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EPSILON AURIGAE IN ECLIPSE. I. ULTRAVIOLET SPECTROSCOPY DURING INGRESS AND TOTALITY

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Epsilon Aurigae is a long-period eclipsing system containing a F0 I*a* supergiant and an unseen slightly less-massive secondary. A primary eclipse began in mid-1982 with the unseen companion passing in front of the supergiant.

Low-resolution ultraviolet (*IUE*) spectra of ϵ Aur in 1982 and early 1983 provide eclipse light curves extending into the total phase of the current eclipse. The depth of eclipse from 3000 Å to 1700 Å is slightly deeper than at visual wavelengths ($0^{\mathrm{m}}.8$). The depth declines for $\lambda < 1700$ Å and is just $0^{\mathrm{m}}.2$ at $\lambda < 1300$ Å.

The disappearance of the eclipse at $\lambda < 1300$ Å may be attributed to a hot star or spot within the disk-shaped secondary. A main-sequence star of spectral type B0 accounts for the observations. However, an alternative site of the ultraviolet excess may be the primary's upper photosphere or chromosphere.

Key words: stars individual—eclipsing binaries—ultraviolet: spectra

I. Introduction

Epsilon Aurigae is a unique long-period eclipsing system consisting of a F0 I*a* supergiant and an unseen slightly less-massive secondary. Every 27.1 years, the secondary eclipses the supergiant which fades by about $0^{\mathrm{m}}.8$ with totality lasting some 330 days. Throughout the eclipse, the primary spectrum remains visible. The shape of the primary eclipse, the lack of a secondary eclipse when the secondary passes behind the primary and the failure to detect the secondary either spectroscopically or spectrophotometrically lead to the currently favored models of the secondary based on Huang's (1965) concept of a central stellar object embedded in a large opaque disk. The opacity is most probably contributed by large dust particles.

The last eclipse occurred in 1955. With the advent of the *International Ultraviolet Explorer* satellite (*IUE*) and the expansion of observing facilities on the ground, a flood of new results may be anticipated from the current primary eclipse which began in mid-1982. In this paper, we discuss our *IUE* spectra obtained between April 1982 and April 1983. First contact occurred in July 1982 and totality began in November–December 1982. Chapman, Kondo, and Stencel (1983) and Boehm, Ferluga, and Hack (1983) have discussed *IUE* spectra covering portions of the ingress. Our more extensive set of low-resolution spectra provide several new results (see Parthasarathy and Lambert 1983).

II. Observations and Results

Epsilon Aurigae was observed on eight occasions; an observing log with a description of the spectra will be presented elsewhere. We have used the standard extracted spectrum provided on the Guest Observer's tapes. When two or more exposures of the same spectral interval were obtained in an observing session, they were combined to reduce the noise. Exposures through the small aperture where only about 50% of a star's flux is transmitted were scaled to the fluxes measured through the large aperture by examining the wavelength interval recorded satisfactorily through both apertures.

The eclipse is conveniently described by the magnitude difference

$$\Delta m_{\lambda}(t) = -2.5 \log f_{\lambda}(t)/f_{\lambda}(\mathrm{ref}) \quad ,$$

where the flux at time t is compared with that on 1982 April 25 ($\equiv$ ref). Light curves for selected wavelengths are shown in Figure 1. The curve for 5000 Å is obtained from the spacecraft's fine-error sensor (FES)—see Holm and Rice (1981). Our superposition (Fig. 1) of the visual light curve upon the ultraviolet light curves shows that the curves for $\lambda \gtrsim 1600$ Å are fairly similar. For $\lambda < 1600$ Å, the eclipse is shallower and the light curve changes progressively with decreasing wavelength. Figure 2 shows that the depth of eclipse for four phases during totality is nearly independent of wavelength from 1800 Å to 5000 Å. The light curves are remarkably regular with only a slight indication of the Cepheid-like $0^{\mathrm{m}}.2$ variations described extensively in the literature (cf. Fredrick 1960; Stub 1972). We suppose that either our sampling rate was too low to define the light variations or the primary was near quiescence during ingress.

