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EPSILON AURIGAE*

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Abstract. In April 1984, fourth contact ended the two year long eclipse of Epsilon Aurigae. An astrometric study of the study of the system was carried out by Van de Kamp (1978) leading to the conclusion that the orbit is seen very close to edge on. The eclipse was monitored by a number of groups from the ground and from spacecraft such as the IUE. Ultraviolet observations of the system from IUE have thrown new light on the nature of the system that lead us to conclude that the secondary object is probably a cold, dusty accretion disk surrounding a star that is completely hidden inside the disk.

Epsilon Aurigae is a particularly appropriate system to be discussed here both because this conference proceedings is in honor of F. W. Bessel, and because the conference was held in Germany. This unique binary system has been observed for many years both astrometrically and spectroscopically. The light variability of the system was first noted in 1821 by a German amateur astronomer and extensive visual brightness estimates were made at the 1848 eclipse in Bonn by Bessel's student Argelander. Early spectroscopic observations were made at Potsdam and at the Yerkes Observatory. Ludendorff recognized the periodic nature of the system and concluded that it is a spectroscopic binary. In 1924 Ludendorff (1924) published the first spectroscopic orbit of the system. His calculations have been updated and then farther refined by Morris (cf. Morris, 1962; Wright, 1970). The relevant quantities are $P = 9890$ days, $e = 0.200 \pm 0.034$, $a_1 \sin i = 12.9$ AU, and mass function $= 3.12 \odot$.

The peculiar nature of the system became clear quite early. No secondary eclipse has ever been observed, suggesting that the secondary is significantly fainter than the primary. During the primary eclipse the light level of the system is reduced by about 0.8 mag. or by about 50% suggesting that either the eclipse is partial or the secondary is smaller than the primary. In fact, both of these possibilities appear to be ruled out by additional observations. The eclipse light curve has the flat bottomed shape typical of a central eclipse and, in addition, the eclipse is quite long; the time period from first contact to fourth contact is roughly 714 days (Figure 1) and totality lasts nearly a year. The length of the eclipse combined with the orbital parameters permits us to calculate the dimensions of the secondary, which must be substantially larger than the primary. Therefore, the primary ought to be totally eclipsed by the larger fainter secondary object, contradicting the depth-of-eclipse observations. There is one additional very important observational fact; during eclipse the spectrum is dimmed uniformly across the entire

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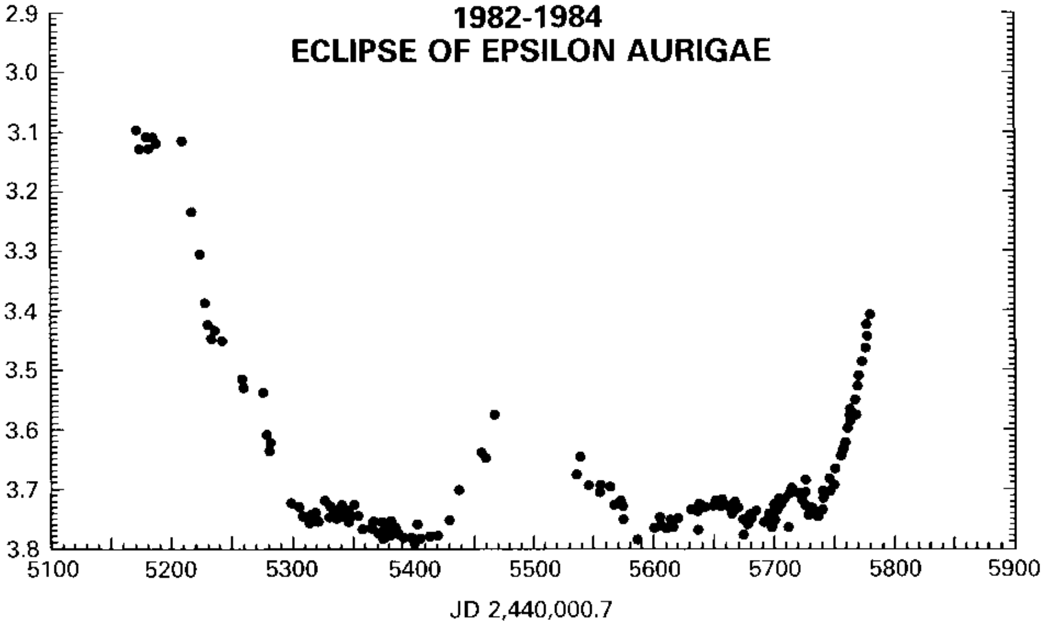

