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INTERPRETING EPSILON AURIGAE

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ABSTRACT

The eclipsing binary ϵ Aurigae consists of an F0 supergiant and a cool, mysterious eclipsing companion with an orbital period of 27.1 yr. The light curve of this system reveals two sources of variability: the eclipses themselves and the variation of the supergiant. Photoelectric observations were made with the 38 cm reflector at the Villanova University Observatory. The bright star undergoes semiregular light variations both inside and outside of eclipse, with a characteristic time scale of a few months which are found to correlate extremely well with changes in color index. It appears that these light and color variations arise from pulsations of the supergiant. The light variations are similar to those found for other luminous A-F supergiants. The leading explanations of the nature of the eclipsing object have been the edge-on disk proposed by Huang and the tilted disk proposed by Wilson. The most recent data show a mid-eclipse brightening that can only be explained by a tilted disk with a central opening and possible transparency changes across the disk. We have developed a computer code to model the eclipse with these constraints, and explore possible configurations of the disk. The properties of the disk appear more consistent with an interpretation as a protoplanetary system than a remnant of mass transfer from the supergiant. This makes ϵ Aur an even more interesting system than was previously believed.

Subject headings: stars: accretion — stars: eclipsing binaries — stars: individual (Epsilon Aurigae)

I. INTRODUCTION

The long period (27.1 yr) eclipsing binary ϵ Aurigae (F0 Iap + ?) is one of the most puzzling stars in the Galaxy. The mysterious nature of the eclipsing object in this unique system has puzzled astronomers for over a century, beginning with the first recorded minimum by Fritsch in 1821. The recent eclipse (1982–1984), however, has provided a wealth of new data from which we can gain more insight than ever before.

The star's 27 year orbital period is the longest known of any eclipsing binary. Photometric observations of the eclipses have revealed a long-lasting, nearly flat-bottomed eclipse. Such a light curve usually indicates a total occultation of one component. However, the spectrum of the system does not change during the eclipse, which means only the spectrum of the bright component is ever seen. The first reasonable explanation for this phenomenon was proposed by Kuiper, Struve, and Strömgren (1937). They postulated that the eclipsing component was a huge, tenuous star which was partially transparent. For much of this century, astronomy textbooks listed the eclipsing member of ϵ Aur as the largest known star in the universe. Hack (1961) envisioned a small B star surrounded by shells of ionized material. However, the extreme size of such an object and the implausibility of the proposed mechanism for the eclipse (electron scattering) led Huang (1965) to advance a disk model. He suggested that the dark component was a star surrounded by a thick, opaque disk seen directly edge-on. In projection the disk will appear as an elongated rectangle. As the rectangle passes in front of the bright star, it covers about one-half of the star's area, and the eclipse remains essentially flat between second and third contact. This model is still considered viable today; one of the purposes of this paper is to examine its status as an explanation for this system. Once such a disk is postulated, an important question involves its origin; is it the result of mass transfer from the supergiant, or is it a remnant of the formation of the system? We shall argue that the disk was not formed by mass transfer, and is indeed a protoplanetary disk similar to those found in many young stars.

The 1982–1984 eclipse of ϵ Aur was the target of more extensive and sophisticated observation and analysis than any previous eclipse. Photoelectric photometry was obtained by many observers as part of a coordinated campaign (see e.g., Hopkins 1985; Donahue *et al.* 1985; Flin *et al.* 1985; Stencel 1986; Schmidtke *et al.* 1985; and many others). Also acquired were optical spectroscopy (Barsony *et al.* 1986; Thompson *et al.* 1987; Ferluga and Hack 1985; Lambert and Sawyer 1986), ultraviolet spectroscopy (Boehm *et al.* 1984; Ake and Simon 1984; Altner *et al.* 1984, 1986), infrared photometry (Backman *et al.* 1984; Backman 1985), infrared spectroscopy (Hinkle and Simon 1987) and polarimetry (Kemp *et al.* 1986; Kemp *et al.* 1985).

In this paper we analyze multibandpass photoelectric photometry of the recent eclipse of Epsilon Aurigae from Villanova University Observatory and elsewhere to help us understand the nature of this unusual system. The depth and shape of the light curve during eclipse offer clues to the morphology and composition of the cool eclipsing object. (We will, in response to the plea from Koch 1986, attempt to refrain from referring to the components as "primary" and "secondary," since it is still uncertain which component is the more massive object.)

