A SPECTROSCOPIC VIEW OF EPSILON AURIGAE

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ABSTRACT: Spectroscopic observations from the ultraviolet, visible, and infrared obtained at the recent eclipse are discussed. The rotation curve for the disk around the secondary suggests that secondary is a low mass star (or binary). This result with the known mass function suggests that the primary may be a low mass ($m_1 \leq$ the Chandraskehar limit, 1.4 $M_\odot$) star leaving the AGB and evolving to the white dwarf region.

1. Introduction

Novel observations made at the 1982-1984 eclipse from the ultraviolet through to the far-infrared comprise a basis for testing old and new models of the enigmatic system ε Aur. This is necessarily an interim report because spectra remain unpublished and unanalysed, a comment especially applicable to the bank of IUE spectra. I emphasize here ideas drawn from a partial analysis of spectra obtained at the McDonald Observatory - see Lambert and Sawyer (1986).

Currently favored models for the 'unseen' secondary attribute primary eclipse to a large opaque dusty disk rotating around a central object. The disk may be thick and perpendicular to the plane of the sky, as in Huang's (1965, 1974) models, or thin, opaque, and inclined to the line of sight so that a large area is projected onto the primary, as in Kopal's (1954) and Wilson's (1971) models - the latter considers the central regions to be semi-transparent. I concentrate here not on these important and interesting geometrical questions, but on the nature of the 'unseen' central object within the disk. I seek answers to the following question: What is the luminosity, mass, and evolutionary state of the central object within the disk and of the primary?

2. The Spectrum During Eclipse

2.1 Visible and Infrared Spectra

In eclipse, low to moderate excitation lines of neutral and singly-ionized lines in the primary's photospheric spectrum are accompanied by a component formed in warm gas in the secondary's disk. The disk's lines are red-shifted prior to mid-eclipse and blue-shifted afterwards: the gas is in direct motion about the central object. This behavior was seen at earlier eclipses - see Struve *et al.* (1958).

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Before reviewing the disk's lines, I inject a cautionary note. With very few exceptions, the disk's line is so blended with the photospheric line that a deconvolution procedure is needed to provide the former. The obvious initial step is to assume that the photospheric spectrum is unchanged through the eclipse. Our exposures near 8710 Å provided profiles of N I high excitation lines. Profile variations seen out-of-eclipse are attributed to an irregular pulsation of the primary's photosphere. Identical variations are seen in eclipse and, as expected, there is no obvious component from the warm disk. Long-term monitoring of two other Ia supergiants (ρ Cas and HR 8752) shows similar variations of the N I lines with more severe variations seen in those lower excitation lines, which, in ε Aur, are blended with a line from the disk. I caution that the assumption that ε Aur primary's lines are invariant should be tested.

Our program included the K I resonance doublet at 7664 Å and 7699 Å. A montage of spectra in Figure 1 illustrates several salient points. The weak out-of-eclipse lines are presumed to be interstellar in origin - see Hobbs (1974) for a higher resolution spectrum. There is no detectable photospheric line from the primary. Development of the disk's line follows the pattern outlined earlier. It is detectable long after fourth (photometric) contact. Note too the much greater strength of the line after mid-eclipse - see Figure 2. Variations of profile and equivalent width through eclipse do not exceed the measuring errors - the disk as integrated over the primary's projected area is quite uniform. Radial velocity variations are shown in Figure 3.

