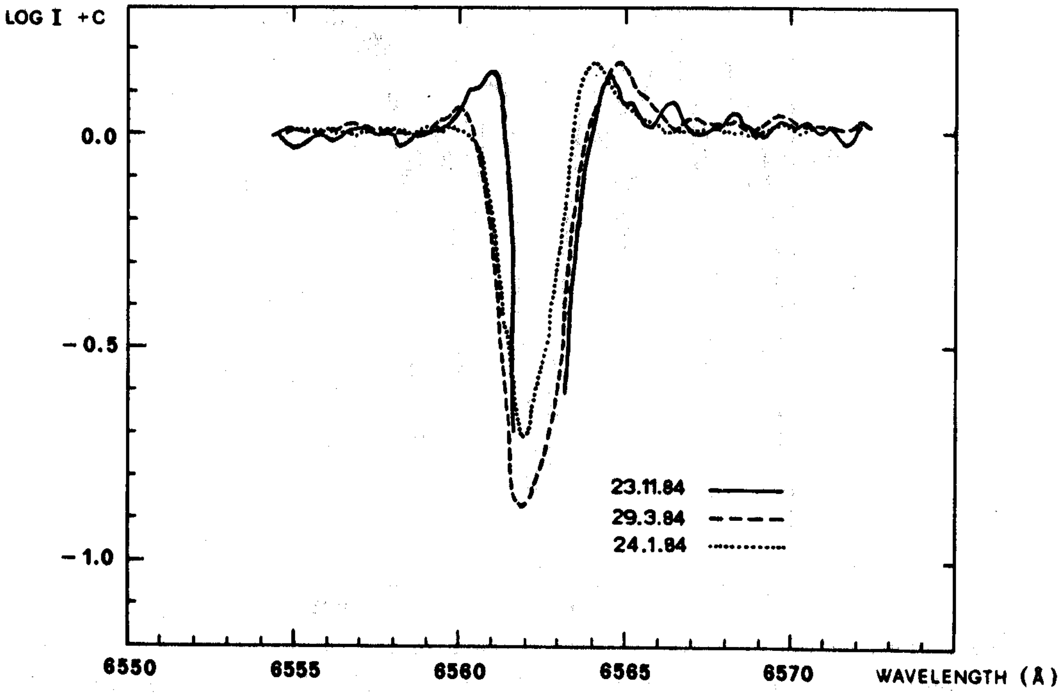

Fig. 3 - The behaviour of H_α at egress. A post-eclipse profile (solid line) is compared with the profiles at egress (dashed) and at early egress (dotted). Profiles on totality are shown in paper I, while the profiles on ingress are given by Boehm, Ferluga, 1984 (IBVS 2326)

light from a part of the shell close to the orbital plane where the density and the rotational velocity are probably higher than above and below the plane.

The strongest lines in the photospheric spectrum, H and K of Ca II, during the partial phases of the eclipse appear to be predominantly due to the FO Ia spectrum, while the contrary is true for the Balmer lines. Moreover, they have a complex structure also out of eclipse . In fact, the spectrum taken in Jan 1981 shows that the H and K lines have a violet-shifted component at about -30 km/s, probably of CS origin, which was observed also by Struve in 1950 (Struve 1951) and by Adams in 1940. The presence of a CS shell is confirmed by the UV emissions O I λ1302 and MgII λ2800 which are not affected by the eclipse.

The general behaviour of H_α (Fig. 3) is very similar to that described by Wright and Kushwaha (1957) during the previous eclipse. The RV of the various absorption components, the half-width and intensity of absorptions and emissions are given in paper I.

During the UV phases of activity observed with IUE the lines of low excitation are weaker, while the lines of higher excitation are not weaker or are just slightly weakened. The weak lines which are all FO Ia photospheric lines (i.e. without shell components) remain unchanged. This suggests (see the next section) that the UV activity of the companion increases the state of excitation of the shell. The same effect can be produced by the activity of a hot spot on the surface of the primary, hypothesized by Parthasarathy and Lambert in 1983 as an alternative explanation of the UV excess observed at λ shorter than about 1600 Å.

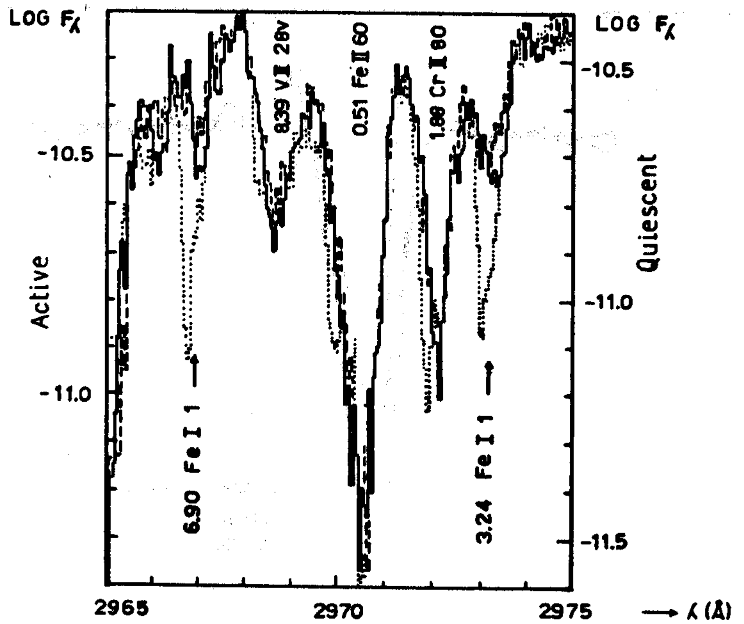

Fig. 4 - Line variations during UV activity. With respect to the quiescent phase on Sep 6, 1984 (······), the profiles of Fe I UV 1 resonance lines are "filled" during activity on March 12, 1982 (———), and they are still more filled during the activity peak on March 26, 1982 (----). Note that the "filling" acts on the doppler-shifted part of the lines.

2. The "active spectrum"

As happens for the depth of the eclipse, also the determination of the shell spectrum, in principle, is affected by the problem of separating the effects of the eclipse from those related with the intrinsic far-UV activity. The influence of this activity, over the spectral lines of the system, can be studied in correspondence of the two active periods which have been observed in the UV since now: the first occurred before the eclipse, on March 1982, while the second occurred during totality, on March 1983. Since for the active period in totality it is difficult, if not impossible, to separate the effects of the eclipse and of the activity, here we shall discuss the pre-eclipse activity period in some detail.

The activity phase in 1982 was the strongest and reached its observed maximum, $\Delta m = 1.75$ mag at 1500 Å, on March 26 (Boehm, Ferluga, Hack, 1984); two weeks before, on March 12, the activity was weaker, $\Delta m = 1.25$ mag at 1500 Å. It is then particularly interesting to compare these two IUE high-resolution spectra, LWR 12777 and LWR 12866, taken in 1982 on March 12 and March 26 respectively (spectral range $\lambda\lambda 2600 \div 3100$ Å); unfortunately, we do not have optical spectrograms at that epoch. Since both spectra are "active", there are no large variations in the line profiles (paper I); but a detailed inspection reveals that some groups of lines appear to change their relative intensities slightly.

In particular, we may notice that, in correspondence of a higher degree of activity, the stronger mid-UV lines of Fe I, such as $\lambda\lambda 2966.9 - 2973.1$ Å resonances or the multiplet V9, seem to be partially "filled". The same thing happens to several low-excitation lines of Ti II, and in particular to the strong low-excitation lines of V II belonging to the multiplets UV 3-10-11-12 (EP $\lesssim 0.4$ eV) and V 26-27-34-42. Also the absorption wings of the Fe II λ 2599 Å resonance line, and particularly the large absorption wings of the Mg II λ 2800 Å resonance doublet, appear to be flattened by the effect of activity. The filling occurs generally on the *red side* of the lines, and on both wings of the Fe II and Mg II resonances; the effect is about 0.2 - 0.3 magnitudes, between March 12 and March 26, 1982. At the same time, the continuum is raised by about 0.1 mag, in the "window" around 3080 - 3087 Å.

Such effects are greatly enlarged, if we compare these *active* pre-eclipse spectra, with a *quiescent* post-eclipse spectrum: in our case let us consider LWP 4158, obtained with IUE at high resolution on September 6, 1984. After overcoming some calibration problems (the last spectrum was taken with a different IUE camera), there still remains a difference of about 0.5 mag, between the mid-UV continuum enhanced by activity (1982), and the quiescent one (1984); then, while the continuum is raised, the behaviour of the line-components of the mid-UV spectrum, with respect to activity, can be classified as follows.

(*i*) *Normal.* The majority of the lines apparently follow the variation of the continuum, increasing their central flux by ~ 0.5 mag in activity, with no remarkable variation in the profile.

(*ii*) *Filled.* This is the case (Fig. 4) of the already-mentioned lines of Fe I, Ti II, V II, and wings of Fe II - Mg II resonance lines, which are filled in pre-eclipse activity by ~ 1 mag. (*)

(*iii*) *Unchanged.* Activity does not affect remarkably the central flux of some high-excitation lines, such as Fe II multiplets UV 62 and higher (EP $\gtrsim 1$ eV), or Cr II multiplets UV 5 and higher (EP $\gtrsim 1.5$ eV); so these lines appear to be deepened, with respect to the enhanced continuum. This effect should be dominant in the far UV, producing the deepening of lines observed at low resolution. Moreover, these lines do not show any remarkable doppler shift depending on activity (or on eclipse phase).

(*iv*) *Circumstellar.* Also the circumstellar emission components of strong resonance lines, such as Fe II λ 2599 Å and Mg II λ 2800 Å, remain unchanged by activity, as well as O I λ 1302 Å (observed in the low-resolution mode).

These observed effects can be easily explained by the presence of an additional spectrum, produced by the source of far-UV variability, and superimposed over the spectrum of the system. This *active spectrum* should be very similar to that of the primary, in order to leave it practically identical; the only difference should be a slightly *higher temperature* (together with the absence of absorption wings in Fe II and Mg II resonance lines).

As a consequence, one would have (*ii*) fainter low-excitation lines, producing the observed filling (and the wings of Fe II and Mg II resonances would be filled as well); moreover, one would also have stronger high-excitation lines, adding no appreciable flux (*iii*) to the underlying stellar spectrum.

(*) Note. The behaviour of an even larger number of low-excitation lines, known to possess a violet-shifted shell component in the post-eclipse spectrum of Sept 1984, is apparently similar. The same behaviour is shown, symmetrically, in the pre-eclipse spectra of March 1982. Just because the shell absorption is weaker at ingress, on comparing a pre-eclipse spectrum with a post-eclipse one, these lines appear to be "filled" on the violet side before the eclipse: this effect has nothing to do with activity, and it should be distinguished from case (ii).

Intermediate situations would generate case (*i*), while circumstellar emission components (*iv*) would clearly remain unaffected. Finally, we note that in case (*ii*) the residual line is not red-shifted in pre-eclipse activity, since the "filling" acts on the *doppler-shifted* part of the line (Fig. 4); also in case (*iii*) there is no shift during activity. This should mean that the hot source is either on the primary, or at the center of the companion, but in any case not rotating with the shell.

3. Conclusions

From the results of the present and previous eclipses of Epsilon Aur it is evident that the spectroscopic and photometric observations are completely explained by the presence of the following bodies:

a) the F0 Ia primary, whose spectrum is always observable;

b) a cool body ($T \sim 500$ K) which is responsible for the photometric eclipse of the primary (Bakman et al., 1984). This dusty disk or ring must be made of particles much larger than those present in the IS dust, because no additional reddening is observed at 2200 Å during the eclipse;

c) a gaseous envelope more extended than the dusty disk, which is responsible for the additional spectrum appearing during the eclipse;

d) an extended envelope surrounding the whole system, where the emissions of OI λ1302 and MgII λ 2800 are formed;

e) a faint hot body which is not eclipsed and whose radiation dominates at $\lambda \lesssim 1500$ Å. In fact the depth of the eclipse tends to become zero at $\lambda \lesssim 1500$ Å, thus indicating that the excess in the UV is real and not due simply to scattered light from longer wavelengths in the spectrum of the primary, or in other-words, it is not simply an instrumental effect. This hot body may be a star (as suggested by Hack and Selvelli, 1979) or a binary system (as suggested by Lissauer and Backman, 1985), whose radiation, escaping from the poles, excites and ionizes the gaseous envelope, producing the shell spectrum; or it may be a hot spot on that part of the surface of the primary which is not occulted by the dusty disk (as suggested by Parthasarathy and Lambert, 1983). The hot body (star, binary system or hot spot) is variable in light.

Acknowledgments

This work is based on observations made at the Haute Provence Obs. (France), and with the IUE satellite from VILSPA (Madrid). Data analysis was performed at the ASTRONET pole of Trieste, Italy.

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EPSILON AURIGAE IN AN EVOLUTIONARY CONTEXT

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ABSTRACT. Basic observational data of Epsilon Aurigae are summarized and used as the basis of a discussion of possible evolutionary states of the system. Constraints posed by the presence of a cold disk surrounding the secondary star are also outlined.