This paper analyzes the eclipse and presents a model for the disk. We also give outcomes of computer simulations of different configurations of the disk, and discuss the results. Preliminary reports of this study were given by Donahue *et al.* (1985) and Carroll *et al.* (1988, 1989).

II. THE BRIGHT SUPERGIANT COMPONENT

a) Distance and Luminosity

Little of what we do know about ϵ Aur is certain (see Table 1). The bright star is usually listed as an F0 supergiant, although spectral types given range from between A8 and F2. Many of its absolute parameters depend on the distance. In 1978, van de Kamp equated his astrometric value for the semimajor axis of $a_1 = 0''.0227 \pm 0''.0010$ with Wright's (1970) spectroscopic value of $a_1 = 13.2$ AU. This method yields a value of 580 ± 30 parsecs. With this distance, and assuming an interstellar absorption of $A_v = 0.84$ (Morris 1963), van de Kamp derives an absolute magnitude of $M_v = -6.7$ mag. However, both the astrometric and spectroscopic values for the semimajor axis are uncertain; for instance, Strand (1959) obtained a value of $a_1 = 0''.014 \pm 0''.004$, which yields a distance close to 1000 pc, which in turn implies an absolute magnitude $M_v = -7.9$ mag. In addition, less direct methods seem to indicate that this latter value is more accurate. Stothers (1971) has suggested that ϵ Aur is a member of the association Aur OB 1. This association lies at a distance of 1340 pc with approximate boundaries $l = 168°$ to $178°$ and $b = -7°$ to $+4°$ (Ruprecht 1966). The space motions and color excess of Aur OB 1 are similar to that of ϵ Aur. If it were a member, the absolute magnitude of the star would be -8.5 mag. This value is also suggested by the semi-period-color-luminosity relation for supergiants (Burki 1978). This empirical relation can be expressed as:

$$M_{\rm bol} = 28.76 - 2.63 \log (P) - 1.32 \log (M) - 7.9 \log (T_e) ,$$

where P is in days, and M is in solar masses. If the mass of the supergiant is 15 $M_\odot$ (and the period is taken to be 110 days) this formula yields an absolute visual magnitude $M_v = -8.8$ mag; a mass of 2 $M_\odot$ yields $M_v = -7.7$ mag. These numbers are corroborated by a relationship discovered by Osmer (1972) between absolute magnitude and the equivalent width of O I at 7774 Å:

$$M_v = -2.62W - 2.55 .$$

Osmer lists an equivalent width $W = 2.51$ Å for ϵ Aur, which indicates $M_v = -9.1$ mag, with a claimed error of ± 0.5 mag. It should be noted that ϵ Aur had the highest value for W of any of the 60 stars in Osmer's study. There are other, similar relations between luminosity and equivalent widths of various lines (e.g., Kondo *et al.* 1976), but none are specifically applicable to F-type supergiants. Finally, we can consider typical values for M_v for F0 Ia stars. However, the values found in the literature are too uncertain to be of much assistance; Blaauw (1963), for example, gives $M_v = -8.5$ as typical for such stars, while Allen (1963) gives $M_v = -6.8$. Further astrometric studies are obviously necessary to determine accurately the distance and luminosity; however, the preponderance of evidence indicates a distance of ~ 1000 pc, and an absolute magnitude of at least $M_v = -8.0$.

b) Evolutionary State

Webbink (1985) has reviewed the possibilities for the evolutionary stage of the supergiant. He concludes that two scenarios are the most likely. The first, long-accepted idea, is a post–main-sequence star in a state of shell helium burning. Such a star would be very massive, at least 11 solar masses and possibly higher. With a mass function of $f(m) = 3.12$ $M_\odot$ (Morris 1962) and an orbital inclination near 90°, this implies that the dark component would be of approximately the same mass. The second model, suggested by Eggleton and Pringle (1985), is that the supergiant is a low-mass, post–Asymptotic Giant Branch star, evolving toward a planetary nebula (PN) phase. One long-standing problem has been how an object as massive as the eclipsing disk is purported to be can be so under-luminous. This recent suggestion helps to deal with that problem by allowing the mass of the supergiant (and therefore the disk, as well) to be lower than previously assumed. However, the pre–PN stage is such a short-lived phase of a star's existence that it seems improbable that this system would contain such a star.