At each of the four phases, the depth of eclipse increases slightly from 5000 Å to 2000 Å: the mean depths are $\Delta m = 0^{\mathrm{m}}.78$ (5000 Å), $0^{\mathrm{m}}.89$ (3090 Å–2655 Å), and $1^{\mathrm{m}}.05$ (2505 Å–2000 Å). The individual results of the separate phases are quite concordant (e.g., $\Delta m = 1^{\mathrm{m}}.05$, $1^{\mathrm{m}}.08$, $1^{\mathrm{m}}.04$, and $1^{\mathrm{m}}.03$ for the 2505 Å to 2000 Å interval) so that the effect is real. Our observations show the

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[*] Guest observer with the *International Ultraviolet Explorer* satellite.

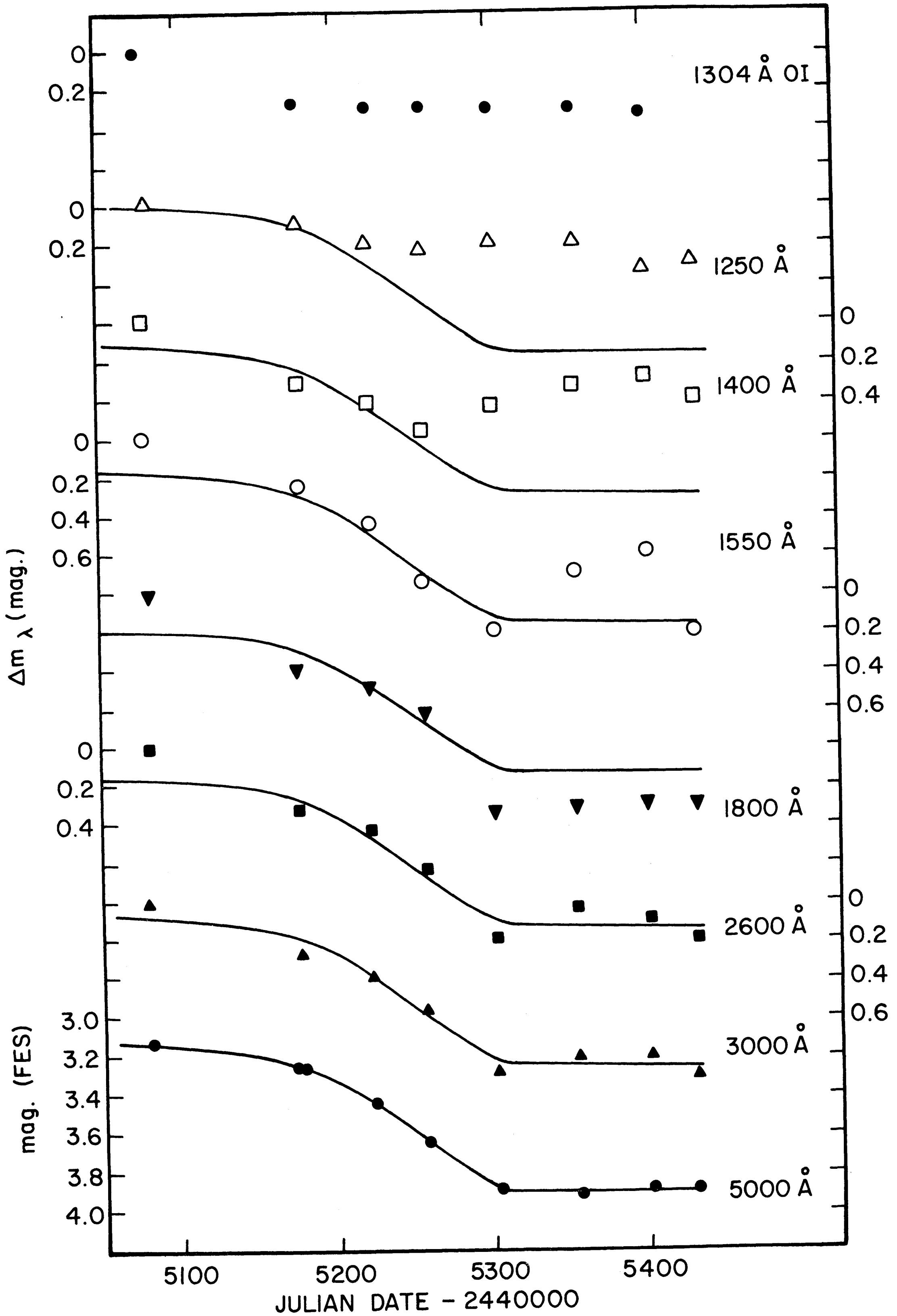

FIG. 1—Light curves for ε Aur. The 5000 Å curve is derived from the FES counts. The curves for six 'continuum' points between 3000 Å and 1250 Å are based on low-resolution *IUE* spectra. The curve drawn through the points is the FES curve shifted to fit by eye the points on the declining portion. The integrated line flux of the 1304 Å O I line is shown at the top of the figure.

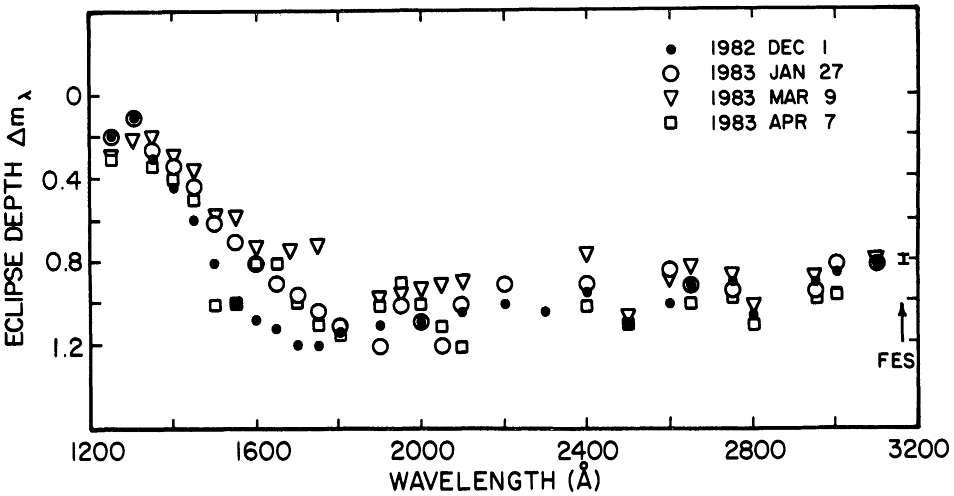

FIG. 2—The wavelength dependence of the depth of the total eclipse at four epochs.

eclipse depth to be about $0^{\mathrm{m}}.2$ for $\lambda \leq 1300$ Å. The absolute level of the scattered light in the spectrograph will be reduced in eclipse. Our best estimate (see below) for the scattered light shows that it makes a $0^{\mathrm{m}}.1$ (and possibly a $0^{\mathrm{m}}.2$) contribution to the eclipse. Since ϵ Aur is slightly variable outside of eclipse, the fluxes for 1982 April 25 may not represent the average condition of ϵ Aur outside of eclipse. In short, we cannot exclude the possibility that the eclipse is absent for $\lambda \lesssim 1300$ Å.