Possible evolutionary models of the F0 Ia supergiant range from pre-main-sequence contraction through shell hydrogen burning, core helium burning, to shell helium burning, depending on the absolute luminosity of the system, for models in which no mass transfer has taken place. Models invoking binary interaction include core and shell helium-burning stars, and pre-white dwarfs, again depending on the absolute luminosity of the system. A massive shell helium burning star or a pre-white dwarf mass transfer remnant would appear the most likely of these models at present. Observational tests of these models are briefly outlined.

1. INTRODUCTION

With an orbital period of 9885 days, Epsilon Aurigae (ε Aur) lies at the long-period extreme of binary star systems which could conceivably undergo mass transfer (see, e.g., Webbink 1979b). That the enigmatic dark secondary in this supergiant (F0 Iap) binary must be highly flattened in profile has long been recognized (Kopal 1954; Hack 1961; see also Ludendorff 1924), a circumstance reminiscent of the accretion disks which commonly occur among interacting binaries (see, e.g., Pringle 1981). In this short paper, we shall therefore explore what evolutionary paths may give rise to an F0 Ia supergiant in a long-period binary.

The basic observational data concerning ε Aur are summarized in Table 1. The effective temperature quoted here for the F0 Iap primary is the mean of the values determined by Castelli (1978) from a fine analysis of its optical spectrum, and by Hack and Selvelli (1979) from

TABLE 1. BASIC DATA

Sp	= F0 Iap	
$T_{eff}^{(1)}$	= 7650 ± 150 K	Castelli 1978; Hack and Selvelli 1979
$T_{eff}^{(2)}$	= 480 ± 45 K	Backman 1985
V	= 3.00	Gyldenkerne 1970
E_{B-V}	= 0.30 ± 0.05	Hack and Selvelli 1979
P	= 9885^d	Huang 1974
r_1	= 0.052	Huang 1974
r_2	= 0.178	Huang 1974
f(m)	= 3.25 ± 0.38 $M_\odot$	Wright 1970
$A_1 \sin i$	= 13.37 ± 0.53 AU	Wright 1970
e	= 0.200 ± 0.034	Wright 1970
π_{rel}	= $-0\farcs0010 \pm 0\farcs0010$	van de Kamp 1978
a_1	= $0\farcs0227 \pm 0\farcs0010$	
i	= 89° ± 3°	

a model atmosphere fitted to its ultraviolet continuum. The temperature attributed to the cool secondary is that characterizing the infrared excess of this system. It is, of course, a well-known quandary that no contribution from the secondary is detected anywhere in the optical or ultraviolet flux distribution of this system (except possibly at wavelengths $\lesssim$1600 Å -- Hack and Selvelli 1979; Parthasarathy and Lambert 1983; Boehm, Ferluga, and Hack 1984). Finally, it should be noted that the fractional radii for the two components quoted here from Huang (1974) are those for his thick-disk model for the cool secondary. Somewhat different values, most notably smaller r_1, were deduced by Wilson (1971) from a thin-disk model.

By equating the spectroscopic and astrometric orbital semimajor axes of the primary, a distance to ε Aur can be derived (van de Kamp 1978), and the absolute parameters of the primary component thereby fixed. The resultant values are listed in Table 2. The mass limit for the primary quoted here follows from an upper limit to its surface gravity (log g < 1.5) dictated by its Ia luminosity classification.

TABLE 2. DERIVED DATA

$d = 578 \pm 51$ pc

$M_V = -6.74 \pm 0.30$

$\log L_1/L_\odot = 4.54 \pm 0.12$

$\log R_1/R_\odot = 2.02 \pm 0.06$

$\log M_1/M_\odot \lesssim 1.11 \pm 0.13$

2. THE COOL DISK

Although very little is known at present about the properties of the disk-like eclipsing object, its mere existence as well as its state could, in principle, place serious constraints on the evolutionary states of the binary. A few of these are summarized here.

First, we note that the infrared temperature deduced for the disk is consistent with its having little or no internal energy sources whatever, but radiating primarily reprocessed light from the supergiant primary. For a thin disk of small radius relative to the orbital separation, A, and irradiated by a spherical star of effective temperature T_1 and radius $R_1 = r_1 A$ lying in the plane of the disk, the equilibrium temperature of the disk is

$$T_d = \left(\frac{r_1^3}{6\pi}\right)^{1/4} T_1 \quad .$$

In the case of ε Aur, the data of Table 1 lead to an expected disk temperature of $T_d = 400 \pm 10$ K, which is comparable with the temperature characterizing the infrared excess. From considerations of vertical hydrostatic equilibrium, we would expect the ratio of thickness h to radius r of a gaseous disk should be of the same order as the ratio of sound speed c_s to orbital velocity v_{orb}. At this temperature $c_s \approx 2.5$ km s^{-1}, and at the outer edge of the disk $v_{orb} \approx 25$ km s^{-1}, giving an aspect ratio $h/r \approx 0.1$ which is in good agreement with that deduced by Huang (1974) for his thick-disk model. It should be noted, however, that the grains, which presumably constitute the dominant opacity source for the disk, could nevertheless settle to a thin layer at the midplane of the disk, depending upon their sizes, the gas density of the disk, and the degree of turbulence in the disk.

The low disk temperature also implies a fairly small net accretion rate through the disk. For a steady-state disk (a reasonable approximation for disks older than their various timescales -- see

Lynden-Bell and Pringle 1974),

$$\dot{M} \approx \frac{8\pi \mathfrak{F}(R)\, R^3}{3G\, M_2} \quad ,$$

where $\mathfrak{F}(R)$ is the net surface brightness of the disk (energy radiated minus that intercepted, per unit area). Applying this relationship at one-half the disk radius, with

$$\mathfrak{F}(R) \lesssim \sigma T_2^4$$

over most of the disk, we deduce

$$\dot{M} \lesssim 10^{-7}\ M_{\odot}\ \mathrm{yr}^{-1} \quad .$$

A similar limit follows from the weakness of the excess ultraviolet emission shortward of 1600 Å (see, e.g., the symbiotic star models of Kenyon and Webbink 1984).

A lower limit to the age of the disk can be derived from standard accretion disk theory (Shakura and Syunyaev 1973; Pringle and Rees 1972). The timescale characterizing decay of the disk is the viscous timescale:

$$\tau_\nu \approx \frac{r^2}{\alpha\, \Omega_{orb}\, h^2} \quad ,$$

where r and h are the disk radius and thickness, as above, Ω_{orb} is the orbital angular frequency of the disk, and α is a dimensionless parameter (the ratio of viscous stress to gas pressure) which must be $\lesssim 1$. The mass flux through the inner disk is controlled by conditions at its outer edge, where, for ε Aur, we obtain an estimate $\tau_\nu \approx 200\ \alpha^{-1}$ yr. Values of α deduced from observations of cataclysmic variable stars ($\alpha \approx 0.1$; Pringle 1981) would suggest that the disk in ε Aur must be at least a few millenia old.

A lower limit to the mass of the disk can be estimated from its projected surface area. We assume its opacity arises from grains, which must have dimensions $r_g \gtrsim 10^{-2}$ cm in order to produce the gray eclipses which are observed. For a projected disk area comparable to that of the primary, with grains of density $\rho_g \approx 3$ g cm^{-3}, a total mass in grains of $M_g \gtrsim 5 \times 10^{24}$ g is indicated. At solar abundances, with all refractory materials condensed into grains, this grain mass corresponds to a total disk mass $M_d \gtrsim 10^{27}$ g. This value is within an order of magnitude or so of the product of the limits obtained above for the accretion rate and disk decay timescale.

3. EVOLUTIONARY STATUS OF THE SUPERGIANT

Strictly speaking, the MK spectral classification of the supergiant fixes only its effective temperature and surface gravity within certain limits. The mass of that component is constrained only by the further introduction of information regarding its distance or absolute dimensions, as in Table 2. It is clear from that table that wide latitude remains in the masses which would satisfy available constraints on ε Aur.

There are in fact a number of possible evolutionary phases in which a star, evolving either singly, or as a member of a close binary system, may pass through an F0 supergiant state. These possible evolutionary states are summarized in Table 3 for three assumed values of the luminosity of the supergiant. These luminosities bracket that deduced above in Table 2 and allow for the possibility that the distance to ε Aur deduced there is still significantly in error. Those models corresponding to mass transfer remnants are listed in boldface type. The table lists, for each solution, logarithms of: M_1, the mass of the supergiant (in solar units); g_1, its surface gravity (in cm s^{-2}); $\tau_T \equiv |T_1/\dot{T}_1|$, the timescale (in years) on which its effective temperature

TABLE 3. POSSIBLE EVOLUTIONARY STATES OF ε Aur

State	log M_1	log g_1	log τ_T	log t_d	log M_2	log $L_{2,0}$
			log $L_1/L_\odot$ = 5.00			
1a Pre-ms	1.48	1.41	3.2 (+)	2.90	1.31	4.71
1d He shell	1.24	1.16	4.7 (-)	6.98	1.18	4.32
			log $L_1/L_\odot$ = 4.50			
1a Pre-ms	1.26	1.69	3.6 (+)	3.32	1.19	4.36
1d He shell	1.06	1.49	4.8 (-)	7.23	1.09	4.04
2c Pre-wd	**0.00**	**0.43**	**3.7:(+)**	**3.7:**	**0.68**	**2.70**
			log $L_1/L_\odot$ = 4.00			
1a Pre-ms	1.09	2.02	4.1 (+)	3.76	1.10	4.08
1b H shell	1.01	1.93	5.0 (-)	7.27	1.06	3.96
1c He core	0.94	1.86	5.1 (+)	7.38	1.03	3.85
1d He shell	0.90	1.83	5.1 (-)	7.50	1.01	3.81
2a He ign	**0.24**	**1.17**	**4.5 (+)**	**4.98**	**0.75**	**2.95**
2b He shell	**0.16**	**1.08**	**5.3 (-)**	**6.87**	**0.72**	**2.86**
2c Pre-wd	**-0.14**	**0.79**	**4.5:(+)**	**4.4:**	**0.65**	**2.60**

is evolving, together with an indication whether T_1 is increasing (+) or decreasing (-); t_d, the age of the disk around the secondary component (in years), presumed to be the interval of time since the supergiant component last filled its Roche lobe or since it last reached its maximum radius, as the case may be; M_2, the mass of the secondary (in solar units), as deduced from the spectroscopic mass function and astrometric orbital inclination; and $L_{2,0}$, the luminosity (in solar units) such a secondary would have on the zero age main sequence. The values in this table assume a solar-type composition, and have been interpolated from the calculations of Iben (1965,1966,1972); Lamb, Iben, and Howard (1976); Becker, Iben, and Tuggle (1977); and, for the mass-transfer remnants, Iben and Tutukov (1985). Briefly, the evolutionary stages indicated in the first column of this table are:

(1a) Approach to the main sequence. This interpretation (see, e.g., Kopal 1971) would make ε Aur very young indeed. It may be rejected on several counts: First, ε Aur lies near no known star-forming region. Second, the masses implied for the secondary are all comparable with or slightly smaller than that of the primary. Since the time required to reach the main sequence increases with decreasing mass (e.g., Iben 1965), the secondary could not have contracted to a significantly smaller radius than the primary, as observations appear to demand, even in the event that the secondary is itself double (see below). Finally, except at the highest luminosity (where the age of the disk is unacceptably short), the surface gravities expected for the supergiant would place it in luminosity class Iab or Ib, not Ia as found observationally.

(1b) Shell hydrogen burning. For $\log L/L_\odot \lesssim 4.3$, a star of intermediate mass ($\sim$8-12 $M_\odot$) and solar composition passes through the F0 supergiant region prior to helium ignition (e.g., Iben 1966). The expected surface gravity of the supergiant would again place it in luminosity class Iab or Ib, and, as with all models do not invoke mass transfer, the expected luminosity of the secondary is uncomfortably large.

(1c) Core helium burning. Stars which pass through stage (1a) loop backwards to the blue in the Hertzsprung-Russell (HR) diagram following core helium ignition, passing through the Cepheid instability strip as they do so. The evolutionary tracks of these models may be quite complicated and highly sensitive to the initial composition (see, e.g., Becker, Iben, and Tuggle 1977), and they may loop through the F0 supergiant region more than once; but, except for the values of τ_T, all such models have properties (and weaknesses) practically identical to those expected for case (1b) above. In particular, solutions of this type require $\log L_1/L_\odot \lesssim 4.3$, which would place ε Aur at a distance $d \lesssim 440$ pc, with a luminosity class Iab or Ib.

(1d) Shell helium burning. Stars with masses above $\sim$12 $M_\odot$ undergo core helium burning before ever reaching F0 supergiant dimensions (Lamb, Iben, and Howard 1976), and those of somewhat smaller masses (as in case 1c above) do so at the high-temperature ends of their blue loops in the HR diagram. They then evolve redward through the F0 supergiant during or following core helium exhaustion and the readjustment to shell helium burning. Such models span the entire range of luminosities of interest, and at higher luminosities ($\log L_1/L_\odot \gtrsim 4.5$) have suitably low surface gravities. Their lifetimes in the F0 supergiant band are at least an order of magnitude longer than those characterizing pre-main sequence models of equal luminosity, making this configuration inherently more likely. However, as in the cases discussed above, it is difficult to understand the low relative luminosity of the secondary.