In support of the proposal that the supergiant is in a rapidly evolving pre–PN state, Saito and Kitamura (1986) present evidence from radial velocities that the star has undergone episodes of catastrophic contraction, and argue from the changes in contact times (Table 2) that the supergiant has decreased by 16% of its radius in the last 27 years. (They equate this to a decrease in radius of 0.2 AU, on the basis of Castelli's 1978 estimate of the radius of the F star, $R = 277$ $R_\odot$. However, the absolute size of the supergiant is uncertain, and would be closer to 100 $R_\odot$ if van de Kamp's distance determination were correct.) This observation, if confirmed, would obviously dramatically support the hypothesis that the bright star is collaps-

TABLE 1

A. Basic Data on Epsilon Aurigae

Period	$P = 27.1$ yr = 9890 days	
Temperature	$T(1)_{\rm eff} = 7800$ K	1
	$T(2)_{\rm eff} = 475$ K	2
Mass function	$\frac{(m_2 \sin i)^3}{(m_1 + m_2)^2} = 3.12$ $M_\odot$	3
Apparent magnitude	$m_V = 2.96$	4
Distance	500–1500 pc	
Galactic coordinates	$l = 162°.79$, $b = +1°.18$	
Radial velocity	$V_0 = -1.29$ km s^{-1}	4

B. Space Motions for Different Distances

r	z(pc)	U'	V'	W'	(km s^{-1})
580	12	−5.5	−3.8	+2.4	(wrt LSR)
750	15	−4.6	−6.7	+1.1	
900	19	−3.8	−9.3	0.0	

References.—(1) Castelli 1978; (2) Backman 1985; (3) Morris 1962; (4) van de Kamp 1978.

TABLE 2

Duration of Phases for ϵ Aurigae Eclipses[a]

Phase (in days)	1982–1984	1955–1957	Previous (Combined)
Ingress	137	135	182
Totality	446	394	330
Egress	64	141	203

[a] From Schmidtke 1985.

ing rapidly. However, there is strong evidence that the star undergoes pulsation, which would tend to cause spurious radial velocity determinations and might mimic a "collapse" of the atmosphere. Further, it seems unlikely that a well-observed star could dramatically shrink over such a short time scale without producing noticeable variations in luminosity. In fact, historical records seem to indicate that ϵ Aur has been near its present luminosity for at least 2000 yr; we have examined star catalogs from antiquity (Baily 1843; Peters and Knobel 1915; Knobel 1917) to search for any evidence that ϵ Aur was once more luminous than today, but none was found.

Nevertheless, neither the high-mass or low-mass configurations can be ruled out by these data. The choice between these two alternatives affects not only the evolutionary status of the binary, but the mass and dimensions of the entire system, as well as the interpretation of the origin of the disk (see below). Thus it is crucial that observations be made which will make that choice more clear.

c) *Photometric Observations*

We observed ϵ Aur with the 38 cm telescope at Villanova University Observatory using a photoelectric photometer equipped with a refrigerated EMI 9558 photomultiplier. The observing sequence was the usual pattern of *sky-comparison variable-comparison-sky*. The comparison star was HR 1644 (BD+42°1170, HD 32655, F2 II, $m_V = +6.20$), which was chosen rather than the more popular choice λ Aur because of HR 1644's angular proximity to the variable star and because of its similar spectral type. Using the closer comparison star significantly reduced the uncertainty arising from differential atmospheric extinction corrections. It also permitted observations to be made through larger air masses, thus extending the observing season of ϵ Aur so that observations near mid-eclipse could be obtained without introducing significant errors. The observations were made with a pair of Hα narrow- and intermediate-band filters and an intermediate-band blue (λ4530) filter. These filters have the following characteristics: HαN ($\lambda_{max} = 6567$ Å; FWHM = 35 Å); HαI ($\lambda_{max} = 6600$ Å; FWHM = 280 Å); and blue ($\lambda_{max} = 4530$ Å; FWHM = 150 Å). The Hα-intermediate band filter has a bandpass broad enough to be little affected by the included Balmer Hα feature and yields a satisfactory continuum measure at λ6600. The Hα filter pair has characteristics close to the filters used to define the Villanova α index system (see Baliunas *et al.* 1975).