These results which were given in a preliminary report (Parthasarathy and Lambert 1983) extend Boehm et al.'s conclusions drawn from a single observation during totality. The *IUE* and other results show that the eclipse is effectively gray from 1600 Å to 5 μm; Bachman et al. (1983) reported infrared photometry. A comparison of LWR images for 1982 April 13 and September 21 led Chapman et al. (1983) to conclude that the eclipse depth during ingress increased significantly across the interval from 3000 Å to 1800 Å; the partial eclipse was $0^{\mathrm{m}}.46$ deep at 3000 Å and $0^{\mathrm{m}}.80$ deep at 1800 Å Boehm et al. attribute this discordant result to Chapman et al.'s selection of 1982 April 13 as the out-of-eclipse reference point. Observations on 1982 March 12 and 26 show a wavelength dependent flux excess at $\lambda \leq 2300$ Å relative to fluxes recorded in August 1981, a year prior to first contact. Boehm et al. suggest that the excess flux persisted through to 1982 April 13 and, therefore, those observations are inappropriate as a standard. We concur. Our selection of 1982 April 25 as the standard epoch for the out-of-eclipse fluxes is justified by two factors. First, the ultraviolet fluxes are quite similar to those reported for August 1981. Second, our major conclusions are unchanged when we select 1982 July 29 as the reference point (the latter observations were obtained just after first contact).