On this last count, those models interpreting ε Aur as a mass-transfer remnant fare much better, as they imply much lower masses for the F0 supergiant, and correspondingly lower masses for the secondary, at a given luminosity. The lower mass assigned to the supergiant also removes any difficulty with the luminosity class assigned to ε Aur: all post-mass transfer supergiants in the luminosity range of interest have very low (class Ia) surface gravities (see Table 3). The possible models summarized in Table 3 are:

(2a) Core helium ignition. In many ways, this is an analogue to case (1c) above. A star of initial mass 8-12 $M_\odot$ in this case fills its Roche lobe and is stripped nearly to its helium core. The star then contracts toward the helium main sequence (see Iben and Tutukov 1985), passing through the F0 supergiant region. There are, however, a number of difficulties with this interpretation: As in cases (1b) and (1c) above, models of this type are limited to lower luminosities ($\log L_1/L_\odot \lesssim 4.3$), again because more massive initial primaries would have passed through core helium burning before ever becoming as red as spectral type F0. Second, single stars in this initial mass range reach maximum radii of ~500 $R_\odot$ at most (Webbink 1979b, Iben and Tutukov 1985), and hence can fill their Roche lobes only for initial orbital periods $P \lesssim 1000^d$; a further increase in orbital period by a factor of 10 would require that the system have lost roughly 70 percent of its total mass in a stellar wind within the ~10^5 years since it last filled its Roche lobe. Mass loss of this magnitude is excluded by the fact that the present secondary component is at least half as massive as the initial primary.

(2b) Shell helium burning. The helium star remnant of case (2a) will, upon core helium exhaustion, once again progress far to the right in the HR diagram (Paczynski 1971; Iben and Tutukov 1985). Aside from the presumed age of the disk, and a much slower traversal of the F0 supergiant band, models of this sort possess the same general properties and difficulties as those of type (2a). They are of course similarly limited to total luminosities $\log L_1/L_\odot \lesssim 4.3$.

(2c) Pre-white dwarf. This is the evolutionary state of the supergiant suggested by Eggleton and Pringle (1985), and corresponds to a primary star in a double-shell-burning phase which has been stripped nearly completely of its hydrogen envelope. Asymptotic giant branch stars with core masses of ~1.0 $M_\odot$ are indeed capable of filling their Roche lobes at 10^4-day orbital periods, so the difficulties concerning excessive mass loss in a stellar wind which appeared in cases (2a) and (2b) do not pertain here. Depending upon the degree of systemic mass loss in this case, significantly lower-mass progenitor stars may be allowed for the primary. An additional virtue of this model is that it requires a lower-luminosity secondary star than any of the others discussed above. It does, however, imply that the F0 supergiant is in a relatively rapidly evolving state, compared, for example, to model (1d) above.

In summary, it appears that the most viable models for the supergiant in ε Aur are, first, the traditional interpretation in terms of a relatively massive, post-main-sequence star in a state of shell helium burning, or, second, one in which the supergiant is contracting toward a white dwarf state, having been stripped of most of its hydrogen-rich envelope by a combination of tidal mass transfer to the secondary component and mass loss in a stellar wind. The latter model accounts much more successfully for the large luminosity difference between the components, but it also implies that ε Aur is in a much more rapidly evolving state than does the former.

4. EPSILON AURIGAE AS A CLOSE TRIPLE SYSTEM

Recently, it has been speculated that the under-luminous secondary component in ε Aur may itself be binary. On the one hand, by subdividing the mass of that component, its expected intrinsic luminosity could be reduced by a factor of as much as 5 (Lissauer and Backman 1984). On the other, a binary central object could also act as an energy and angular momentum source to the disk, strongly inhibiting its decay while at the same time maintaining it at relatively large thickness by gravitational agitation (Eggleton and Pringle 1985).

The hypothesis of a binary secondary component carries an additional benefit for those interpretations of this system as a post-mass-transfer object. In these models, the primary would have filled its Roche lobe after reaching the giant or asymptotic giant branch, with a deep convective envelope. This tends to be a violently unstable situation. Hydrostatic equilibrium at the base of a deep envelope requires that pressure, P, scale as $P \sim M^2/R^4$. Adiabatic convective equilibrium, on the other hand, gives $P \sim \rho^{5/3}$ (for an ideal gas), or $P \sim M^{5/3}/R^3$. It follows that the adiabatic response of the star to mass is to expand, with $R \sim M^{-1/3}$. At the same time, the Roche lobe radius varies with mass roughly as

$$\frac{d \ell n R_L}{d \ell n M} \approx 2 q - \frac{5}{3} \quad ,$$

where q is the mass ratio (mass of the lobe-filling star divided by that of its companion. It follows that the Roche lobe increases in radius with decreasing mass fast enough to accommodate the hydrostatic response of the lobe-filling star only if $q \leq 2/3$, i.e., the lobe-filling star is significantly less massive than its companion. Otherwise mass transfer tends to proceed on a dynamical timescale, and catastrophic losses of systemic mass and angular momentum probably ensue (Meyer and Meyer-Hofmeister 1979; Webbink 1979a). Thus, splitting the secondary's mass between two stars permits the primary star to be at the same time the most massive of the three (and hence first to evolve), and also sufficiently less massive than the total mass of the secondary (and hence stable against dynamical mass transfer).

How common are such triple systems? The system HD 157978/9 which Eggleton and Pringle (1985) chose as their prototype is in fact only one of 26 known close triple systems (i.e., close enough for all three stars to interact during their lifetimes) in the survey by Fekel (1981). Of these, all but five appear in the Bright Star Catalogue, and in at least one-third of these systems the distant member is the most massive component of the system. Considering the profound difficulty in detecting close triple systems, especially among fainter stars, Fekel's list is undoubtedly very incomplete. Considerations of dynamical stability (which limits allowable period ratios in close triple systems), the hierarchical structure of multiple star systems (e.g., Batten 1973), and the distribution of binary and multiple systems in orbital period (Abt and Levy 1976, 1978) yield a very rough estimate that close triple systems occur with perhaps 10 percent of the frequency of close binary systems. Models of ε Aur as a triple system are therefore not at all inherently implausible.

5. OBSERVATIONAL NEEDS

As indicated above, the number and types of possible evolutionary models of ε Aur depend crucially on an accurate estimate of its distance, and hence of its absolute dimensions. The fact that both spectroscopic and astrometric orbits can be measured is an extremely powerful tool for this purpose, but significant differences remain in the orbits obtained by these methods. The radial velocity solutions may be strongly affected by intrinsic pulsations of the supergiant itself, and the reality of the measured orbital eccentricity is open to some doubt on this account. The astrometric orbit is quite small, and vulnerable to a variety of long-term systematic errors, given that it is based on only slightly more than one complete orbit. A simultaneous solution for both spectroscopic and astrometric orbits could provide a more realistic assessment of the uncertainty in the distance and absolute dimensions of the system.

As a rule, post-mass-transfer models of ε Aur predict that its atmosphere should be depleted in hydrogen and oxygen, and enhanced in helium and nitrogen, with carbon possibly either enhanced or depleted (see, e.g., Iben and Tutukov 1985). The fine analyses by Castelli

(1978) and Castelli, Hoekstra, and Kondo (1982) give some evidence of enhancement relative to hydrogen elements from Si to Ba in ε Aur, compared with φ Cas, another F0 Ia star. This result is quite uncertain, however, because the hydrogen Balmer lines are themselves contaminated by emission. Modeling of the ultraviolet spectrum at shorter wavelengths could yield abundances for carbon and oxygen, and possibly nitrogen, and infrared spectroscopy of the Paschen or Brackett lines might resolve the uncertainty in the hydrogen abundance itself. It should also be noted that mass-transfer-remnant models also yield surface gravities an order of magnitude smaller than those predicted for massive supergiant models. A quantitative spectroscopic determination of log g could thus prove immensely valuable.

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PHOTOMETRIC SUPPORT FOR FUTURE ASTRONOMICAL RESEARCH

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The purpose of this paper is to describe I.A.P.P.P. and how that organization can provide photometric support for future astronomical research projects such as the 1982-1984 eclipse of epsilon Aurigae discussed at this Workshop.

I.A.P.P.P., the initials standing for International Amateur-Professional Photoelectric Photometry, is an organization founded in Fairborn, Ohio by the authors in 1980. Its purpose is to encourage contact between amateur and professional astronomers interested in photoelectric photometry, for their mutual benefit and for the benefit of astronomical research. Aspects dealt with include instrumentation, electronics, computer hardware and software, observing techniques, data reduction, and observing programs. Starting with the June 1980 issue, I.A.P.P.P. has published the quarterly I.A.P.P.P. Communications. The Communications contain articles dealing with all the above aspects of photoelectric photometry, although it does not publish observational results as such. Photoelectric photometry obtained by amateurs is published in the same journals which publish photometry obtained by professionals. Additional communication between amateurs and professionals continues via telephone conversations, correspondence, one- on-one visits, and symposia and workshops which are held in various parts of this country and in several other countries.

Originally it was envisaged that typically amateurs would work on photoelectric observing projects described by professionals in articles in the Communications. This has proven true, especially on projects which small telescopes in backyard observatories can do best: stars too bright for large telescopes, variables with periods too long for complete coverage during short observing runs at Kitt Peak or other national observatories, and projects where wide geographical distribution is an asset: ground-based support for scheduled pointings of satellites like I.U.E. and H.E.A.O., 24-hour coverage of complicated binaries like beta Lyrae, unpredicted transient events like Nova Cygni 1975, and asteroid occultations where tens of kilometers on the Earth's surface are important. Recently, however, a significant switch in roles has occurred. Amateur astronomers who are professionals in relevant fields such as electrical engineering have made contributions to photoelectric photometry which are so valuable that professional astronomers are learning from them. An excellent example of this is the automatic photoelectric telescope developed recently by Louis J. Boyd (Boyd, Genet, Hall 1984a) and discussed at the I.A.P.P.P. Symposium held in Phoenix prior to the 165th A.A.S. meeting in Tucson.

I.A.P.P.P. has in excess of 500 members in more than 40 countries in 6 of the 7 continents. They are divided roughly 50/50 between amateurs and professionals. The December 1984 issue of the Communications was the 18th published to date. Observing projects described in the Communications have included variable stars (eclipsing binaries, Be stars, Mira variables, RV Tau variables, RS CVn variables, symbiotic variables, Cepheids), times of minimum and maximum, tumbling asteroids, the Moon, comets, asteroid and lunar occultations, galaxy nuclei, atmospheric extinction, and light pollution. Amateur telescopes equipped for photoelectric photometry and responsible for published photometric data range in aperture from 4 inches to 24 inches. A regular feature in the Communications is a listing of papers co-authored by amateurs and presenting observational results of their photoelectric photometry. To date over 120 such papers have appeared in 15 different astronomical publications. Another measure of scientific productivity, although admittedly only one such measure, is the total of 34 new variable stars discovered as a result of photoelectric photometry by amateurs. All of them are quite bright (about 2/3 are in the Yale Bright Star Catalogue) and quite a few (such as HR 1099) are important stars now well known to many astronomers. The photometric periods range from as short as 1.07 days to as long as 140.8 days. The total light variation shown by one of these new variables was only 0.01 magnitude. Amateur astronomers can achieve photoelectric accuracy equal to that of professionals. One example is the light curve of HR 1063, a helium-rich B-type star with a total amplitude of only 0.02 magnitude in V, obtained by Howard J. Landis and Howard Louth. The rms deviation from a best fit curve (Landis, Louth, Hall 1985) was only ± 0.003 magnitude and any systematic difference between Landis and Louth was less than 0.001 magnitude, indicative of the best photoelectric photometry professionals are capable of achieving on a regular basis.

Subscriptions to the quarterly I.A.P.P.P. Communications, at present still $15.00 per year, can be obtained by contacting Assistant Editor Robert C. Reisenweber, Rolling Ridge Observatory, 3621 Ridge Parkway, Erie, Pennsylvania 16510.

This recent epsilon Aurigae campaign is a prime example of what I.A.P.P.P. can do. Dana Backman made the first contact with I.A.P.P.P. After consultation with Mirek Plavec and Brad Wood, the 1982-1984 epsilon Aurigae campaign was officially announced by Genet and Stencel (1981), with I.A.P.P.P. taking responsibility for the photometry. Actual coordination of photometry and compilation of results was taken over by Jeffrey L. Hopkins, who edited and distributed most of the Epsilon Aurigae Campaign Newsletters. It is significant that, whereas photometry of the 1955-1957 eclipse (Gyldenkerne 1970) included NO observations made by amateur astronomers, photometry of the 1982-1984 eclipse was provided PREDOMINANTLY by amateurs and the light curve would have gone virtually unobserved had the professional astronomical community been relied upon exclusively.

One of the contributed papers at this Workshop was a presentation of the UBV photometry made by the automatic photoelectric telescope of Louis J. Boyd in Phoenix, Arizona, a superlative example of what can be done by an active amateur working through I.A.P.P.P. in collaboration with other astronomers. It observed virtually continuously (except when epsilon Aurigae was blocked by the Sun) for more than one year, producing differential measures accurate to approximately ±0.01 magnitude. Although not included in any of the Epsilon Aurigae Campaign Newsletters, these measures have been published in two papers by Boyd, Genet, and Hall (1984b, 1985).