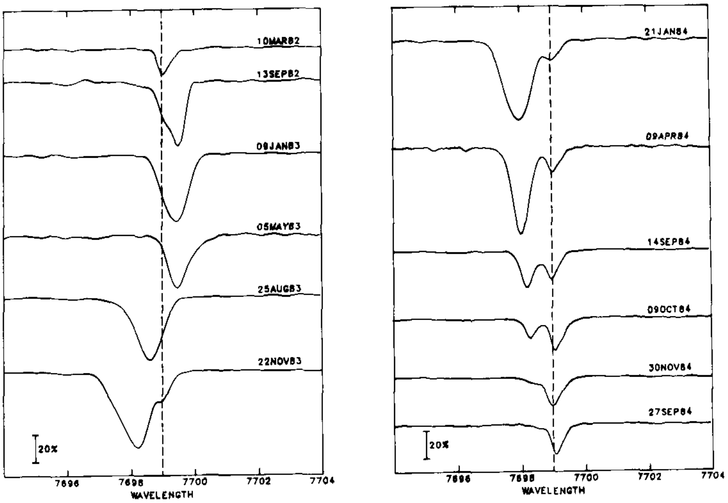

Fig. 1. Profiles of the 7699 Å K I line. The rest wavelength is shown by the broken line. The wavelength scale has been corrected for the earth's motion. Weak telluric O_2 lines have been removed by dividing the ε Aur spectrum by that of a hot (i.e., line free) star. (The correct date of the spectrum in the lower right corner is 27 Sept. 1985.) Contact times as estimated by Schmidtke (1985) from UBV photometry are:

First	1982 Jul. 14	Third	1984 Feb. 17
Second	1982 Nov. 28	Fourth	1984 Apr. 21

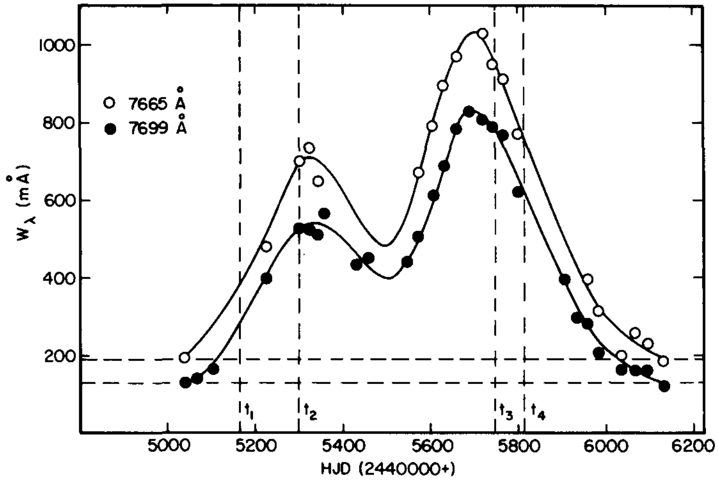

Fig. 2. Variation of the equivalent width (W_λ) of the K I 7664 and 7699 Å lines. Schmidtke's (1985) estimated times of first through fourth contact are indicated by the broken lines. The W_λ increase prior to first contact is based on additional spectra not shown here (Parthasarathy 1982).

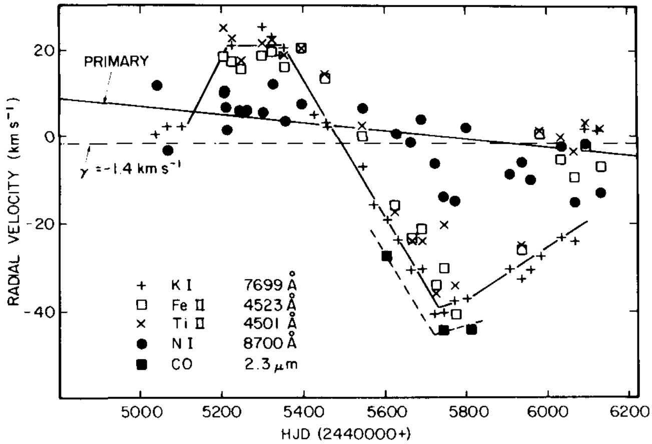

Fig. 3. Radial velocities for selected lines from before ingress to beyond egress. The systemic velocity (-1.4 km s^{-1}) and the predicted orbital velocity of the primary are from elements by Batten *et al* (1978). Velocities are given for the primary's photosphere (N I lines near 8690 Å), and the secondary's disk (K I 7699 Å, Fe II 4523 Å, Ti II 4501 Å, and the CO 2.3 μm lines).