Differential magnitudes in the sense *variable-comparison star* $(V-C)$ were computed from the data. These were averaged to determine nightly means for observations made in each filter. Differential α indices ($\Delta\alpha$) were formed from the Hα filter set as

$$\Delta\alpha'(V-C) = \Delta m(\text{H}\alpha N) - \Delta m(\text{H}\alpha I) .$$

Differential $\Delta(b-r)$ color indices were formed from the differential blue (b) and Hα intermediate band measures:

$$\Delta(b-r)' = \Delta m(b) - \Delta m(\text{H}\alpha I) .$$

The nightly mean differential blue (λ4530) and red (λ6600) observations of ϵ Aur are plotted against time in the upper panel of Figure 1. The nightly mean differential $\Delta(b-r)$ colors and $\Delta\alpha'$ indices are plotted in the bottom panel of Figure 1. The estimated first, second, third, and fourth contact times as well as the time of mid-eclipse are shown. From the definition of the α index, more negative values of $\Delta\alpha'$ indicate a net increase in Hα emission or a decrease in absorption. The level of no significant Hα emission is indicated in the figure and was determined by comparing the Hα indices for ϵ Aur and its comparison star with stars of similar spectral type showing no Hα emission.

Also plotted in the figure are differential V-band observations of ϵ Aur made at Tjornisland Astronomical Observatory in Sweden (Ingvarsson 1984) during the time of mid-eclipse. These were used to supplement the Villanova observations when ϵ Aur was difficult or impossible to observe elsewhere because of its low elevation in the late spring and early summer. These observations are indicated in the figure by the symbol "V."

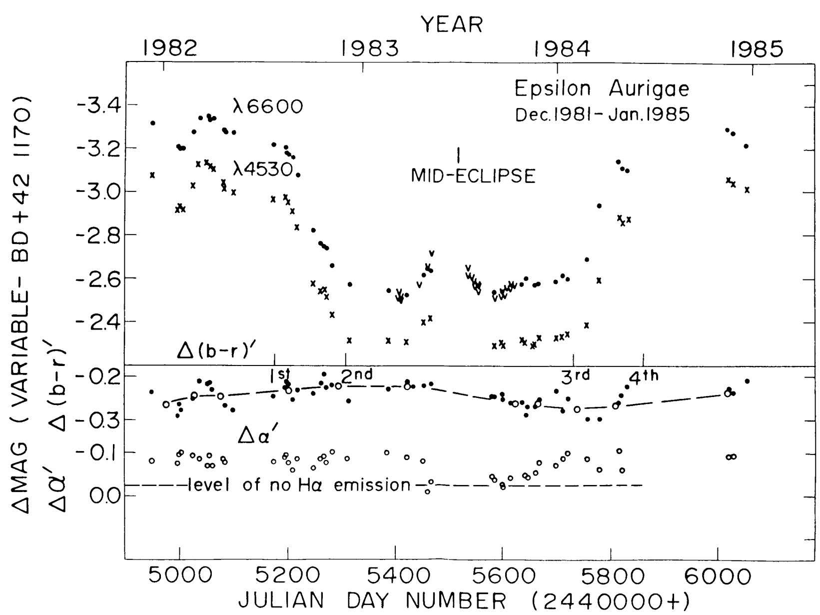

FIG. 1.—Photoelectric photometry, color index $\Delta(b-r)'$ and Hα index $\Delta\alpha'$ for Epsilon Aur from 1981 to 1985. A different comparison star was used in place of the usual choice λ Aur, due to the large angular separation of the latter from ϵ Aur.

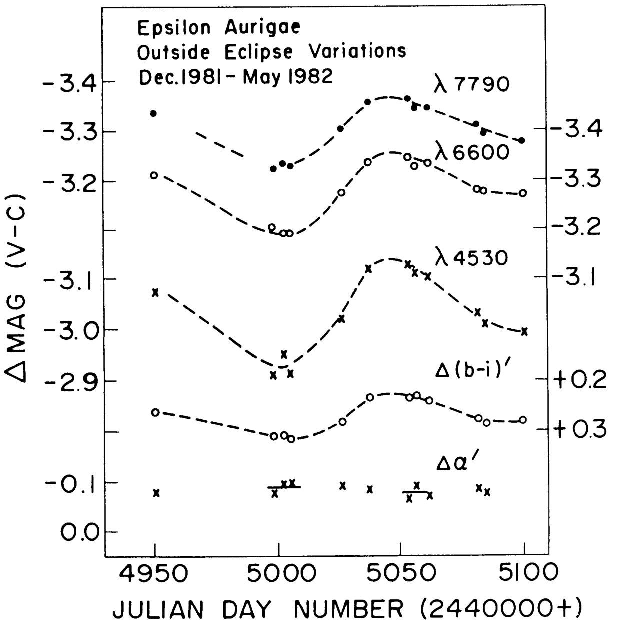

FIG. 2.—A detail of Fig. 1; light variations of the supergiant before eclipse. From this, it is clear that the luminosity is correlated with the color, while the Hα index is constant.