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CONTRIBUTED PAPERS

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

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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		Observed Time	
	Date	JD	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 ℓ_D be the distance from the observer to the deflector star responsible for the lensing, and let ℓ_{CD} 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

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

where $\mu = 1+(\ell_D/\ell_{CD})$, 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 μ is important to the possibility of seeing a lens effect in a binary system. For close binaries with small separations, μ becomes so large that Θ is very small. Perhaps in wide binaries, such as Epsilon Aurigae, the value of μ is small enough to permit a lens to occur. Inserting the constants c and G and transforming the units of measurement, equation 1 becomes

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

where Θ is measured in milliseconds of arc (mas), $\mathcal{M}$ is in solar masses, ℓ_D is in parsecs, and ℓ_{CD} in astronomical units. For Epsilon Aurigae the following values are assumed: $\mathcal{M} = 3.5 \mathcal{M}_\odot$, ℓ_D=600pc, and ℓ_{CD}=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 Θ=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.

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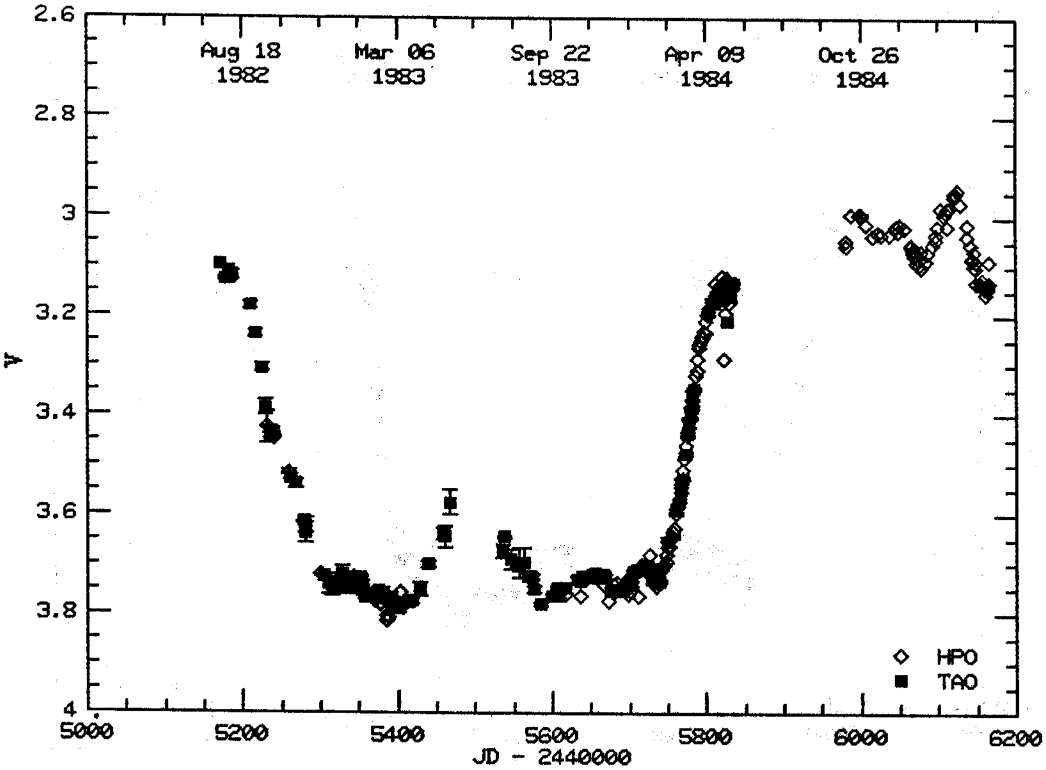

Fig. 1. V light curve of the 1982-4 eclipse of Epsilon Aurigae.

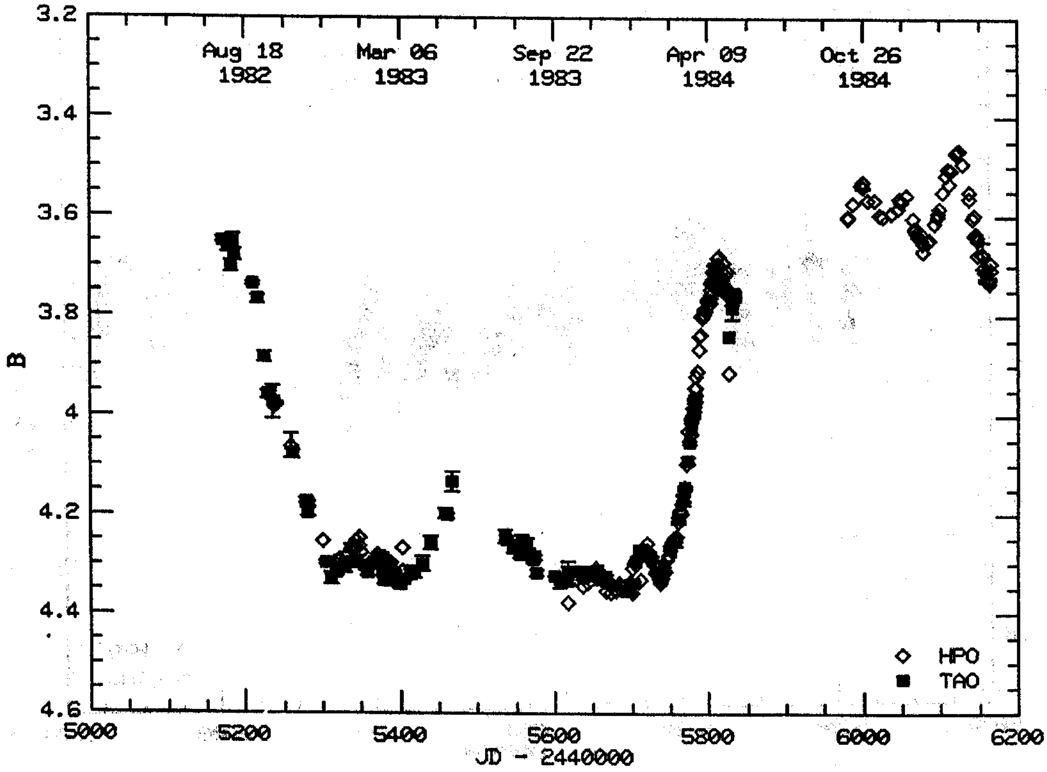

Fig. 2. B light curve of the 1982-4 eclipse of Epsilon Aurigae.

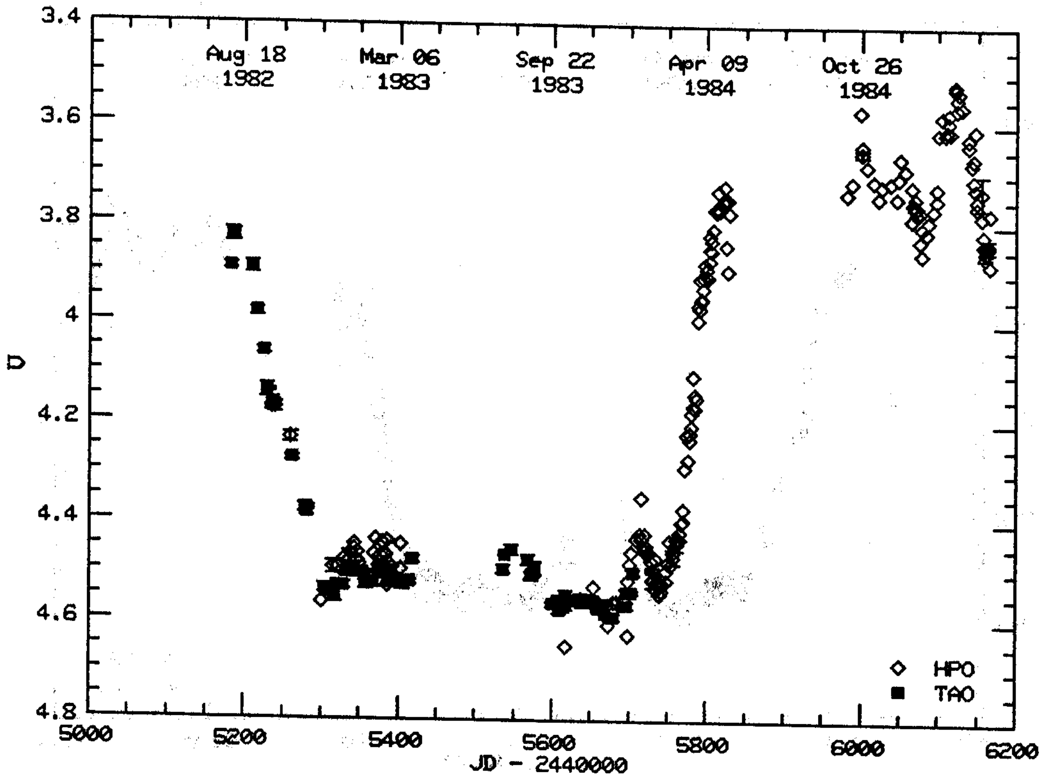

Fig. 3. U light curve of the 1982-4 eclipse of Epsilon Aurigae.

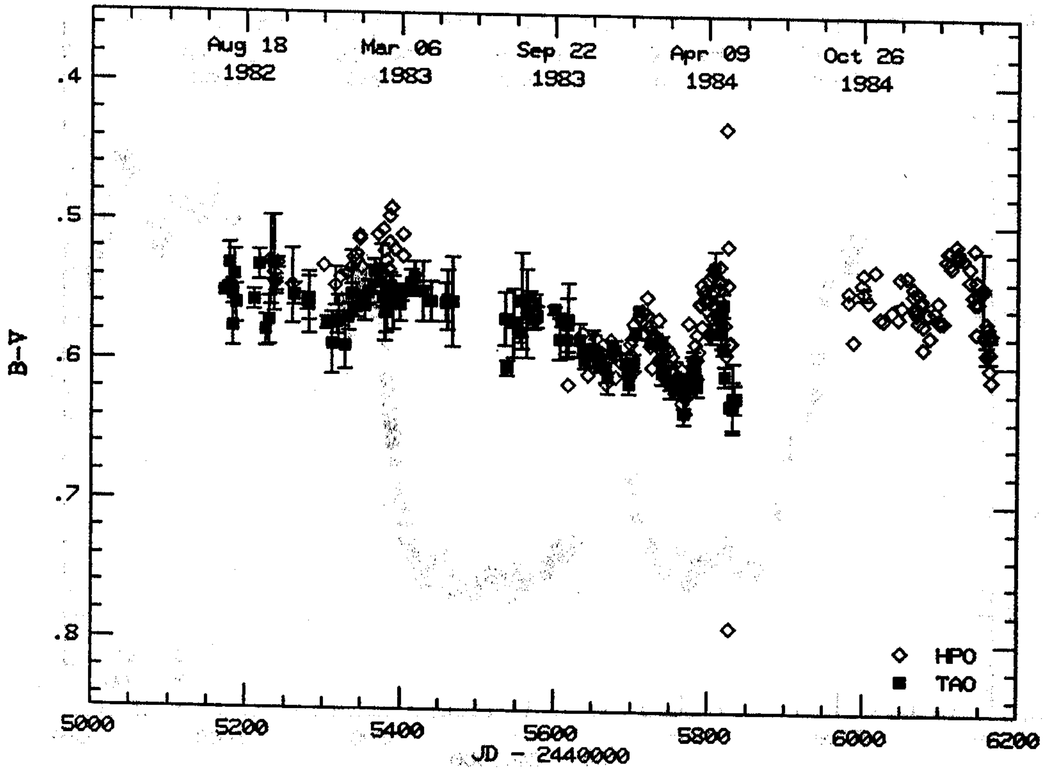

Fig. 4. (B-V) light curve of the 1982-4 eclipse of Epsilon Aurigae.