The O I 1304 Å and the Mg II 2800 Å lines are in emission. Our spectra extend into totality Chapman et al.'s observation that the emission cores of the Mg II resonance doublet are unaffected by the eclipse; our high-resolution spectra will be discussed elsewhere. The O I emission-line flux is also largely unaffected by the eclipse (see also Ake and Simon 1983; Parthasarathy and Lambert 1983; Boehm et al. 1983). Figure 1 shows that the flux in the O I line is a factor of 2 less during the partial and total eclipse than on 1982 April 25. An observation on August 1981 shows the line at the level reported by the 1982–83 eclipse. Apparently, the line is of variable intensity.

III. Does the Secondary Contain a Hot Star?

The shallow eclipse at $\lambda \lesssim 1400$ Å suggests that the uneclipsed secondary is hot (Boehm et al. 1983). Hack and Selvelli (1979) proposed this idea after comparing *IUE* spectra of ϵ Aur (out of eclipse) and Canopus (spectral type F0 I*a*) and noting that ϵ Aur exhibits a flux excess at $\lambda \lesssim 1600$ Å. After their examination of recent *IUE* spectra, we present a more complete characterization of the supposed hot secondary, discuss some difficulties with the concept and, in the following section, propose an alternative explanation for the shallowing of the eclipse in the ultraviolet.

Out of eclipse, the observed flux is the sum of contributions from the primary and secondary

$$f_\lambda^{\mathrm{out}} = f_\lambda^{\mathrm{pr}} + S_\lambda^{\mathrm{pr}}(\Lambda) + f_\lambda^{\mathrm{sec}}$$

in a straightforward notation. Here $S_\lambda^{\mathrm{pr}}(\Lambda)$ denotes the contamination at wavelength λ by scattered light in the spectrograph. We assume that the primary whose flux increases steeply to longer wavelengths contributes the scattered light (i.e., $\Lambda > \lambda$). During eclipse when the primary's flux is decreased by a factor *r*, the observed flux may be written

$$f_\lambda^{\mathrm{in}} = r(f_\lambda^{\mathrm{pr}} + S_\lambda^{\mathrm{pr}}(\Lambda)) + f_\lambda^{\mathrm{sec}}$$

Observations at the longer wavelengths where we may expect the secondary to make a negligible contribution provide an estimate of r. Then, observations in and out of eclipse are readily combined to yield $(f_\lambda^{\mathrm{pr}} + S_\lambda^{\mathrm{pr}}(\Lambda))$ and f_λ^{sec} with the latter providing information on the secondary's temperature and radius. Our method is based on some simple assumptions. For example, the factor r is taken to be wavelength independent. Large dust grains (i.e., grain size larger than the wavelength of light) in the secondary's disk appear to be the only plausible explanation for the wavelength independent (1600 Å to 5 μm) eclipse and the opacity of such grains will not increase below 1600 Å. Since the response of the spectrograph's camera is wavelength dependent, the analysis should be applied to the raw signals (flux numbers) for highest accuracy.

Inspection of Figures 1 and 2 shows that ϵ Aur fails to recognize our assumptions because the 1300 Å to 1600 Å flux varies during totality. Although observations through to egress will be the test, the variation is possibly symmetrical about mideclipse and, hence, its origin if the secondary is a hot star, should be sought in the eclipse geometry; i.e., one or both of the stars is not spherically symmetric or the ultraviolet transmission of the disk varies with position angle.