Figure 2, a detail of Figure 1, shows the light variations before the most recent eclipse; these represent the intrinsic variation of the bright component. As other observers have found (Ferro 1985; Burki 1978), Epsilon Aurigae exhibits semi regular, out-of-eclipse light variations with a quasi-periodicity of ~110 days (Donahue *et al.* 1985). The observed color-brightness dependency for ϵ Aur indicates that the variations arise from radial pulsations of the supergiant. If we scale the light and color variations with those observed for classical Cepheids, we expect radius changes of up to 15%–20%. As shown in Figure 3, the photometry obtained prior to the eclipse during late 1981 and early 1982 indicates a close correlation between brightness and color in the sense that the star is

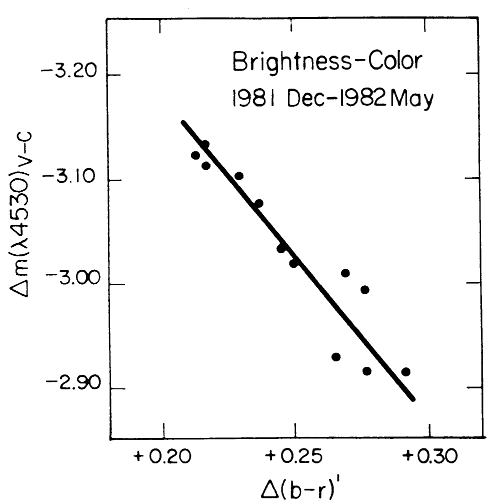

FIG. 3.—The linear relationship between brightness and color, outside eclipse. A similar graph appears in Gyldenkerne (1970).

bluest when brightest, a relationship which was first discovered by Gyldenkerne (1970). This dependency is similar to that observed for pulsating stars such as Cepheids and other luminous supergiants and indicates that a significant change in temperature and radius of the star is occurring. Additional observations obtained by us after fourth contact (not shown) confirm that this behavior still applies. Both the period and the amplitude of the pulsations, however, are irregular; there are periods in the photometric history of the star when no significant light variations were observed, and the color curve seems to indicate that this also occurred during most of the recent eclipse. Ferro (1985) has searched for periodicity in the data before 1961, and found several periods, notably at ~100, 160, and 520 days. These periods appear both in photometric data and in radial velocity curves. The 520 day period may correspond to the long-period variation evident in the $(b-r)'$ color curve of Figure 1. It should be noted that variations of the bright component also occur inside the eclipse, and will tend to affect our perceptions of the eclipse shape and contact times.

d) *Kinematics*

While the photometric behavior is crucial to understanding the true nature of the supergiant, too little is known about what the variability of such stars should be to allow us to distinguish between the high-mass and low-mass models. There is little direct evidence to favor one scenario over the other. The relevant data we could find include the space motions of the system and its chemical composition compared to similar stars. The Galactic latitude is very small ($b = +1^\circ.2$), indicating a star close to the Galactic plane. Since ϵ Aurigae's proper motion and radial velocity are known, it is trivial to determine its true motion once a distance is assumed. We have listed in Table 1 the results for three different distances, computed from published values of radial velocity and proper motion. We have also included the distance in parsecs from the Galactic plane. The location close to the plane, together with its small space motions, indicate that ϵ Aur is a young Pop I object. Although these features do not rule out the low-mass model of the system, they constitute compelling circumstantial evidence that ϵ Aur is a very young system (as in the massive model).

Several authors, meanwhile, have identified a class of stars which they believe to be A-F supergiants which are in a stage of rapid evolution toward white dwarfs (Bond, Carney, and Grauer 1984; Hrivnak, Kwok, and Volk 1989; Luck, Bond, and Lambert 1990). The characteristics of these stars are that they typically have high Galactic latitudes, low iron abundances and high CNO abundances. All of these are understandable for evolved stars, but do not apply to ϵ Aurigae. The chemical composition, while difficult to determine with precision, seems to be normal for an F supergiant (Castelli 1978). Therefore, we think that the high-mass model is more likely, although neither alternative seriously affects the feasibility of our proposal concerning the eclipsing body.