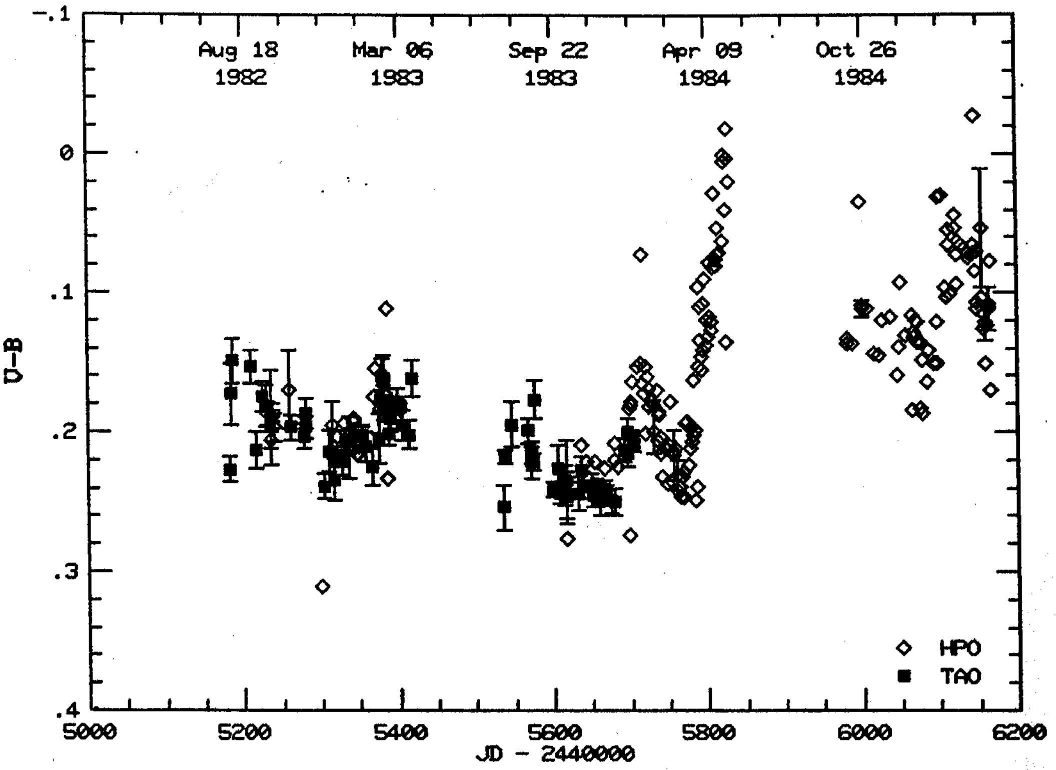

Fig. 5. (U-B) light curve of the 1982-4 eclipse of Epsilon Aurigae.

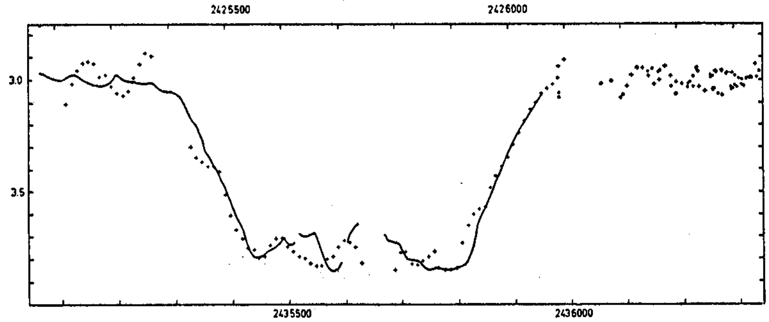

Fig. 6. The 1928-30 light-curve (plus signs, upper abscissa scale) superposed upon the 1955-57 light-curve (smooth curve, dots in post-eclipse phases; lower abscissa scale). The ordinate scale represents V for the 1955-57 eclipse. From Gyldenkerne (1970).

Contributed paper

Intermediate and Narrow Band Photometry of Epsilon Aurigae

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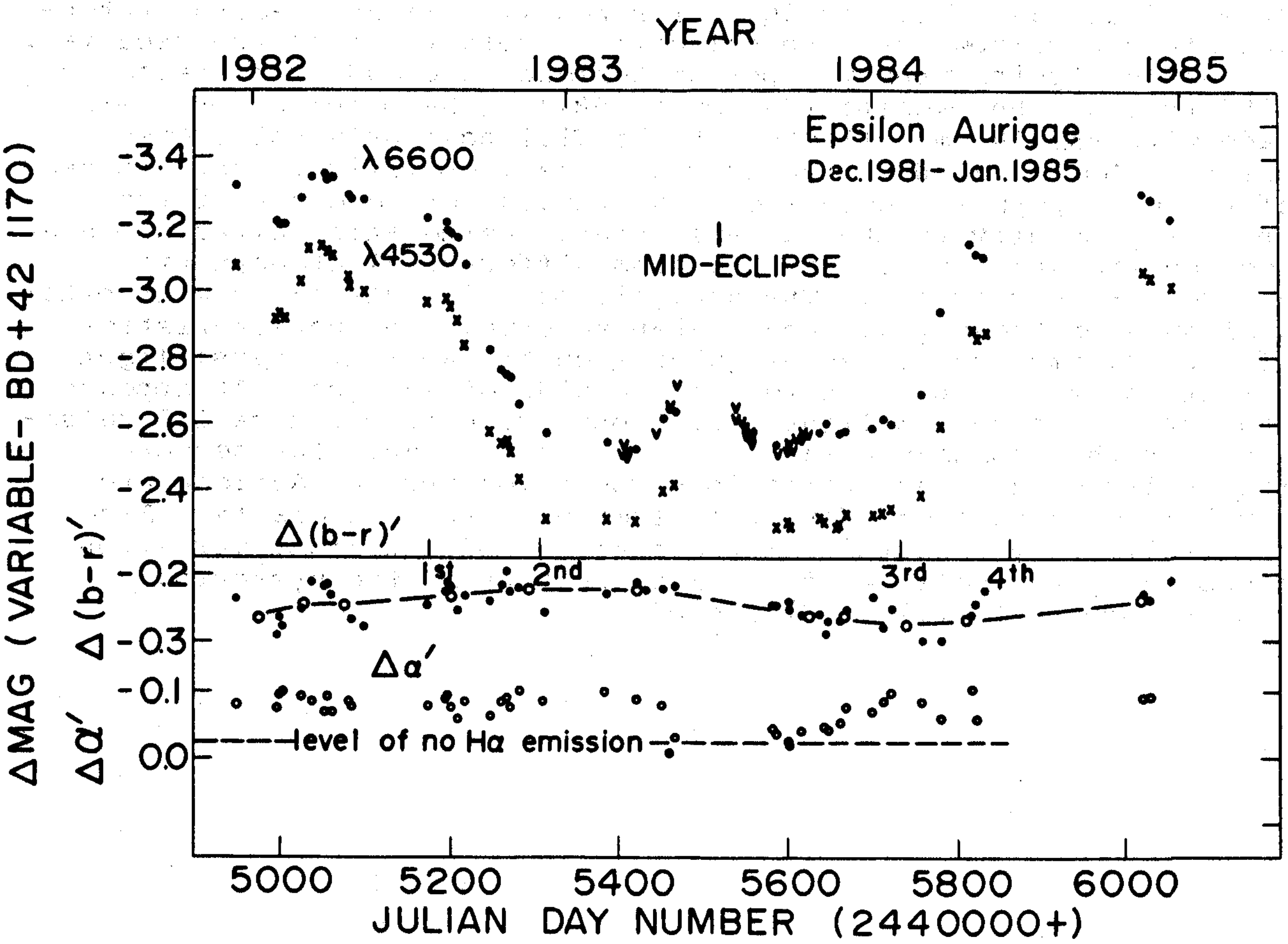
Intermediate-band blue (4530A), far red (7790A) and H-alpha intermediate and narrow band photoelectric observations of the peculiar, 27 year eclipsing binary, Epsilon Aurigae were made from December 1981 through the present (December 1984). The observations were made with the 38 cm reflector at the Villanova University Observatory. BD +42 1170 served as the primary comparison star (instead of the more popular comparison star Lambda Aur) because of its angular proximity to the variable star. Using this comparison star reduced the uncertainty arising from differential atmospheric extinction corrections. The analysis of this data along with other available photometry was undertaken to study the characteristics of the low amplitude, semi-regular (roughly 80 - 120 days) light variations that appear inside and outside of eclipse. It appears that these short-term light variations arise from non-radial pulsations of the luminous F supergiant in the system. Furthermore, the semi-regular light variations found for Epsilon Aurigae are similar to those found for other luminous A-F supergiants. Also, the preliminary results from the analyses of the light variations produced by the eclipse of the F-supergiant by the mysterious cooler component will be discussed.

Donovan
Guinan 1985
McCook



Contributed paper

Spectrophotometry of ε Aur, 3295-8880 A

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and J. Sowell (University of Michigan)

We obtained spectrophotometric scans at 8 A resolution from 3295 to 8880 A on twenty nights before, during, and after the recent eclipse of ε Aurigae, beginning with a pre-eclipse observation on 5 March 1982 U.T. The observations were reduced to absolute flux using the standard stars 109 Vir or ξ^2 Ceti. Our data confirm that the eclipse is essentially gray over the entire visible spectrum, as others have noted from broadband photometry. High-resolution echellograms (4500-6700 A) made through mid-eclipse and the scans show changes in the equivalent widths of Hα, Na D, and O I as large as a factor of two.

ABSTRACT

2μm CO in the Eclipse Spectrum of ϵ Aur

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The 2μm spectrum of ϵ Aur was observed at high resolution ($\lambda/\Delta\lambda \sim 40000$) with the KPNO 4m telescope and FTS approximately every 100 days during the recent eclipse. CO $\Delta v=2$ lines appeared in the spectrum only after mid-totality. No CO features were present JD 2445478 but weak absorption lines were present on 2445592. The CO strengthened in the spectrum and remained present until at least 2445812. CO was again absent after forth contact when the spectrum was observed on 2445912. The CO appears to originate in a cool ($\sim 10^3$ K), turbulent region. Excitation temperatures, velocities, and column densities will be presented.

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[1] Operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

Scattered Light in the IUE Spectra of ϵ Aurigae

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1. Introduction

Observations of the ϵ Aurigae system early in the International Ultraviolet Explorer (IUE) program revealed an apparent UV excess shortward of 1500Å which was interpreted as the contribution of a hot dwarf companion (Hack and Selvelli 1979). Further observation, both before and during the ensuing eclipse cycle, revealed that the source of the UV excess was highly variable (Boehm, Ferluga and Hack 1984). However, as demonstrated by several researchers (Clarke 1981; Crivellari and Praderie 1982; Basri, Clarke, and Haisch 1985, hereafter BCH) the IUE cross-disperser grating acts to redistribute a measurable percentage of the longer wavelength light into the range of the short wavelength prime (SWP) camera, causing errors in both line and continuum flux levels in the uncorrected spectra.

There have been earlier attempts to correct the ϵ Aurigae IUE spectra for scattered light. Hack and Selvelli (1979) subtracted 500 flux units (FN) from the entire spectrum, treating the scattering as if it were a uniform background contamination, independent of wavelength. Parthasarathay and Lambert (1983) also recognized that scattered light might be important in establishing the properties, and indeed the very existence, of a hot companion. They used the descattering methods suggested by Clarke (1981) and Crivellari et al. (1980) and concluded that the signal shortward of 1250 Å was purely scattered light. They also suggested several alternatives to the hot companion model for the remaining UV excess shortward of 1600 Å (see section 4).

It is clearly of crucial importance to our understanding of the nature of the UV excess that we carefully evaluate the level of scattered light contributing to it. In order to do so we have applied the BCH algorithm to a number of low dispersion IUE spectra of ϵ Aurigae from very early pre-eclipse through the most recent post-eclipse epochs. As noted in BCH, scattered light is most significant when there is a great deal of contrast between adjacent spectral regions. Indeed, ϵ Aurigae has such a spectrum, being of the same spectral type as Canopus, the star chosen by BCH as the best candidate for their scattered light study.

We have found that the IUE spectra vary on timescales comparable to the optical photometry (Schmidtke 1985) in agreement with Ake (1985) and that they are indeed partially contaminated by scattered light. Even after correction for this instrumental effect, however, a significant, time dependent UV excess is still present.

2. Data Reduction and the Descattering Procedure

The BCH correction for scattered light in IUE spectra goes beyond the earlier work mentioned above in being more general and is therefore of wider applicability. The authors determined a "best fit" empirical scattering profile for the cross-disperser grating by convolving an assumed scattering profile with a "true" Canopus spectrum and comparing the result to various IUE images of this F0 Ib-II star. The "true" Canopus consisted of a Kurucz (1979) model (T_{eff} = 7500 K, log g = 2.0 and log A = 0.0) except in the spectral range $1420 < \lambda < 3440$, where TD-1 and OAO II fluxes were used. The adopted scattering profile was derived from results of tests on a replica of a grating made from the same master as that used to produce the one actually flown aboard IUE (Mount and Fastie 1978). The profile was modified to include scattering from the cores of emission lines and extended by adding exponentially decreasing wings. Four free parameters are needed to describe these modifications to the Mount and Fastie profile. The interested reader is referred to the BCH paper for more details of these parameters and the errors associated with their determination.

Once the best fit profile is determined it can be deconvolved from any IUE spectrum to return a "descattered" spectrum, and this is the approach that we used. The default, normalized scattering profile assumes a level of 4% scattering from a bin at the reference wavelength (arbitrarily selected at the midpoint of the combined short and long wavelength range) as one of the four parameters. That light is then redistributed to all other wavelengths in accordance with the shape of the adopted profile. For other than the reference bin the efficiency scales as $(\lambda_{ref}/\lambda)^2$. Hence, a value of 4% at 2450 implies a 16% scattering efficiency in the region of the Lyman α line.

Because the light scattered into the range of the SWP camera originates from longer wavelengths, we have merged all SWP spectra with LWR or LWP observations taken on the same day. The spectra input into our subsequent procedures are absolutely calibrated fluxes from the SWP camera for $\lambda \leq$ 1950 Å and from the LWR or LWP cameras at $\lambda \geq$ 1950 Å, yielding an effective wavelength coverage of $1150 \leq \lambda \leq 3350$ Å. We have applied the absolute calibration of Bohlin and Holm (1980) to the SWP and LWR spectra and that of Cassatella and Harris (1982) to the LWP images. In addition, we have used the correction suggested by Holm, et al. (1982) for errors due to variations in the camera head amplifier temperature.