With the fluxes observed on 1982 April 25 as the f_λ^{out}s, we derived the primary $(f_\lambda^{\mathrm{pr}} + S_\lambda^{\mathrm{pr}}(\Lambda))$ and secondary f_λ^{sec} fluxes for four dates following second contact. The mean fluxes and the total range are indicated in Figure 3. We adopted $r = 0.38$ ($\Delta m = 1.05$) which is the grand mean for the interval 2000 Å to 2505 Å to which the secondary should not contribute. An extrapolation of the measured r's over the 3090 Å to 2000 Å interval would suggest a slightly smaller value of r. On the other hand, the value of r appropriate to the scattered light will be somewhat larger than $r = 0.38$. The observed range, which is dominated by the uncertainties of the observed fluxes, exceeds the range resulting from the possible range in r.

The primary's flux (Fig. 3b) decreases sharply with decreasing wavelength. At the shortest wavelengths, scattered light is expected to make the dominant contribution. When we use recipes outlined by Clarke (1981) and Crivellari, Morossi, and Ramella (1980), we estimate the scattered light at $\lambda \lesssim 1600$ Å to be $S_\lambda^{\mathrm{pr}}(\Lambda) \approx 0.2 \times 10^{-13}$ with an upper limit of 0.35×10^{-13} (units = ergs cm^{-2} sec^{-1} Å^{-1}). The derived flux at 1250 Å is $f_\lambda^{\mathrm{pr}} + S_\lambda^{\mathrm{pr}}(\Lambda) \simeq S_\lambda^{\mathrm{pr}}(\Lambda) \simeq 0.24 \times 10^{-13}$, which is consistent with our estimate for the scattered light.

The secondary's flux is obtainable for $\lambda \lesssim 1500$ Å; at longer wavelengths, the secondary's contribution is too small to be extracted reliably. In Figure 3a, we show the flux after correction for interstellar reddening equivalent to $A_V = 1$ mag, which is appropriate for a star at a dis-

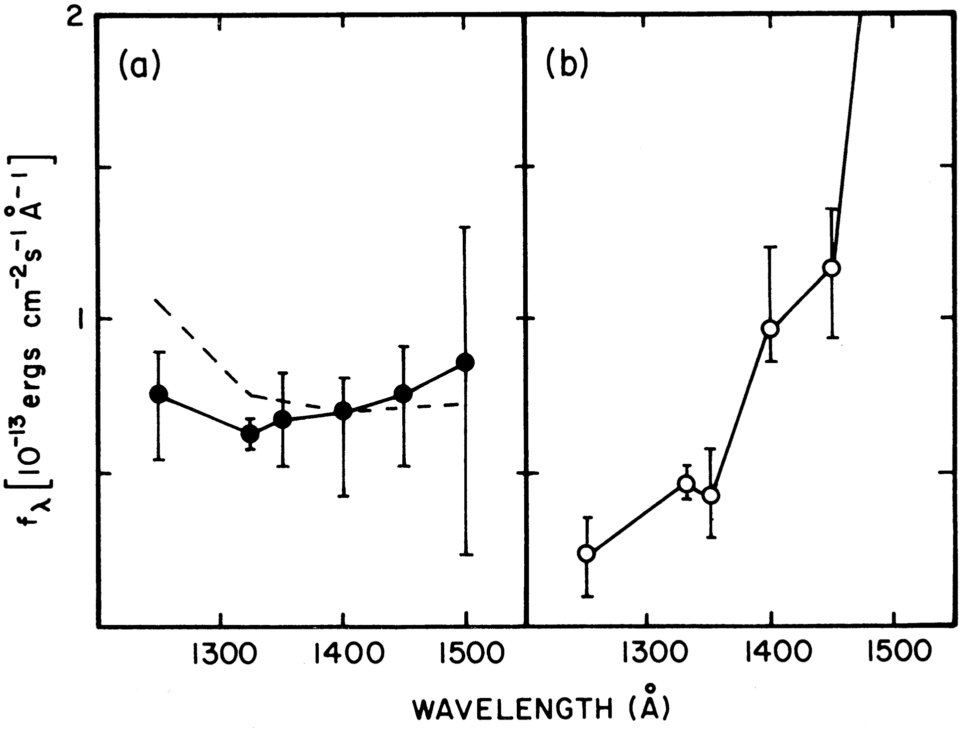

FIG. 3—The derived secondary (f_λ^{sec} in panel (a)) and primary ($f_\lambda^{\mathrm{pr}} + S_\lambda^{\mathrm{pr}}(\Lambda)$ in panel (b)) fluxes—see text. The broken line in panel (a) shows the secondary fluxes after correction for interstellar reddening and normalized to 1400 Å.