III. THE DISK

a) *Observations of the Eclipsing Body*

What distinguishes ϵ Aur from the typical mysterious binary are the eclipses and the search for a model to consistently explain them. With an overall duration of 647 days (Schmidtke 1985), the eclipse appears total: there is a long period (446 days) in the middle of the eclipse when the light curve is relatively flat. This is almost always associated with a total or annular eclipse. An annular eclipse is ruled out by the very length of the event. A total eclipse, on the other hand, seems inconsistent with the spectroscopic observations, which show the spectrum of the supergiant to remain unchanged throughout the eclipse. Thus, as mentioned, the most popular interpretation of the dark object is a large disk seen edge-on or nearly edge-on. At the center is presumably a star, or perhaps a binary.

Fairly complete photometric coverage is available for the eclipses in 1928–1930 (Huffer 1932) and 1955–1957 (Gyldenkerne 1970) as well as scattered points for earlier epochs. The recent eclipse, as we have noted, witnessed a greater amount of observing time and a greater number of observational methods over a broader range of wavelengths than ever before; perhaps the most significant discovery has been unambiguous observation of light from the disk itself. Despite the impressive amount of data collected, however, we still have little direct knowledge about the nature of the disk. The most direct piece of information we have is its temperature, which was measured during the recent eclipse using infrared photometry from Mauna Kea and Kitt Peak (Backman *et al.* 1984; Backman 1985). While a slight infrared excess had previously been noticed during the eclipses, Backman's research has showed conclusively that the "grey," wavelength-independent nature of the visual eclipse does not carry over into longer wavelengths. While the data at 2.2 μm follows the visual light curve closely, the 10 μm eclipse is not quite as deep and the eclipse is only one-half as deep at 20 μm. Comparison with additional ground-based infrared photometry and *IRAS* data yields a disk temperature of 475 ± 50°K.

The disk may also be observable in ultraviolet. Even outside of eclipse, there is a UV excess in the spectrum of the system above what would be expected for an F0 supergiant (Altner *et al.* 1986). The eclipse is grey to wavelengths as short as 1400 Å, but significantly shallower in the far UV than in the visible (Boehm *et al.* 1984). This is probably due to a hot emitting body at the center of the disk. A secondary eclipse, due in January 1997, has never been observed in visual light, and should be searched for in both the UV and IR.

The final pieces of information concern the kinematics and positioning of the disk, which can be inferred from its rotation curve (Lambert and Sawyer 1986; Saito *et al.* 1987) and polarimetry (Kemp *et al.* 1986). The velocity curve, assuming that the absorption arises from gas in the disk, is described by Lambert (1986) as "barely consistent" with a heavy (13 to 20 $M_\odot$) object, and entirely consistent with a low-mass (2 to 4 $M_\odot$) object. The interpretation, however, is complicated by our lack of knowledge about the disk; we do not know from where in the disk the lines we see originate, nor how much of the mass is concentrated near the center. From polarimetry we can deduce that the disk is tilted with respect to its direction of motion. Kemp *et al.* (1986) have assigned a value of 2°.3 for this angle. Again, however, the interpretation is complex; the pulsation of the star, for instance, adds an as yet undetermined contribution to the polarization.

b) Features of the Eclipse

The observed eclipses of ϵ Aur share many identical features, but differ in some respects. Schmidtke (1985; Schmidtke *et al.* 1985) notes a perceptible change in the duration of the eclipse and the spacing of the contact times (see Table 2). Specifically, the duration of totality appears to have become shorter and the ingress and egress phases have become longer. An obvious explanation for this, just from considering the geometry of the eclipse, is that the supergiant has decreased in size between the 1955–1957 and the 1982–1984 eclipses (Saito and Kitamura 1986). However, the light output of the system has stayed nearly constant, or at least not changed nearly as much as one would expect to cause the star to shrink enough to change the appearance of the eclipse. A more likely explanation is that the intrinsic pulsations of the supergiant have slightly altered the eclipse, or the disk has changed in size or orientation.

The light curve during totality, while certainly appearing as flat overall, shows variation during each eclipse. This variation, while undoubtedly due for the most part to the variability of the bright star, might also be caused by inhomogeneities in the eclipsing object. If the correlation between the color and magnitude of the star can be firmly established, it may be possible to subtract the variations of the supergiant from the light curve, even during eclipse. Even though this is not yet practical, it is still possible to tell when a large variation is due to the supergiant, because the temperature of the star should rise, changing the color index. During the most recent eclipse, there is an unmistakable increase in luminosity almost exactly in the middle of the eclipse (see Fig. 1). Unfortunately, the precise center of the eclipse occurred when the star was behind the Sun and was thus not well observed. However, the color variations one would expect to accompany such a large mid-eclipse brightening are clearly not present—there must be another explanation besides the pulsations of the bright star.