Other low excitation lines show the same behavior; velocities of representative Fe II and Ti II lines are shown in Figure 3. At egress, an additional and cooler gas stream was revealed through infrared spectroscopy. Hinkle and Simon (1985) discovered weak absorption lines of the carbon monoxide molecule's vibration-rotation (ground electronic state) spectrum. Radial velocities for the CO lines are summarized in Figure 3. This stream's kinetic temperature may be close to the CO excitation temperature, T_{exc} = 1000 K

(Hinkle and Simon 1985). In the visible spectrum, the stream provides many weak and sharp lines from low-lying energy levels. This gas may be in transit between the primary and the secondary's accretion disk.

Balmer lines, the signatures of ionized hot gas, reveal a component arising near the disk; Wright and Kushwaha (1958) discuss Hα at the 1955-57 eclipse, Ferluga and Hack (1985a), and Saito *et al.* (1985) discuss variations of Balmer lines seen at the recent eclipse. In Figure 4, I show a sample of our McDonald spectra of Hα. One can readily see the appearance at ingress of red-shifted additional absorption and the switch to blue-shifted absorption at egress. Whereas the disk's metal lines are weaker at mid-eclipse, Hα is greatly strengthened and broadened - see the spectrum for 1983 August 1 taken within a few days of mid-eclipse. Saitō *et al.* show that the rotation of the ionized gas, which is concentrated to the central regions of the disk and presumably ionized by a hot secondary star, follows an approximately Keplerian variation ($V_{rot} \propto r^{-1}$).

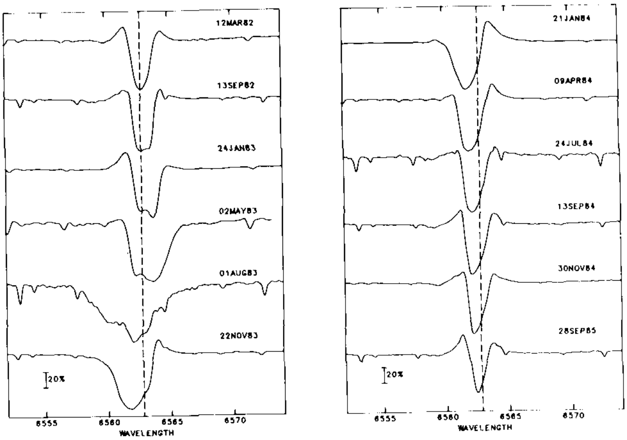

Fig. 4. - Profiles of Hα. The rest wavelength is shown by the broken line. The wavelength scale has been corrected for the earth's motion. The sharp lines of variable intensity and position are due to H_2O in the earth's atmosphere; they are especially strong in the 1983 August 1 spectrum, the spectrum taken closest to mid-eclipse.

The weak emission in the blue and red wings appears to belong to the primary. Observations out of eclipse show that these emissions are variable. Backman, Simon, and Hinkle (1986) discuss high-resolution infrared spectra providing the hydrogen Br α and Br γ lines. The former is in emission. The latter contains an emission component. Backman *et al.* show that the regions providing the emission components are not eclipsed by the secondary and that the strong emission at Br α has a radial velocity approximately that of the primary. Variations in the radial velocity of the absorption (Br α) and emission components (Br α and γ) appear to be confined to an interval around mid-eclipse and to reflect mutilation imposed by the central regions of the disk. Backman *et al.* argue that the emission arises from "a flow of some kind". Alternatively, the emission may come from an active region on the uneclipsed portion of the primary, as proposed earlier by Parthasarathy and Lambert (1983) to account for the lack of an eclipse below 1400 Å.

2.2 Ultraviolet Spectra

Many observations of ε Aur were obtained with the IUE satellite. I draw on the few short reports presently availalbe in the literature - see Ake and Simon (1984), Ake (1985), Ferluga and Hack (1985a,b). A full analysis of IUE low and high resolution spectra is awaited with interest. High-resolution spectra were obtainable in a few minutes at the long-wavelength limit of IUE. Continuum fluxes drop so steeply towards shorter wavelengths that the exposure time increases to about 8 hours (a full IUE shift) for 1700 Å. Shorter (and longer) wavelengths were monitored at low resolution. As Ake (1985) notes, the C IV and Si IV resonance doublets which betray the presence of hot stellar winds (and photospheres) may have escaped detection because high-resolution spectra were unobtainable below 1700 Å; close scrutiny of low resolution spectra would be of interest.