The BCH procedure was originally designed to work with input data in 5 Å steps, wider bins being inappropriate for spectral *line* studies. Our primary concern in this work is the short wavelength *continuum* ; hence we are not similarly restricted. Moreover, the signal/noise is quite poor in certain spectral intervals of key importance, i.e., $1150 \leq \lambda \leq 1550$ Å (the region which purportedly shows a UV excess but which has the smallest intrinsic SWP flux) and $2000 \leq \lambda \leq 2400$ (the "nearest" region of the long wavelength spectrum and hence the most sensitive to the actual shape of the redistribution function for scattering into the short wavelength region). Therefore, we averaged the data in 50 Å wide bins, appropriately weighted to eliminate reseaux and other flagged points of questionable quality, and modified the original BCH code so as to allow input data of any reasonable bin size.

These merged, absolutely calibrated, binned spectra were then passed to the descattering algorithm. In all cases we have used the "best fit" parameters determined by BCH for the scattering profile, motivated in part by the similarity in spectral type of Canopus and ϵ Aurigae. We have investigated the effect of a twofold reduction in the assumed scattering efficiency, however, in light of some evidence that the 4% value might be too large (c.f., see discussion below).

3. Results and Discussion

Figure 1 depicts the wavelength and time dependence of the scattered light found by the BCH procedure for spectra obtained throughout the eclipse. The quantity plotted is the scattered light fraction, defined as

$$R(\lambda,\Phi) = 100 \times (F^{o}(\lambda,\Phi) - F^{c}(\lambda,\Phi))/F^{o}(\lambda,\Phi)$$

where $F^{o}(\lambda,\Phi)$ = the flux at wavelength λ and eclipse phase Φ, for the uncorrected (input) spectrum, and

$F^{c}(\lambda,\Phi)$ = the flux at wavelength λ and eclipse phase Φ, for the corrected (output) spectrum.

A quadratic interpolation was applied to the data along the phase axis in order to display non-uniformly spaced points on a uniform scale. In most cases the scattered light fraction among the longer wavelength bins is insignificant, whereas for $\lambda \leq 1550$ Å $R(\lambda,\Phi)$ increases rapidly. One exception is the region $\lambda\lambda$ 2000-2400 which, as mentioned above, is the least sensitive portion of the long wavelength cameras.

Without even considering the vertical axis of Figure 1 we can easily detect an interesting facet of the phase dependence of $R(\lambda,\Phi)$ in the short wavelength bins. Not surprisingly, the figure implies that the amount of scattered light is greatest when the star is brightest, i.e., before first contact, after fourth contact and during the mid-totality brightness enhancement. Since we would not expect an uneclipsed hot secondary to show the same time dependence as the eclipsed primary we interpret this result as an independent verification that we are indeed dealing with scattered light. *Now* if we consider the values along the vertical axis we see that up to 20% of the flux at the short wavelengths is scattered light. Two important questions then arise: 1) how reliable are the assumptions that set the scale of the vertical axis? and 2) what about the flux that *is not* scattered light? We shall consider each question in turn.

In his application of the BCH algorithm to the spectra of comets Feldman (private communication) derived a scattering profile from the shape of an overexposed Lyman α emisssion line. He found an efficiency of scattering from line center of about 2%, compared to the 4% found by BCH. This was partially compensated by a larger fractional scattering into the near wings, important for emission line studies but not for the continuum case under study here. In Figure 2 we show the results of a test comparison of the two cases, 4% and 2% scattering efficiency, for our most recent post-eclipse observation. Although the fractional scattered light is also reduced by the expected factor of two, we note that there is still agreement in the regions of overlapping uncertainty (± 1 σ). Hence, it seems reasonable to consider the 2% case as a *lower limit* to the actual values of $R(\lambda,\Phi)$, for this and all other epochs.

A rough method for estimating the amount of scattered light in an IUE spectrum has recently been suggested by Imhoff (1985). Her empirically derived procedure determines the number of DN per second scattered into the SWP camera range from the long wavelength spectrum at 2400 Å. Since the BCH procedure sums the contribution from the entire long wavelength spectrum it might be expected that the values of $R(\lambda,\Phi)$ derived from it would be larger than those determined from Imhoff's "rule of thumb". However, it is evident from Figure 2 that this is not the case. Even with the rather large uncertainties Imhoff's approximation predicts a larger fractional scattered light than that found using the BCH algorithm. This suggests either that the "rule of thumb" procedure overestimates the scattered light or that the profile adopted by BCH leads to a considerable underestimate. The latter seems unlikely, since the profile was determined from a best fit to a star of the same spectral type as ϵ Aurigae. Lacking further information as to the validity of the assumptions that were made in constructing the BCH profile (i.e., do the far wings really fall off exponentially?) we shall henceforth interpret the larger values derived from the Imhoff procedure as convenient *upper* limits to the full BCH treatment. We shall use the upper limit results in the later figures, in lieu of error bars, to represent the maximum correction for scattered light.

Let us return to the second question posed in the discussion of Figure 1. Having subtracted away the scattered light contribution in each wavelength bin for each of the spectra, we are now in a position to examine the intrinsic UV flux, and note how it behaves as a function of "eclipse phase". Units of eclipse phase are defined such that first contact occurs at $\Phi = 0.00$ and last contact at 1.00, based on dates predicted by Gyldenkerne (1970) for the eclipse in *optical wavelengths.* In these units second contact occurs at $\Phi = 0.200$ and third contact at 0.790.

In Figure 3 we present eclipse light curves, both before and after the scattered light correction, for three representative wavelength bins, 1350, 1450, and 1600 Å. In all cases we plot magnitude versus Φ, defined as

$$m_\lambda(\Phi) = -2.5 \log F_\lambda(\Phi) -21.1$$

where the constant 21.1 refers to the absolute energy calibration of Vega derived by Hayes and Latham (1975). One can easily show that the difference between the light curve corrected for scattered light and the uncorrected curve is related to the R values discussed above by

$$\delta m_\lambda(\Phi) = m_\lambda{}^c(\Phi) - m_\lambda{}^o(\Phi) = -2.5 \log (1 - R(\lambda,\Phi))$$

where R is used here as a fraction, rather than a percentage.

Inspection of Figure 3 demonstrates a number of interesting results. First, it can be easily seen that, with increasing wavelength, the corrected light curves fall closer and closer to the uncorrected curves. For $\lambda > 1700$Å the curves are virtually indistinguishable. This trend is entirely consistent with the result, noted in Figure 1, that the percent scattered light is greatest for the short wavelengths in the SWP camera and approaches zero at the longer wavelengths. Second, we note that the corrected and uncorrected light curves differ most at the "brightest" phases, i.e., before and after the eclipse itself and during those phases associated with the central brightening feature (for those wavelengths where there is still a difference), again in accord with the results of Figure 1. We see that the effect of scattered light is to "fill in" the curve, making it shallower than it should be at the shortest wavelengths. Most notably, it is quite disputable whether or not the curve at 1350 Å is an eclipse curve, especially considering the large uncertainties concomitant with the low intrinsic flux levels.

To address directly the question of the reality of a UV excess in the ϵ Aurigae system we examine the spectra after we have removed the scattered light component. Does evidence for an apparent hot component remain? The answer seems to be "yes". For several of our observations a modest percentage of the UV excess is accounted for once we subtract away the scattered light. In others, almost none of the excess is removed. Figure 4 shows a typical example of the former case, in which subtracting even the upper limit of scattered light does not significantly reduce the UV excess at wavelengths below 1550 Å. The format of Figure 4 is deliberately similar to that used by Hack and Selvelli (1979), the first report of an excess in IUE spectra of ϵ Aurigae to appear in the literature.

When spectra (corrected for scattered light) from several different dates throughout the eclipse are plotted in a manner similar to that used in Figure 4, large variations are seen in slope of the continuum shortward of 1600 Å. Figure 5 is a schematic illustration of the short wavelength variations observed. The fluxes in Figure 5 have all been arbitrarily adjusted to yield the same value at 3300 Å as the model atmosphere of Kurucz (1979) used in Figure 4, a procedure which presumably removes the eclipse time dependence from the data. The time variations that remain are associated either with the eclipse-independent fluctuations of the hot component itself, with gaps or tunnels in the occulting secondary (Wilson

1971; Altner et al. 1984), or with the cepheid-like pulsations of the primary, which can be quite large at short wavelengths (Ake and Simon 1984). Figure 6 shows the data at 1300, 1400 and 1500 Å, adjusted in the same manner, plotted versus time. There is some suggestion of cyclic behavior in the curves, and a detailed study of this time dependence is presently underway.

In early February of 1984 the ultraviolet spectrometer (UVS) aboard the Voyager I spacecraft observed ϵ Aurigae (R. Polidan, private communication). The spectrum obtained is consistent with a star of spectral type B5; however, since a known B5 star is close enough to ϵ Aurigae to have been included in the 0.1 degree by 0.9 degree aperture, the identification is suspect. An additional UVS observation is planned, from which it is hoped that the uncertainty in the identification of the UV source will be resolved. Ake and Simon (1984) noted that the *line* spectrum of ϵ Aurigae shortward of 1400 Å does not match that of a B5 star.They concluded from this that whatever the hot component is, it is *not* a hot star, which suggests that the flux observed by the UVS instrument was due to the known B5 star. Nevertheless, the UVS data seems not to be inconsistent with the fluxes in the short wavelength IUE spectrum obtained in mid-February of 1984. We will follow with great interest future UVS observations of ϵ Aurigae, with the intent being to compare the results with future IUE data and U, B, and V photometry.

4. Summary

As a result of this work we have found that light scattered from the longer wavelengths constitutes a small but non-negligible, wavelength and time dependent fraction of the measured flux in the far UV. We have not been able to unambiguously rule out the reality of the UV excess. However, we note that there are still uncertainties in the assumed scattering profile. New measurements of the scattering properties of the cross-disperser grating are planned in order to verify the results of Mount and Fastie (1978) and extend the wavelength coverage into the far wings of the profile (B. Woodgate, private communication). The results of these measurements will no doubt reduce some of these uncertainties. For the present, we feel that the BCH approach is a significant improvement over the methods heretofore available for the treatment of scattered light in IUE spectra.

IUE imposed constraints on the particle size and temperature of the disk surrounding the secondary were first discussed by Castelli et al. (1982) and Chapman et al. (1983). Later infrared results confirmed the prediction that the disk temperature had to be significantly lower than that of the supergiant (Backman et al. 1984). The apparent contradiction inherent in the coexistence of an ultraviolet excess and an infrared temperature around 500 K was one of the primary motivations for undertaking this study. Future observations, such as those possible with the Voyager UVS and other instruments, will undoubtedly gain us new insight into the problem. Of particular interest, in the long term, is observation of the ϵ Aurigae secondary at quadrature and, later still, in eclipse.

Meanwhile, we look to theoretical models which allow both a UV excess and a cold disk, such as star spots on the surface of the primary (Parthasarathy and Lambert 1983), or polar flows associated with a double star embedded in the disk (Lissauer and Backman 1985).

We acknowledge the assistance of the IUE staff in acquiring the spectra of ϵ Aurigae throughout the many months of the eclipse cycle, and of the staff of the Regional Data Analysis Facility at Goddard Space Flight Center, whose helpful advice in reducing the data was an invaluable resource. We are grateful to Dr. G. Basri for providing the FORTRAN code of the BCH procedure and for taking the time to clarify some of the finer points involved in its application.

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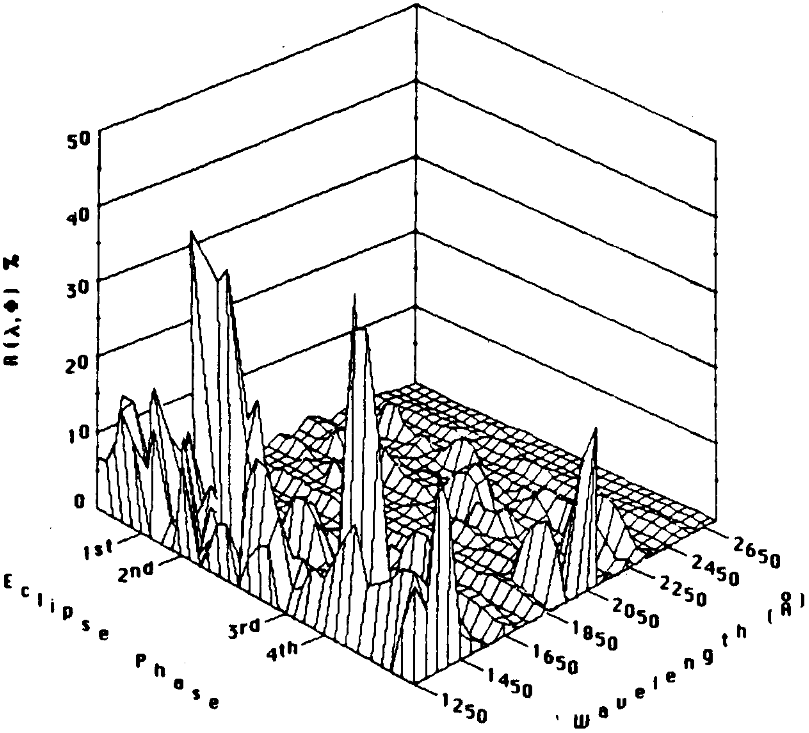

Figure 1

The relative percentage of scattered light in each wavelength bin for each observation (data is interpolated to give uniform spacing in the time coordinate). The tic marks along the phase axis refer to the contact points of the eclipse. An apparent trend toward larger amounts of scattered light during the uneclipsed (i.e., brighter) phases can be seen, as well as during the mid-eclipse brightness enhancement apparent in the light curves. This behavior at the shortest wavelengths is expected if the signal is scattered light.