Figure 4 shows spectra of the Hα feature during eclipse. These spectra were obtained by S. Baliunas and Guinan with the 1.5 m telescope at Whipple Observatory, Mount Hopkins, Arizona. The two examples of spectra shown, one taken near mid-eclipse (near the time of the brightness enhancement) and the other late in the eclipse, indicate that there was significantly greater Hα absorption near mid-eclipse. This is in accord with the behavior of the α index shown in Figure 1, which indicates an increase in the α index of ≈ 0.05 mag near mid-eclipse. As noted earlier, a numerical increase in the α index corresponds to a net increase in Hα absorption. The apparent increase in the strength of Hα absorption near mid-eclipse is also evident

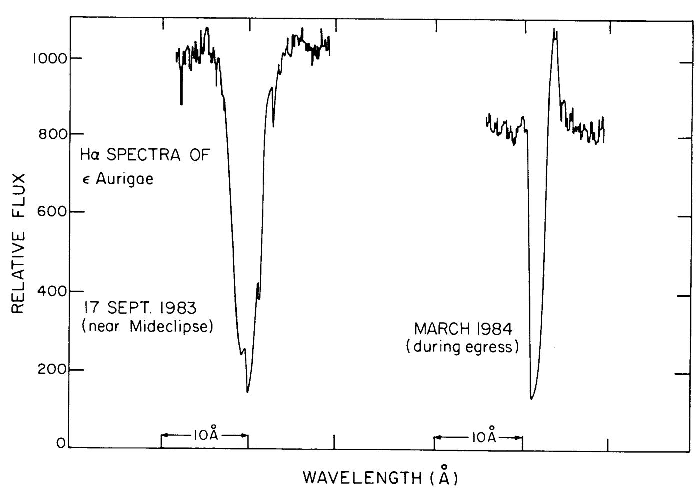

FIG. 4.—Hα spectra of ϵ Aur at two different phases of eclipse. There is clear evidence of increased absorption in the spectrum taken near mid-eclipse compared to that during egress. Flux is in arbitrary units.

in the measurements of the Hα equivalent width reported by Thompson *et al.* (1987) and Barsony *et al.* (1986). We speculate that the increase in the strength of the Hα absorption observed near mid-eclipse arises from hydrogen gas in the central region of the disk. This gas produces an additional Hα absorption in the spectrum of the F0 star near mid eclipse as its light shines through the central opening of the disk.

c) *Possible Interpretations*

As Stencel (1985) has noted, ε Aurigae has demonstrated a remarkable ability to make use of every astrophysical phenomenon in vogue during a given time. Shell stars and disks in the 1960's, black holes in the 1970's, and polar jets in the 1980's have all been invoked to explain the structure of the disk; some have had more success than others. Otto Struve was moved to call ε Aur, "In many respects the history of astrophysics since the beginning of the twentieth century."

One controversy involves the body at the center of the disk. The obvious candidate, a single main-sequence star, is difficult to accept since we do not see the expected luminosity. This difficulty motivated Cameron (1971) to suggest a black hole. In fact, ε Aur was included in the survey of black hole candidates by Trimble and Thorne (1969), who did not accord it serious consideration since there were no observed X-rays or gamma rays. However, while such observations would be compelling evidence that a collapsed object was present, they should not be thought of as necessary to its existence. High-energy radiation would only be prominent in an accreting system, and it is plausible that this doesn't occur in ε Aur. (For example, if the hole had a less massive close companion, accretion would be suppressed by angular momentum transfer to the disk.) Furthermore, it is still possible that X-rays from a disk are beamed away from us or attenuated, as is believed to occur in the system A0620-00 (Blandford 1987).

Nevertheless, it would perhaps be more satisfying if there were an explanation which did not invoke such exotic phenomena as a black hole. An alternative suggestion places a binary star at the center of the disk. This has been suggested by both Lissauer and Backman (1984) and Eggleton and Pringle (1985). Lissauer and Backman argue that a binary would have only 1/10 the luminosity of a single star of the same mass, which would explain why the companion is not visible. Such a configuration (in a high-mass model) would be hot enough to ionize the central portion of the disk and evacuate the region very close to the binary. Orbital resonance of the close binary might also serve as a mechanism for keeping the edge of the disk as sharp as is implied by the light curve. Eggleton and Pringle propose the binary in the disk as part of their low-mass model. This configuration would also explain the low luminosity of the eclipsing component.