The photospheric ultraviolet spectrum ~ that expected for an F-type supergiant. In eclipse, the low-excitation lines (now in the majority) are blended with a component to the red at ingress and to the blue at egress. Although detailed analyses have not been published, the behavior of this component mimics the disk's contribution to lines in the visible, as summarized here by Figures 1 to 3. This is no surprise. Some authors have reported structure within the combined profile disk and photospheric lines (e.g., Ferluga and Hack 1984). Of course, structure in absorption lines may be simulated by overlying emission, a suggestion compatible with a report that certain lines are filled in by emission (Castelli, Hoekstra, and Kondo 1982).

The Mg II h and k lines near 2800 Å show a P Cygni profile in their inner cores. In eclipse, the flux in the broad wings declines as the photosphere is eclipsed, but the emission in the core is unaffected (Ake and Simon 1984; Ake 1985). Ake reports that "the Mg II line wings dropped more rapidly than the continuum, and during egress, recovered more slowly", a behavior resembling that in Figure 2. The P Cygni absorption core is displaced by -13 km s^{-1} relative to the photospheric lines. The absorption cores appear to be formed in circumstellar gas; an interstellar contribution is likely. Circumstellar - interstellar lines are seen accompanying other resonance and low excitation lines of abundant ions and atoms: Struve (1951) remarked upon a -30 km s^{-1} component to the Ca II H and K lines. Several sites for the non-varying P Cygni emission may be identified: an active region on the primary, circumbinary gas including a wind off the primary or the secondary. Ake and Simon (1984) point out that after mid-eclipse, the absorption was broader and extended to -300 km s^{-1}. This absorption may arise in the gas responsible for the extreme broadening of the Hα line near mid-eclipse (Figure 4).

The O I 1302 Å emission line, which is a prominent feature of short-wavelength low resolution IUE spectra, appears not to have weakened in eclipse. This line is probably excited by fluorescence with hydrogen Ly β (Bowen 1947). The emitting oxygen atoms may be colocated with the Mg^+ ions responsible for the 2800 Å P Cygni profiles. A high resolution measurement of the O I profile may help to locate the emitting gas. If the site is a bi-polar flow out of the secondary's disk, which is responsible for the broad Hα absorption at mid-eclipse, the O I profile should also be broad. If the principal emission comes from an extended region around or between the stars, the emission line could be sharp and, perhaps, double-peaked. Observations with the Space Telescope are awaited with interest.

IUE observers (e.g., Ake and Simon 1984) have reported that the ultraviolet flux was enhanced for a short period near first and third contacts. Ake (1985) attributes these enhancements to "a periodic Cepheid-like pulsation of the primary". Ferluga and Hack (1985b) discuss differences between the normal ultraviolet line spectrum and that taken at a time of maximum ultraviolet flux (the "active" spectrum). They suggest that "the UV activity of the companion increases the state of excitation of the shell". Changes in the visible spectra appear to be very small, however.

3. Epsilon Aurigae and Stellar Evolution

With the wealth of ultraviolet, visible, and infrared spectra acquired at the recent eclipse, much should soon be learned about the physical conditions of gas within and around the secondary's disk. Here, I sketch how the radial velocity curve (Figure 3) may be used to infer the mass of the secondary and, hence, through the known mass function, the mass of the primary. An expanded discussion of the following sections is given by Lambert and Sawyer (1986).