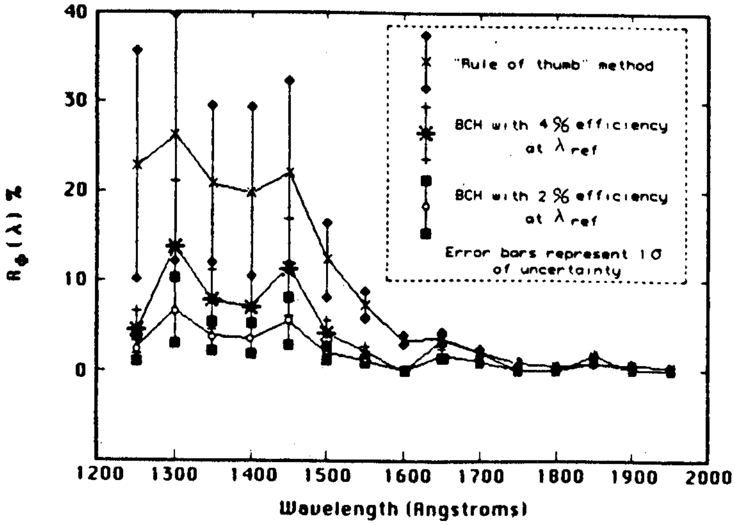

Figure 2

Relative percent scattered light as a function of wavelength for a typical IUE observation of Epsilon Aurigae ($\Phi_e = 1.434$). The effect of varying the scattering efficiency parameter is shown. Although the two cases give percentages which differ by a factor of two, the overlapping uncertainties show that this parameter is not critical, at least for the case of continuum scattering. At its upper limit the 4% case approaches the rough estimate derived using Imhoff's (1985) "rule of thumb".

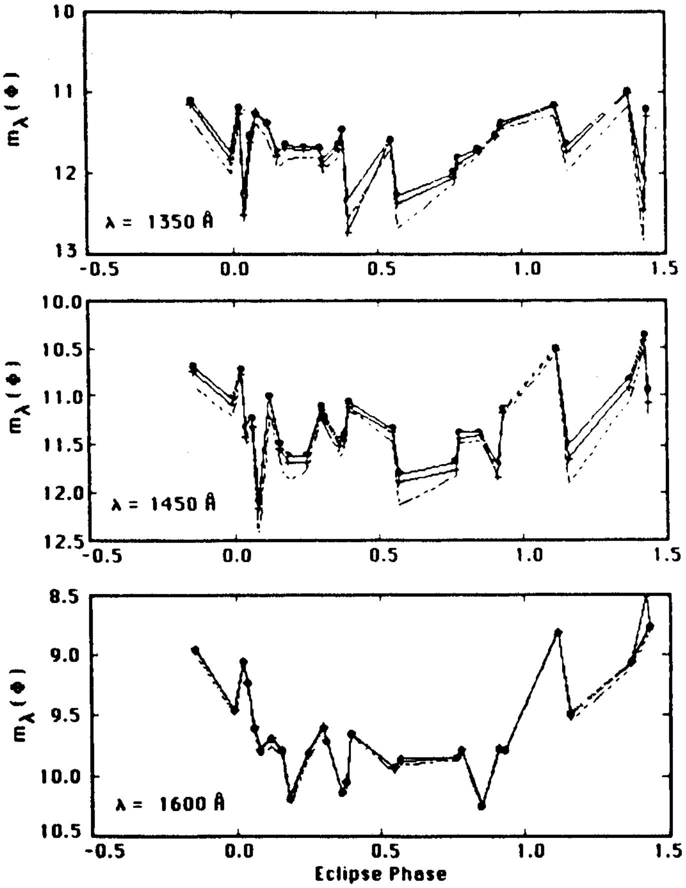

Figure 3

Eclipse light curves for three different wavelength bins In each case the filled dots represent the uncorrected data while the plus signs are the same data corrected for scattered light using the BCH program with the default parameters, and the dashed line is the curve corrected using the "rule of thumb" method At wavelengths longward of 1700 A the three curves are virtually indistinguishable

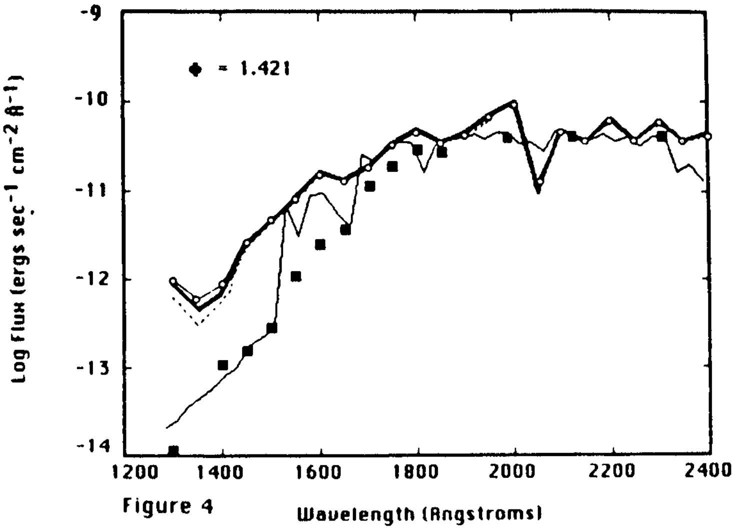

Figure 4

A typical example of the partial reduction in the apparent UV excess after subtracting the scattered light component The thin line is a Kurucz (1979) model stellar atmosphere with T_{eff} = 7500 K, log g = 1.0, and log A = 0.0, adjusted to the distance and angular diameter of Canopus The filled squares are the TD-1 and OAO-2 data for Canopus, scaled as in Hack & Selvelli (1979) The spectrum of Epsilon Aurigae well outside of eclipse is shown by the remaining curves Open circles no correction for scattered light, heavy line correction using the BCH code with default paramters, dotted line correction using Imhoff's "rule of thumb" estimate

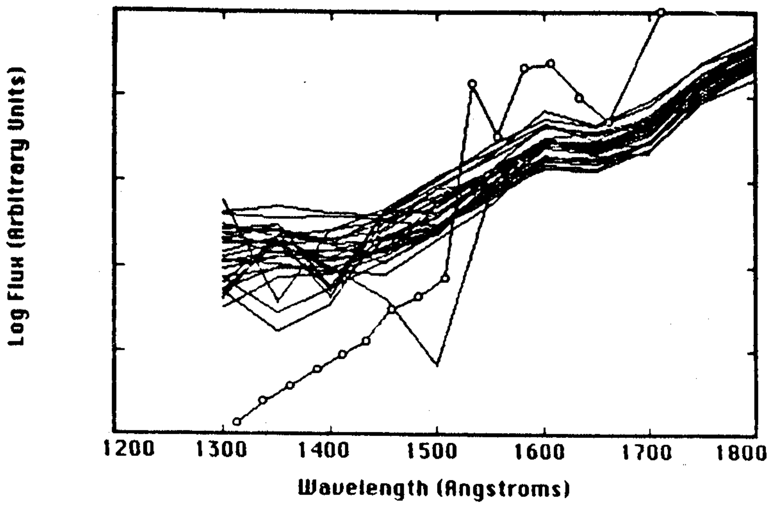

Figure 5

A demonstration of the time variation of the short wavelength spectra with variations due to the eclipse "filtered out" by adjusting all the continua to the value of the Kurucz (1979) model (open circles; same model as used in the previous figure) at 3300 Å At the extreme short wavelength end, the variations range over almost 2 magnitudes.

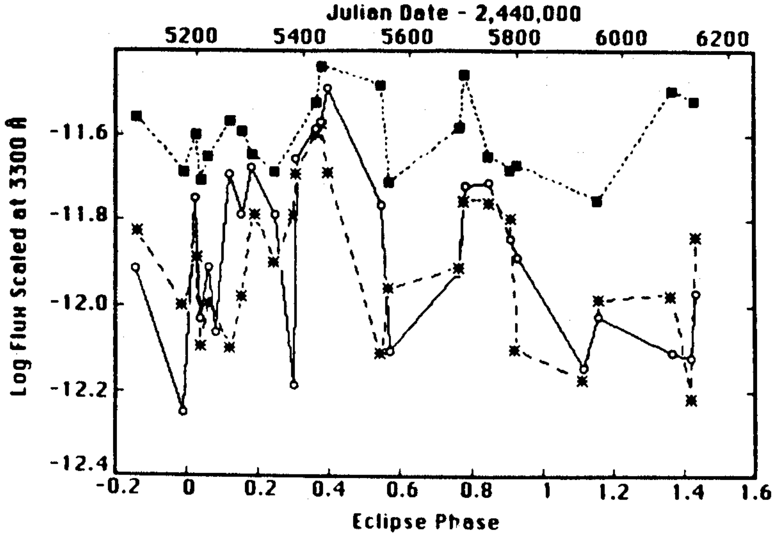

Figure 6

Logarithm of the Epsilon Aurigae fluxes, corrected for scattered light and adjusted to the same value at 3300 A, as a function of time By scaling the fluxes in the near UV the time variation due to the eclipse is suppressed, leaving evidence of another time dependence, associated either with the UV excess itself or with the cepheid-like pulsations of the primary Open circles 1300 A, asterisks 1400 A, filled squares 1500 A

Modelling ε Aurigae Without Solid Particles

A. Y. S. Cheng and N. J. Woolf (U. Arizona)

Three components can be expected to contribute to the emission of ε Aurigae. There is a primary F star. There is an opaque disk which occults it, and there is a gas stream which is observed to produce absorption lines. Evidence that the disk is not responsible for the gas stream lines comes both from the radial velocities, which are too small, and from the IR energy distribution out of eclipse, which shows free-free emission that would produce inadequate optical depth in electron scattering. The color temperature of the IR excess can give misleading indications of low temperature material. Free-free emission at 10^4°K between 10 and 20μ has a color temperature of 350°K. We discuss our attempts to mold the system.

ASTRONOMICAL RESEARCH AT THE HOPKINS PHOENIX OBSERVATORY

BY

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ABSTRACT

After trying astrophotography and radio astronomy it was decided that the best way to do meaningful astronomical research at a small private observatory was by doing photoelectric photometry. Being located in the suburbs of a large city does not produce very dark skies, however, the skies are usually clear for a high percentage of the year. Having the observatory located in the back yard of a private residence affords the luxury of observing any time the sky conditions permit. Also modest equipment is all that is needed to do accurate UBV photometry of stars 8th magnitude and brighter. Since beginning in 1980 the HOPKINS PHOENIX OBSERVATORY has published papers on several RS CVn star systems, 31 Cygni, 22 Vul, 18 Tau Per, and has followed the 1982-1984 eclipse of Epsilon Aurigae from its start to the present with over 1000 UBV measurements. In addition the HOPKINS PHOENIX OBSERVATORY has developed several pieces of photometry equipment including the HPO PEPH-101 photometer head and photon counting electronics.

I. INTRODUCTION

Seeing Doug Hall's article, "The Strange RS Canum Venaticorum Binary Stars," in the February 1979 issue of SKY and TELESCOPE I was inspired to write Doug about helping him do some science with my astronomical equipment. After about a year of frustration, mainly in trying to figure out how to get my photometry equipment built and how to actually do photometry, I received a letter from Russ Genet asking me to join the IAPPP. Through many hundreds of letters Russ guided and encouraged me to the point where I actually had my own photometry equipment and was doing real photometry. As Russ once said, "It takes about a year to get on the air with photometry."

II. PURPOSE

In 1980 the HOPKINS PHOENIX OBSERVATORY was erected. A Celestron C-8 telescope and home built photometry equipment were installed. With the help of Doug Hall the first project was observing the RS CVn binary lambda Andromendae. In 1983 a paper was published in ASTROPHYSICS and SPACE SCIENCE which included data from the HPO. This was sufficient inspiration to spur me on to a very active role in photoelectric photometry.

III. THE OBSERVATORY

The original observatory was an 8 foot square wooden frame structure with a sliding aluminum roof. In the fall of 1983 the "new" HOPKINS PHOENIX OBSERVATORY was dedicated to photoelectric photometry. The new HPO is a 14 foot square two story block building. For economical and zoning reasons a sliding roof was again used. The telescope and photometry equipment are located on the second floor while the office, computer equipment, and workshop are on the ground floor. The main reason for the new observatory was an addition to the family who required my office space within our house.