Fig. 1. The visible light curve of ε Aurigae during the recent eclipse. The numerical values of the magnitudes are taken from various observers as reported in the ε Aurigae *Newsletter* and should be viewed as provisional.

visible light observations are summarized in a number of reviews, including Wright (1970) and Sahade and Wood (1978).

There have been several models proposed to explain these unusual observations (see, for instance, the review of Sahade and Wood, 1978). Kuiper *et al.* (1937) asserted that the secondary is a very large, cool infrared I-star that is partially transparent. In that model, the gray absorption would have been caused by electron scattering in a layer of the I-star that is ionized by the F-supergiant. It is difficult to understand how one could avoid additional non-gray continuous absorptions in such a system; if the material is ionized by phototons from the primary, then why do we not see photoionization continua in the spectrum? New 20-micron infrared observations of the system (Backman *et al.*, 1984) do show the presence of a large object with a temperature of about 500 K. A way out of the non-gray absorption problems posed by a semi-transparent secondary is to accept Huang's (1965) model of a flat, rotating disk that is opaque when viewed edge on. The extent of the disk in the orbital plane is sufficient to explain the length of the eclipse (about 1000 solar radii), but the extent perpendicular to the orbital plane is less than the diameter of the supergiant so that, even at mid eclipse, the 'poles' of the primary are observed 'above' and 'below' the disk. The projected area of the disk is consistent with the IR observations (Backman *et al.*, 1984). If we accept the existence of a disk, then we must try to ascertain its nature. Kopal (1954, 1971, 1972) suggested that the secondary disk is a semi-transparent ring of solid particles surrounding a secondary component. Handbury and Williams (1976) have expanded on this idea and speculated that the system might be very young, with the primary being a pre-Main-Sequence star and the secondary being a embryonic solar system. If these were true, then one should see measurable changes in the massive primary on time-scales of decades, based on the predicted evolutionary rates of such objects. Parsons (1984) has made a careful study of high-dispersion spectra from the 1890's used by Maury and Pickering (1897) and found no convincing evidence of spectral changes. These observations appear to rule out the primary as a pre-Main-Sequence star. We will briefly introduce an alternative model below.

A detailed study of Epsilon Aurigae as an astrometric binary has been carried out by Van de Kamp (1978), who used plate material covering the years 1939 to 1977. He found the angular elements

$$i = 89^\circ \pm 3^\circ\,, \qquad \Omega = 92^\circ \pm 3^\circ$$

and

$$a = 0\overset{''}{.}0227 \pm 0\overset{''}{.}0010\,.$$

Van de Kamp's inclination is significantly different from an earlier value of 72° found by Strand (1959), who used plate material covering the period 1962 to 1958. This latter value for i would lead to a grazing eclipse. As far as the physical dimensions of the system are concerned, there is little difference between 72° and 89° since the relevant quantities are $\sin i$ and $\sin^3 i$, which differ by less than the inclinations themselves. Strand's (1959) analysis is published only as an abstract and was never followed up by a referred paper; so that it is difficult to evaluate his results. The linear semi-major axis from the spectroscopic solution of the system and the angular semi-major axis from the astrometric solution can be combined to yield an absolute parallax

$$\pi = 0\overset{''}{.}00172 \pm 0\overset{''}{.}00008\,,$$

which leads to an absolute visual magnitude $M = -6.7$ corrected for interstellar absorption (Van de Kamp, 1978). Schmidt-Kaler (1961) has made a careful study of these rare late-type supergiants in galactic clusters and associations and concludes that the absolute magnitude of an F0 Ia star is -8.5. Bouw and Parsons (1971) have extended this work, based on a somewhat larger set of observational data and arrive at a similar value, though their work shows that the inferred absolute magnitude values exhibit a total scatter of slightly over a magnitude. Given all the uncertainties in both the canonical M for F0 Ia and the value for Epsilon Aurigae, we conclude that the values are not inconsistent. Kuiper *et al.* (1937) favoured an inclination close to 70°. Their argument was based on the absolute magnitudes that were inferred from various orbit solutions. As it turns out, the greater baseline used by Morris and by Van de Kamp has led to better orbital solution. Together with the more recent determinations of the canonical values for supergiants the absolute magnitudes no longer presents such a difficulty, even with an assumed inclination of 90°. Therefore, we will assume Van de Kamp's value here.