tance of 1 kpc in the Galactic plane. Seaton's (1979) formulae for the ultraviolet extinction were adopted. We assume that extinction within the disk is gray.

On the assumption that the secondary is a blackbody radiator of 1 kpc, the flux corrected for interstellar reddening requires a source with an effective radius of 1.7 $R_\odot$ for $T_{bb} = 15{,}000$ K, 0.3 $R_\odot$ for $T_{bb} = 30{,}000$ K, and 0.06 $R_\odot$ for $T_{bb} = 100{,}000$ K. The radius of the secondary cannot be readily estimated because we lack critical information on the extinction within the disk and the geometry of the hot star and the disk. Of course, $R_{sec} \geq R_{eff}$ is necessary. If the hot star is at the disk's center and our line of sight is in the plane of the optically thick disk, the emission must come from the stellar poles peeking above and below the disk. Since the thickness of the disk is 340 $R_\odot$ (Huang 1965; Morris 1965), this geometry requires $R_{sec} \sim 170$ $R_\odot$ for all probable T_{bb}'s. Such an estimate seems unreasonable because it exceeds by a factor of five or more the radii of early-type supergiants.

An alternative model of a disk with 'tunnels' through which the hot star is viewed would permit the stellar radius to be much smaller than the disk thickness. Motions within the disk will cause 'tunnels' to open and close and, hence, produce ultraviolet flux variations. This model accounts for the factor of 4 increase in flux at $\lambda \lesssim 1600$ Å which occurred in March 1982 before first contact (Boehm et al. 1983). The wavelength dependence of f_λ^{sec} is not well determined. The possible increase in the reddening-corrected flux from 1400 Å to 1250 Å suggests $T_{bb} \gtrsim 30{,}000$ K. The slope of the flux curve is dependent on our assumption that the extinction with the disk is gray. A B0 main-sequence star with mass $\mathfrak{M} \sim 18$ $\mathfrak{M}_\odot$, radius $R \sim 7$ $R_\odot$, and effective temperature $T_{eff} \sim 28{,}000$ K (Allen 1973) is a plausible candidate for the hot star. In this picture, the less-massive secondary lags the primary in its evolution. The star may not yet be on the main sequence. The existence of the disk suggests a protostar.

A potential difficulty with the model may be the lack of emission lines from gas within the system which ought to be photoionized by a hot star. The O I 1304 Å emission probably results from fluorescence with $L\beta$ photons which are, perhaps, produced by recombinations in the photoionized gas. A large increase in the strength of resonance lines of Na I and K I (Parthasarathy and Lambert 1983) shows that neutral gas resides within the disk and is shielded from the hot star. The model with 'tunnels' would explain this observation. If a hot star resides within the disk, the secondary eclipse, which is not seen in the visible, is expected to be nearly total at $\lambda \lesssim 1300$ Å. This test in 1996 may be required to establish conclusively the existence of a hot star (or spot) with the secondary's disk.