The velocity curve at this eclipse matches very well that obtained at the two previous eclipses. Our assumption is that the absorbing gas lies in a disk which is in Keplerian rotation about a stellar object (possibly a binary system). This assumption establishes a relation between the observed velocity and the mass of the secondary. Although this argument appears to have been appreciated by observers of prior eclipses, the first quantitative applications have followed the recent eclipse (Saito *et al.* 1985). The fact that lines of differing types provide similar velocity curves suggests that the observed gas is confined to particular locations and is not observable throughout the disk. I suggest that the lines come from an 'atmosphere' about the periphery of an opaque disk. Gas at the trailing edge of the disk must extend to large distances because the secondary's lines are seen for a considerable time after the end of the eclipse. The eclipsing object is assumed to be an opaque disk seen edge-on. The depth of the eclipse is set by the disk's thickness (relative to the primary's diameter) as projected onto the primary; in fact, the disk extends beyond the primary. The duration of the eclipse is set by the primary's diameter and the projected diameter of the disk. Interpretation of the disk's velocity field would not be changed materially by adopting Kopal-Wilson's model instead of Huang's thick disk.

There is a striking difference between the amplitude of the secondary lines' radial velocity (relative to the systemic velocity) at ingress (22 km s^{-1}) and egress (38 km s^{-1}). Two possible interpretations arise; (i) the mass ratio ($\alpha = m_1/m_2$) is sufficiently large that the velocities when measured with respect to the secondary's orbital velocity are equal at ingress and egress and, hence, the central object sits in the center of the disk; - (ii) geometry and departures from Keplerian motions are responsible for the difference, i.e., the disk may be elliptical with the central object closer to the disk's edge at egress.

An assumption that the disk is circular provides $\alpha = 1.9 \pm 0.4$ and the rotational velocity $v_{rot} = 33 \pm 4$ km s^{-1}. The assumption of a symmetric circular disk does not account for the fact that the absorption lines are much stronger at egress than at ingress. Perhaps the edge of the disk facing the primary is heated so that more gas is released by grains and, hence, the column density of gas at egress is increased. Our estimate of v_{rot} comes from the core of the K I 7699 Å line. The true Keplerian velocity is almost certainly larger than the measured velocity. Suppose that the gas is confined to a single circular orbit. Thanks to the finite width of the primary, gas along an arc contributes to the absorption line. The maximum velocity occurs when the tangent to the orbit intersects the primary, but all other lines of sight intersect gas moving at a smaller radial velocity, i.e., the absorption line's core velocity is displaced from the circular velocity. Since gas is distributed radially, too, and its density may decrease with increasing radius, a line's core will not be at the circular velocity (v_K) corresponding to the radius grazed by the tangent to the mid-point of the eclipsed portion of the primary. II write the inferred circular velocity as $v_K = pv_{rot}$. Saitō *et al.* predict p ~ 1.05 to 1.20 for selected lines near ingress and egress.

Radial distances across the disk may be estimated from the net velocity of the secondary across the primary and the contact times - see Saitō *et al.* (1985), Lambert and Sawyer (1986). We find a disk diameter $S_2[\mathrm{Km}] = 7.1 \times 10^8(1 + \alpha)$ and the primary's diameter $D_1[\mathrm{Km}] = 1.9 \times 10^8\ (1 + \alpha)$.

If the velocity v_{rot} (actually v_K) is identified with the Keplerian velocity at the disk's edge:

$$v_K^2 = \frac{2Gm_2}{S_2} \text{ and, thence, } \frac{m_2}{m_\odot} = 2.9\ (1 + \alpha)p^2$$

A second relation between m_2 and α is provided by the mass function f(m) = 3.25 ± 0.38 (Wright 1970, Webbink 1985),

$$\frac{m_2}{m_\odot} = 3.06\ (1 + \alpha)^2 \text{ (see Lambert and Sawyer 1986).}$$