The most recent eclipse of Epsilon Aurigae began with first contact in July, 1982 and ended with fourth contact in May, 1984. Observations with the International Ultraviolet Explorer (IUE) have revealed at least two very interesting results (Altner *et al.*, 1984). The first result was found by intercomparing the shapes of the low-dispersion spectra

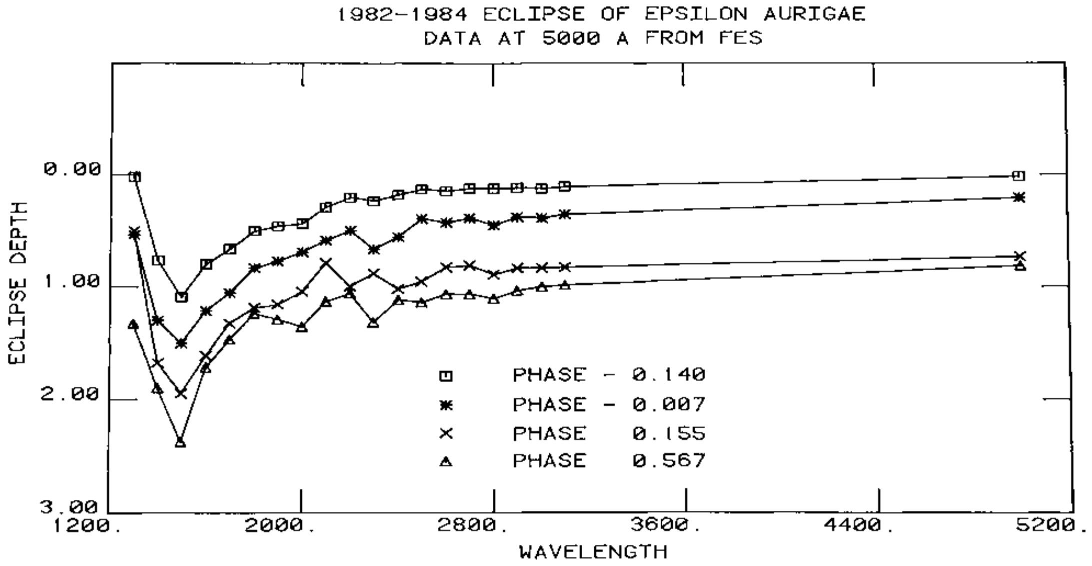

Fig. 2. The 1982–1984 eclipse of ε Aurigae as observed by IUE. The ordinate is depth of eclipse using a spectrum obtained on 4 April, 1982 by T. Ake and T. Simon as the out-of-eclipse fiducial. The UV data is from low dispersion spectra and was averaged into 100 Å bins. The 5000 Å point is from the IUE Fine Error Sensor. Note that the eclipse is essentially gray longward of about 2400 Å.

taken at various phases during the eclipse. Figure 2 shows a plot of eclipse depth vs wavelength for several typical phases covering ingress and totality. The pre-eclipse reference spectrum was obtained by T. Ake and T. Simon on 4 April, 1982. Note that the depth is nearly wavelength independent at all phases from about 2400 Å longward to 5000 Å. This observation is consistent with the earlier results from ground-based studies. Between 2400 and 1500 Å, the eclipse depth increases with decreasing wavelength. Chapman *et al.* (1983) have suggested that the extra source of opacity at short wavelengths may be due to dust in the vicinity of the secondary object, particularly in the outer regions where the material density is low and the disk may not be fully opaque. In their paper, Chapman *et al.* (1983) used a spectrum obtained on 13 April, 1982 as the out-of-eclipse reference and a spectrum obtained on 21 September, 1982 as the in-eclipse spectrum. Two papers (Boehm *et al.*, 1984; and Parthasarathy and Lambert, 1983) take issue with the dust interpretation. Those authors assert that the 13 April, 1983 spectrum was obtained at a time when the supergiant star was ‘active’ and the 21 September, 1982 spectrum was taken at a quiescent period, then the apparent deepening of the eclipse is dominated by intrinsic variability of the supergiant. The 4 April, 1982 spectrum used as a fiducial in the newer analysis shown in Figure 2 was not obtained at an ‘active’ period and the Chapman *et al.* (1983) result remains valid. The decrease in eclipse depth shortward of 1500 Å may be due to the fact that the shorter wavelength emission is dominated by a hot object imbedded in the secondary (Boehm *et al.*, 1984). The second result from the IUE observations concerns the Mg II resonance lines which show a very broad absorption feature, superposed on which appear to be lines with P Cygni profiles at the expected wavelengths of the two members of the