IV. An Alternative Model

After correction for interstellar reddening, the fluxes from 3200 Å to 1300 Å are reproduced quite well by the predicted fluxes for a model bracketed by published models (Kurucz 1979) for $T_{eff} = 7500$ K and 8000 K at a surface gravity $\log g = 1$. This suggests that a hot star (or spot) is not a required ingredient. Inspection of the ratio of the predicted fluxes for the two models shows a dramatic change to occur at 1520 Å; e.g., $f_\lambda(8000)/f_\lambda(7500) = 3$ near 2000 Å, 8 near 1600 Å but 130 at 1500 Å. A large but less remarkable change occurs between $T_{eff} = 8000$ K and 8500 K; e.g., $f_\lambda(8500/f_\lambda(8000) = 2.6$ at 1600 Å and 10 at 1400 Å. These changes reflect, in part, a large increase in the total continuous opacity at $\lambda < 1520$ Å arising from photoionization of neutral Si atoms in the $3p^2$ ^3P ground term. The presence of the Si I photoionization edge encourages us to sketch alternative models. These refer to the supergiant primary and consider the secondary to be opaque and dark in the visible and ultraviolet. (The sensitivity of the emergent flux at $\lambda \lesssim 1500$ Å to atmospheric structure implies that it is nigh impossible to tify a standard comparison star for ϵ Aur from examination of fluxes at longer wavelengths.)

The primary may possess a thin chromosphere such that the star may be strongly brightened at $\lambda \lesssim 1520$ Å. If the ultraviolet flux is provided by a thin layer around the star's circumference, it is readily shown that a central eclipse dimming the star by $0^m\!.8$ at long wavelengths will dim the star by $0^m\!.33$ at wavelength for which the thin layer dominates the emission. Figure 2 shows that the eclipse depth is about $0^m\!.25$ at $\lambda \lesssim 1300$ Å; the actual depth is less than this thanks to contamination by scattered light (see above). The discrepancy of $0^m\!.1$ to $0^m\!.2$ between the observations and the simple model is removed if we suppose that either the primary's chromosphere and upper photosphere are not spherically symmetric or the chromospheric emission is variable. If the poles are marginally warmer than the equatorial zones crossed by the opaque secondary, the eclipse depth predicted for 1300 Å and below can be made very small. In this model, the O I 1304 Å and the Mg II 2800 Å emission, which do not participate in the eclipse, are also produced in the primary's chromosphere.

A second family of models may be constructed around the idea that the primary is not spherically symmetric owing to an interaction between the primary and secondary. The appearance of line doubling in excited lines of metallic ions (see Struve, Pillans, and Zebergs 1958) suggests that ionized gas exists between the stars. We speculate that the primary's upper photosphere is heated such that in eclipse, the surface brightness at ultraviolet wavelengths is higher than at other times. Although inappropriate to such distorted atmospheres, Kurucz's

(1979) models show that a temperature increase of about 10 K over the uneclipsed area is sufficient to eliminate the eclipse at $\lambda \lesssim 1400$ Å. Perhaps, it is more probable that the heated regions by confined to a portion of the surface. Then, if the basic photosphere corresponds to the $T_{\rm eff} = 7500$ K model, a spot at $T_{\rm eff} = 8000$ K having an uneclipsed fractional area of 0.1% of the primary's surface area suffices to reproduce the observations. The spot's area is increased to 2% for a spot at 8500 K in a photosphere of $T_{\rm eff} = 8000$ K. The spot may be considerably larger with most of its area obscured by the opaque secondary. In Figure 4, we show the predicted wavelength dependence of the eclipse for these two spot models. Clearly, the agreement is good. This second family of models is open to one basic objection. The emergent flux at $\lambda < 1520$ Å is so sensitive to the temperature profile of the upper atmosphere that alterations should often result in a higher flux. Perhaps, our span of *IUE* observations is too short. We may note that before first contact the flux at $\lambda \lesssim 1600$ Å was higher than normal by a factor of four. Had this brightening occurred in eclipse, it could have pushed the flux above its pre-eclipse levels.

The slight increase in the depth of totality over the interval 5000 Å to 1700 Å (Fig. 2) is possibly attributable to limb darkening of the primary's absorption lines; the line blocking is enhanced as the central zones of the star are eclipsed. A careful examination of high-resolution spectra may test this idea.

V. Concluding Remarks

The observations reported here greatly extend previous discussions of the ultraviolet spectrum of ϵ Aur (Chapman et al. 1983; Boehm et al. 1983). A marked characteristic of the primary eclipse is its wavelength independent shape from the visible to the infrared ($\lambda \lesssim 5$ μm). Our results show that this characteristic extends to about 1600 Å; the total eclipse is about $0^{\rm m}.25$ deeper around 1800 Å than at 5000 Å. For $\lambda < 1600$ Å, the depth of the total eclipse decreases with decreasing wavelength such that there may be no eclipse at $\lambda \lesssim$ 1300 Å.