IV. THE EQUIPMENT

The telescope is a Celestron C-8, which is an 8 inch Schmidt Cassigrain with a fork mount. Originally an analog system was used which had a homemade DC amplifier, homemade high voltage power supply, and Heathkit Chart recorder. As more experience was gained it was decided to switch to a photon counting system. At the same time it was discovered that the original photometer head was far from adequate for the desired programs. This required designing a photometer head that was light and compact for use with the C-8 telescope. That design turned out to be the HOPKINS PHOENIX OBSERVATORY PEPH-101 UBV photometer head. In addition, a new regulated and adjustable high voltage power supply with 3 1/2 digit LED readouts plus an 8 digit photon counter were developed. These units have been in use for over three years and have provided very satisfactory service.

The original computer system was a Sinclair ZX-81 computer (the last I saw these computers advertised they were selling for $19). While it certainly beat doing data reduction by hand, it was soon apparent a more powerful system was needed. A Heathkit H-100 (same as the Zenith Z-100) computer was purchased and assembled. This provided the necessary improved computation speed plus several other functions such as word processing and data communications. A Commodore C-64 has been experimented with as a data acquisition and reduction computer. The price and ease of use of the C-64 makes this system very attractive.

V. THE OBSERVING PROGRAMS

While the original observing program was RS CVn binary stars, the HOPKINS PHOENIX OBSERVATORY has expanded its observing program to include high speed lunar occultation photometry of spectroscopic binaries. On 9 May 1983 a high speed observation of eta Leonis (HR 3975) was made. Data were obtained through a blue filter with data points integrated and recorded for 1 millisecond every millisecond for 48 seconds (that's 48,000 data points in less than a minute). The telescope was stopped down about 60% due to the high counts from this 3.5 magnitude star.

Long period eclipsing binaries have also been included in the observing program. The first one was Epsilon Aurigae. I succeeded Russ Genet as photoelectric photometry editor of the Epsilon Aurigae Campaign Newsletter in 1982 and have acted as editor and publisher of 10 of the 12 newsletters. After starting to observe Epsilon Aurigae Bob Stencel notified me that the 10 year eclipsing binary 31 Cygni needed observations. The fall 1983 eclipse was observed for 53 nights and the resulting data were published in THE ASTROPHYSICAL JOURNAL 15 June 1984. Since then the 1984 August-September eclipse of 22 Vul and part of the November 1984 eclipse of 18 tau Per have been observed. Observations of Epsilon Aurigae will continue as more out-of-eclipse data are needed. Recent interest in the possible gravitational lensing effect of long period eclipsing binaries has guaranteed a continued observation of these and similar star systems.

AUTOMATIC PHOTOELECTRIC OBSERVATIONS OF EPSILON AURIGAE

Louis J. Boyd (Fairborn Observatory)
Russell M. Genet (Fairborn Obs. & Wright State Univ.)
Douglas S. Hall (Vanderbilt Univ.)

The Automatic Photoelectric Telescope (APT) at Fairborn Observatory West in Phoenix, Arizona, has been used to make UBV observations of Epsilon Aurigae starting in totality (shortly after the system became operational) and continueing to the present. A sequence of 33 10-second observations have been made once or twice a night on most clar nights. It is planned to continue these observations well into the future to firmly establish the out-of-eclipse photometric behavior of Epsilon Aurigae.

APPENDIX

Directory to Additional Epsilon Aurigae Eclipse Data

1. George Wallerstein/Univ. Washington: several coude spectrograms obtained at Palomar 5 meter (see attached summary).

2. Dana Backman/Univ. Hawaii and Arizona: 9 FTS tapes, K band, 20,000 to 60,000 resolution, including H-Bracket gamma line, 1/82 through 2/85 (cf. Backman et al. 1985 Ap. J. Submitted).

3. David Lambert/Univ. Texas: red reticon spectra, McDonald Obs.

4. Mirek Plavec/UCLA: coude spectrograms acquired at Lick Observatory at approximately monthly intervals from ingress through egress, some ingress material PDS-scanned.

5. George Lockwood/Lowell Obs. -- see attached list.

6. Yonsei Obs. photoelectric observations -- see attached abstract.

7. Ultraviolet spectra: contact ESA and/or NASA International Ultraviolet Explorer offices (Vilspa, Spain or Greenbelt, Maryland, USA).

8. Bibliographical data: Bibliographical Star Index, Centre de Donnees Stellaires, Strasbourg, France and/or Astronomical Data Center, NASA Goddard Code 600, Greenbelt, Maryland, USA. Listing for 1950-1979 attached (133 references).

9. See also numerous I.B.V.S. issues (Konkoly Observatory, Budapest).

10. Photoelectric Photometry of Epsilon Aurigae, 1982-1985: P. Flin et al. 1985. I.B.V.S. No. 2678.

High Dispersion Observations of ϵ Aur
from Sept. 1982 to March 1983

George Wallerstein, University of Washington

Between September 1982 and March 1983 I obtained high dispersion spectra of ϵ Aur in selected regions using the Palomar 200-inch coude spectrograph and the Dominion Astrophysical Observatory 48-coude spectrograph. All spectra were taken with the 90-mm ITT image tube and IIa-D emulsion. Since further observations during this eclipse are not currently planned, the raw data will be presented here for others who may find them useful.

In Table 1 we list our radial velocities for the sodium D lines, KI lines, Hα, and a few other features. While most of the sodium and potassium features are surely circumstellar there is certainly an interstellar component present. In the direction of ϵ Aur interstellar gas is seen mostly with radial velocities between +5 and +10 km s^{-1}. The sodium D lines and potassium lines show incipient resolution which may involve the interstellar components.

The equivalent widths of the sodium and potassium lines are given in Table 2. For potassium, blending with atmospheric O_2 makes the line at λ7664 unmeasurable on the dates of these observations. The increase in equivalent widths already noted by Pathasarathy and Lambert is evident.

Blending and partial resolution of the circumstellar and interstellar features may account for much of the velocity structure which is only partially discernable at the available resolution.

This research was conducted by the author as a guest investigator at the Palomar Observatory, Calif. Inst. of Technology and the Dominion Astrophysical Observatory, Herzberg Institute for Astrophysics, National Research Council, Canada.

TABLE I

		Radial Velocity (km s^{-1})					
Date (UT)	Disp	metals	Hα (abs)	Hα (em)	NaI	KI	OI (λ7772)
3.53 Sept.1982	6.7A/mm	+3.5±1.1	+11.3±1.0	+72	+12.8	+21.8±1.5*	+14.3
15.41 Oct. 1982	4.8A/mm				(+19.1 1.4)† (+6.7 0.8)		
18.60 Oct. 1982	4.8A/mm					+22.4±0.5$^{\Delta}$	
19.17 Mar. 1983	4.8A/mm	+1.5	+25.4$^{\nabla}$		+15.5$^{\square}$		
21.14 Mar. 1983	4.8A/mm				+13.9	+9.9±1.5**	

* partially resolved component at +8±2 km s^{-1} is present

† two nearly equal components are clearly present but poorly resolved.

Δ partially resolved component at + 4 km s^{-1} is present.

∇ the deepest point in the line is at +36.6 km s^{-1} and an uncertain absorption feature may be present at -4.6 km s^{-1}. Weak emission further to the violet may be present.

□ the deepest point of the D2 line is at +5.3 km s^{-1}

** a little fuzz is visible on the positive side of the KI lines.

Table 2

Equivalent Widths (in Å)

Date	D1	D2	KI(λ7699)
3.53/9/1982	0.77	0.82	0.36
15.41/10/1982	0.95	1.03	-
18.60/10/1982	-	-	0.40
21.14/3/1983	1.24	1.33	0.50

LOWELL OBSERVATORY SPECTROPHOTOMETRY OF EPSILON AURIGAE 1982-1984.

G.W.Lockwood, B.L.Lutz, D.T.Thompson and J.Sowell

Date,M.S.T.	J.D. 2440000+	Wavelength Range	Resolution in Ang.	Std. Star
March 4,1982	5030	Y,R	8	109 Vir
April 4,1982	5063	B	4	109 Vir
Sept. 28,1982	5240	B,Y,R	*	Xi^2 Ceti
Sept. 29,1982	5241	B,Y,R	*	Xi^2 Ceti
Nov. 25,1982	5298	B,Y,R	*	Xi^2 Ceti
Dec. 19,1982	5322	B,Y,R	*	Xi^2 Ceti
Jan. 21,1983	5355	B,Y,R	*	Xi^2 Ceti
Feb. 21,1983	5386	B,Y,R	*	Xi^2 Ceti
March 29,1983	5422	Y,R	8	Xi^2 Ceti
April 17,1983	5441	B,Y,R	*	109 Vir
Oct. 25,1983	5632	B,Y,R	*	Xi^2 Ceti
Nov. 14,1983	5652	B,Y,R	*	Xi^2 Ceti
Nov. 15,1983	5653	B,Y,R	*	Xi^2 Ceti
Dec. 28,1983	5696	B,Y,R	*	Xi^2 Ceti
Jan. 23,1984	5722	B,Y,R	*	Xi^2 Ceti
March 16,1984	5775	B,Y,R	*	109 Vir
April 12,1984	5802	Y,R	8	109 Vir
April 14,1984	5804	B	8	109 Vir
April 15,1984	5805	B,Y,R	8	109 Vir
Sept. 7,1984	5950	B,Y,R	*	Xi^2 Ceti

* Blue resolution 4 Angstroms, Yellow and Red 8 Angstroms
B=3295 to 5495 Angstroms
Y=5200 to 7676 Angstroms
R=7500 to 8880 Angstroms

Presented to 3rd IAU-Asia
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Kyoto, Japan, Oct. 1984

PHOTOELECTRIC OBSERVATIONS OF THE LONG-PERIOD ECLIPSING BINARIES AT YONSEI UNIVERSITY OBSERVATORY *

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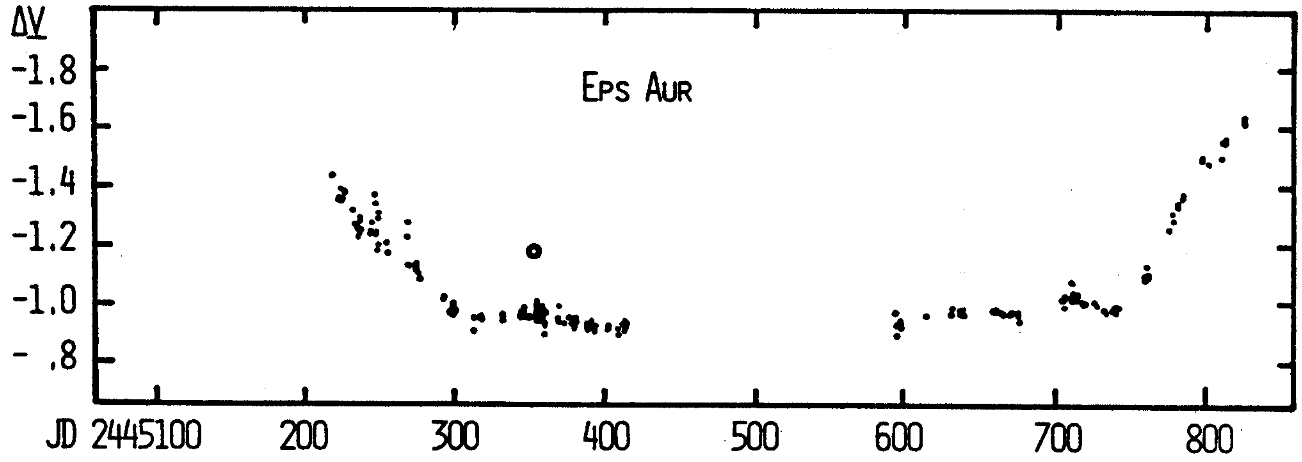
ABSTRACT

A long-term project (ten-years; 1982-92) for the photoelectric observation in the UBV passbands of selected eclipsing binaries with $p \gtrsim 10$ days has initiated at Yonsei University Observatory using 40-cm and 61-cm reflectors. The instrumentation used and the observation techniques and the reduction procedures applied to this investigation are described.



Eps Aur: The observed light curve of this star shows that the bottom of the eclipse is not flat as was expected. Two brightenings are clear; one is at the phase right after the second contact and the other just before the third contact. Moreover the light curve had several flare phenomena, and one of them, marked with an open circle, had been reported elsewhere (Nha and Lee IBVS 1983). The datas for the second and third contacts are, respectively, JD2445305 and JD2445733, and therefore, the duration of the total eclipse is 428 days, which is longer than that of the 1955-57 eclipse by 34 days and that of 1928-30 by 98 days (Fig.3d).

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16. Abstract

This document reports the proceedings of a workshop held in January 1985 in Tucson, Arizona. The workshop concerned the new data collected during the 1982-1984 eclipse period of the 27-year system Epsilon Aurigae. This binary star has been a classic problem in astrophysics because the opaque eclipsing object is non-stellar, and probably disk shaped. Invited papers concerning the history of the system, optical, infrared and ultraviolet photometry, optical polarimetry and ultraviolet spectroscopy are included. An invited paper concerning comprehensive theoretical interpretation in the context of stellar evolution also is included. Several contributed papers and an appendix describing further data sources are part of this document. The information collected herein is unparalleled in scope and will remain a standard reference until the next eclipse cycle in the year 2009 A.D., in all probability.

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