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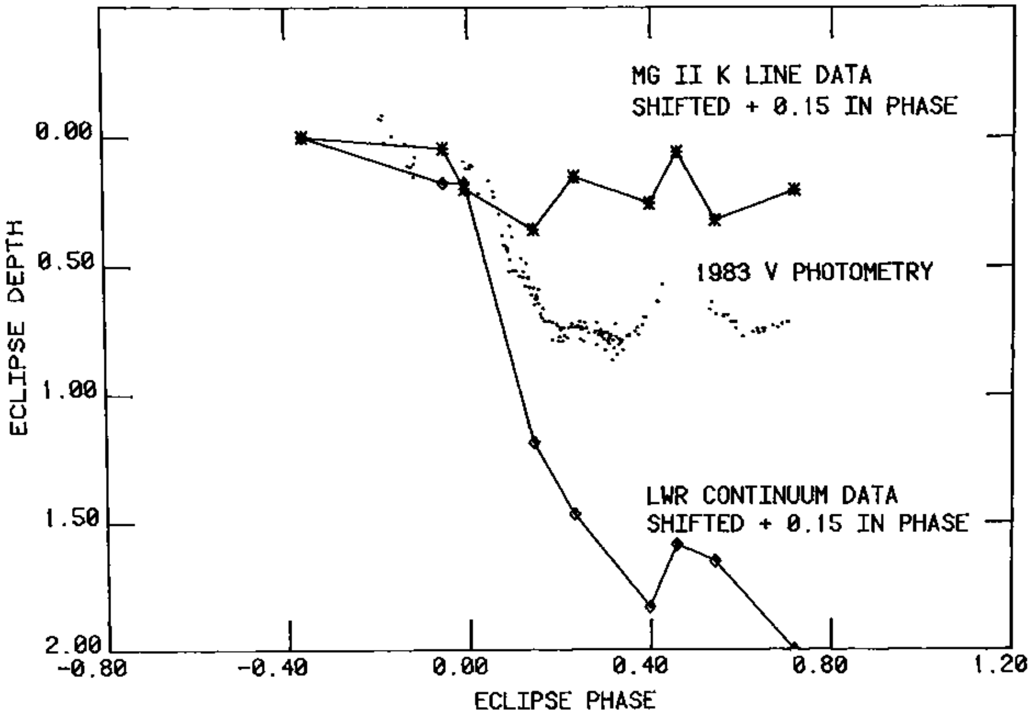

Fig. 3. The change in flux of the Mg II K line as a function of eclipse phase compared with a point in the nearby continuum. Note that the flux in the Mg II emission is affected very little by the eclipse. The *V*-magnitudes are plotted on the same graph, but have been shifted left by 100 days. The UV eclipse, as illustrated by the continuum data is, therefore, seen to be about 100 days earlier than the visible eclipse.

doublet. In fact, we believe that we are not seeing P Cygni lines but rather emission which arises somewhere in the stellar system with a narrow, blueward interstellar absorption. Casual inspection of the Mg II resonance lines shows an increase in the relative intensity of the emission as the eclipse progresses. A more careful study shows the result in Figure 3. The asterisks are the intensity of the Mg II K line as a function of phase while the diamonds are the intensity in the nearby continuum. The eclipse phase is calculated such that phase 0.0 is at the time of first contact and phase 1.0 at the time of fourth contact, using Gyldenkerne's 1970 prediction times of the contact. Plotted on the same graph is the *V* magnitude from the 1983 eclipse. Note that one must shift the UV data by +0.15 in phase to make the steepest declines in visible and UV light correspond; that is, the UV eclipse starts 0.15 in phase earlier than the visible light eclipse. The fact that Mg II emission does not change significantly in intensity means that the source of the emission is not eclipsed by the secondary. Parthasarathy and Lambert (1983) argue that the Mg II emission comes from the chromosphere of the supergiant and arises mainly from the limb. If that was the case, one can visualize a situation where the fraction of the limb that is eclipsed is less than the fraction of the disk that is eclipsed.