This absence of an eclipse suggests that a hot source lies within the disk-like secondary. Although we show that a main-sequence star near spectral type B0 will account for the derived ultraviolet spectrum of the secondary, we point out that the primary alone may account for the absence of an eclipse. A thin chromosphere, polar caps, or an active region near the subsecondary point would account qualitatively for the maintenance of the flux at $\lambda \lesssim 1600$ Å in eclipse at out-of-eclipse levels. The wavelength dependence is a rational consequence of the Si I photoionization edge at 1520 Å. In this interpretation, the secondary is dark in the ultraviolet just as it is in the visible and near-infrared; large dust grains are the most likely source of the disk's opacity.

Continued study of ϵ Aur during this eclipse may clarify the rôles of a hot star or spot within the secondary and chromospheric inhomogenieties on the primary. Our

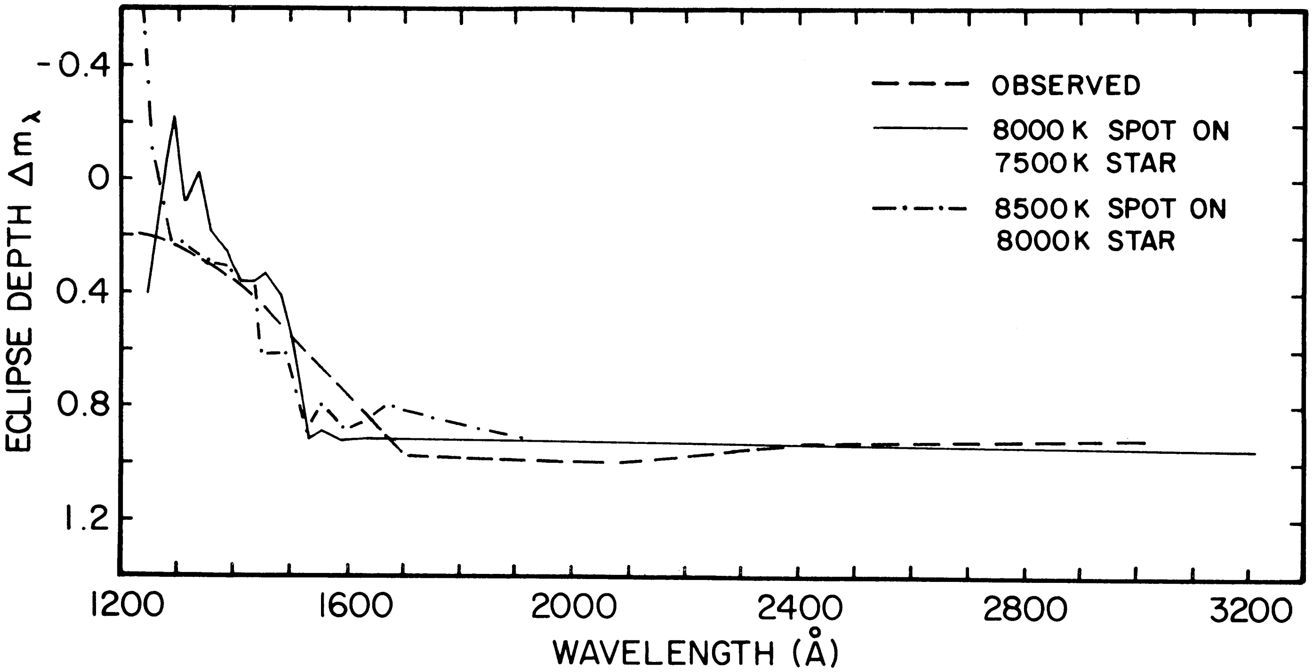

FIG. 4—The predicted eclipse depths for a primary with a warm spot (see text). The broken line is the mean observed relation based on Figure 3.

current investigation suggests that both may contribute to the ultraviolet flux variations seen in and out of eclipse.

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