Combining the equations, we find

$$(1 + \alpha) = 0.95\ p^2 \text{ and } \frac{m_2}{m_\odot} = 2.8\ p^4.$$

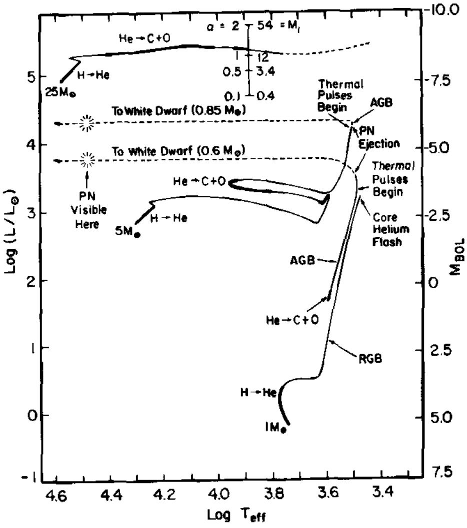

Fig. 5. The H-R diagram adapted from Iben (1985). Predicted luminosities for the primary star are shown as a function of the mass ratio α.

For p = 1.2 (maximum value?), we find α = 0.4, and $m_2 \cong 5.8\ m_\odot$. The estimate of α is less than that (α = 1.9 ± 0.4) required to make the velocity of the disk relative to the secondary's center of mass equal at ingress and egress. We suppose that a resolution of this discrepancy lies in the geometry of the disk and the binary orbit.

Now, I comment on the evolutionary status of the primary and secondary. By combining the stellar radius ($D_1/2$) with an estimate of the effective temperature, one obtains the luminosity of the primary ($L_1/L_\odot$): $\log L_1/L_\odot = 4.73 + 2 \log (1 + \alpha)$, see Figure 5. Two evolutionary scenarios for the primary are possible: (i) It is a massive star evolving from the main sequence to become a red supergiant. This the status customarily assigned to the primary, calls for $m_1 \sim 20$ to $30\ M_\odot$ and $\alpha \sim 1.5$ in order to be consistent with the theoretical tracks. The secondary mass $m_2 \sim 13$ to $20\ M_\odot$ is barely consistent with the range derived from the rotation of its disk. This primary is one of the most luminous stars in the Galaxy. Wilson (1971) noted that the primary has an "almost unprecedented luminosity" and constructed an alternative geometry for the secondary that permits the primary to have a smaller radius and, hence, a lower luminosity; (ii) the star is evolving rapidly to the left in the diagram having completed life on the AGB. This scenario (Eggleton and Pringle 1985) requires the present mass to be $m_1 \sim 1\ m_\odot$ and $\alpha \sim 0.3$ (i.e., $m_2 \sim 3\ m_\odot$). On the assumption that the primary evolved independently prior to mass transfer, its initial mass would appear to have been in the range $m_1 \sim 5$ to $10\ m_\odot$. The prediction that $m_2 \sim 3\ m_\odot$ is consistent with the rotation of the disk. The secondary's mass is so lowered on this picture that the puzzling absence of evidence for a luminous secondary is essentially resolved. This picture exploits the realization that mass transfer across a binary system can profoundly influence the evolution of the system's components. Although this idea is considered briefly in early papers on ε Aur (e.g. Woolf 1971), a recent concise reconstruction of ε Aur's history (Eggleton and Pringle 1985) influenced greatly our thinking.

Additional observational tests may be identified. A thorough spectroscopic analysis of the primary ought to provide the surface gravity and an estimate of the mass. The chemical composition may confirm that the primary has lost a considerable amount of mass, inspection of C I, N I, and O I lines reveals no hint of the rearrangement of CNO nuclei expected from H burning via the CNO-cycles. Infrared spectroscopy longward of about 10 μm should be attempted in a search for absorption or emission lines from the secondary's cool disk; their radial velocities should give the secondary's velocity amplitude and, hence, the mass ratio. The ultraviolet emission lines (e.g., O I 1302 Å, the Mg II 2800 Å cores) may arise from gas in the vicinity of the secondary, ionized by it, and sharing its orbital motion. The star(s) within the disk may be the source of the ultraviolet flux which, at wavelengths below about 1400 Å, was not reduced during eclipse (Parthasarathy and Lambert 1983). With the Space Telescope, spectroscopic examination of this flux should provide the spectral type of the star and, ultimately, its radial velocity and so the mass ratio of the system. A search for velocity variations should test the idea that the secondary is itself a binary.

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