Using Morris' mass function and his estimated mass of 15.5 solar masses for the primary, the mass of the secondary is roughly 13.7 solar masses. I believe that this secondary may be a fossil accretion disk around a very compact star. The disk was formed at an earlier stage in the evolution of the system when the primary was losing mass at a high rate and after the secondary had evolved into a condensed object, perhaps a black hole. Today, the rate of accretion onto the secondary is so slow that the energetic phenomena usually though to be characteristic of such systems are not observed. The disk has cooled to the observed 500 K and small dust grains have condensed. Following the analysis of McCluskey and Kondo (1971), we have addressed ourselves to the question: could the present secondary have been much more massive in the past, thereby evolving into a compact object and losing significant mass in the process and ending with the present masses? If the present secondary could have started as say an 18 solar mass star, and if it could evolve into a compact object without too violent a supernova explosion, then the answer to the question is yes. A more detailed analysis of the situation is under way now and will be published in the near future.

References

Altner, B. M., Chapman, R. D., Kondo, Y., and Stencel, R. E.: 1984, in J. M. Mead, R. D. Chapman, and Y. Kondo (eds.), *The Future of Ultraviolet Astronomy Based on Six Years of IUE Research*, NASA CP (in press).

Backman, D. E., Becklin, E. E., Cruikshank, D. P., Joyce, R. R., Simon, T., and Tokunaga, A.: 1984, preprint.

Boehm, C., Ferluga, S., and Hack, M.: 1984, *Astron. Astrophys.* **130**, 419.

Bouw, G. D. and Parsons, S. B.: 1971, in M. Hack (ed.), *Colloquium on Supergiant Stars*, Proc. 3rd Colloq. on Astrophysics, Trieste, p. 22.

Chapman, R. D., Kondo, Y., and Stencel, R. E.: 1983, *Astrophys. J.* **269**, L17.

Gyldenkerne, K.: 1970, *Vistas Astron.* **12**, 199.

Handbury, M. J. and Williams, I. P.: 1976, *Astrophys. Space Sci.* **45**, 439.

Huang, S.-S.: 1965, *Astrophys. J.* **141**, 976.

Kopal, Z.: 1954, *Observatory* **74**, 14.

Kopal, Z.: 1971, *Astrophys. Space Sci.* **10**, 332.

Kopal, Z.: 1972, in *Nobel Symp. Stockholm*, No. 21, pp. 39–47.

Kuiper, G. P., Struve, O., and Strömgren, B.: 1937, *Astrophys. J.* **86**, 570.

Ludendorff, H.: 1924, *Sitzber. Berlin Preuss. Akad. Wiss.* **9**, 49.

McCluskey, G. E. and Kondo, Y.: 1971, *Astrophys. Space Sci.* **10**, 464.

Maury, A. C. and Pickering, E. C.: 1897, *Harvard Ann.* **28**.

Morris, S. C.: 1962, *J. Roy. Astron. Soc. Canada* **56**, 210.

Parsons, S. B.: 1984, private communication.

Parthasarathy, M. and Lambert, D. L.: 1983, *Publ. Astron. Soc. Pacific* **95**, 1012.

Sahade, J. and Wood, F. B.: 1978, *Interacting Binary Stars*, Pergamon Press, New York, p. 152.

Schmidt-Kaler, T.: 1961, *Z. Astrophys.* **53**, 1, 28.

Strand, K. Aa.: 1959, *Astron. J.* **64**, 346.

Van de Kamp, P.: 1978, *Astron. J.* **83**, 975.

Wright, K. O.: 1970, *Vistas Astron.* **12**, 147.