As mentioned above, the prevalent model for the eclipsing object is a large disk seen edge-on. The disk must be geometrically thick enough to obstruct half of the light from the supergiant. The only alternative thought to be viable at present is a thin disk which is slightly tilted with respect to the orbital plane, thus presenting an elongated ellipse to our point of view (Wilson 1971). This model has the obvious difficulty of explaining how a flat bottom can come about from a partial eclipse by an elliptical body. Wilson suggests that there is a large region in the center of the disk that is partially transparent, and that only a thin region at the perimeter of the disk is completely opaque. (It should perhaps be noted that Huang, in a later paper [1974], agreed that the thin, tilted disk was a reasonable solution and that the true answer was probably somewhere between his model and Wilson's—a thick disk with slight tilt.) The manifest mid-eclipse brightening that we observe in the most recent eclipse has inspired proposals that the very center of the (tilted) disk is completely transparent, a hole through which light can shine to create the brightening (Guinan 1985; Wilson and van Hamme 1986). Last, it has been suggested that the proposed binary at the center causes the disk to be warped to a thickness sufficient enough to cover the necessary area of the star (Eggleton and Pringle 1985; Kumar 1987).

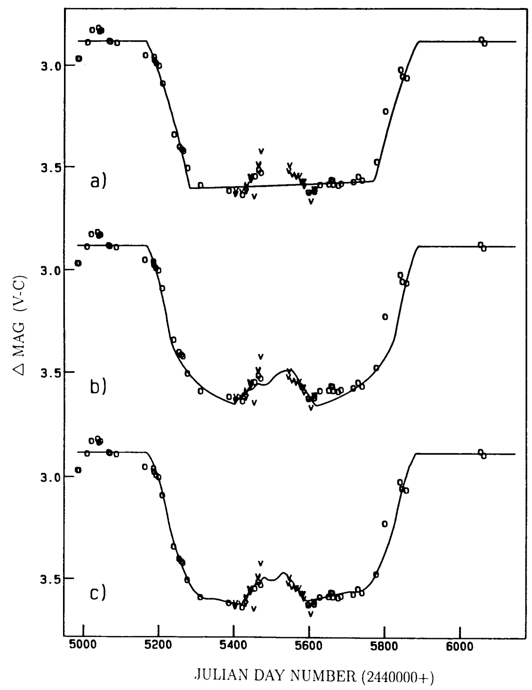

FIG. 5.—Theoretical and observational light curves for the 1982–1984 eclipse. (*a*) An attempt to fit the data with Huang's (1965) thick-disk model; this cannot account for the mid-eclipse brightening. (*b*) A thick, tilted opaque disk with small central opening. Although this gives a fairly good fit to the data, we felt that it did not reproduce with sufficient accuracy the flat bottom characteristic of this and previous eclipses. (*c*) An excellent fit is achieved by using a thin disk with variable opacity.

d) *Computations and Results*

To distinguish between the predictions of the various models, we have developed a computer code to numerically model the eclipse. The resultant light curves are given in Figure 5, and the adopted models are given in Table 3. The code was implemented on an IBM AT at Villanova University. The free parameters in the complete model included i, the inclination of the disk with respect to the plane of the sky; j, the angle of the disk from a line perpendicular to its orbit; d, the thickness of the disk; b, the "impact parameter" which gave the distance from the center of the disk to the center of the star at closest approach; r, the radius of the disk and the different regions of it; and t, transparency of the disk for the different regions at different distances from the center. The calculation consisted of simple numerical integration of the area of the bright star eclipsed by the disk, multiplied by the opacity. Factors that were not considered include possible inhomogeneities or warpings of the disk and nonuniform brightness distribution on the

TABLE 3

ADOPTED PARAMETERS FOR DISK MODELS

Parameter	1955–1957 Eclipse: Previous Papers (1) Thick	1955–1957 Eclipse: Previous Papers (2) Tilted	1982–1984 Eclipse: This Paper Thick Edge-on	1982–1984 Eclipse: This Paper Thick Tilted	1982–1984 Eclipse: This Paper Thin Tilted
b	0.00	0.00	0.22	0.52	0.45
i	90.00	87.22	90.00	87.50	86.50
j	90.00	91.00	91.00	90.10	90.25
d	0.85	0.00	0.80	0.35	0.00
r_1	2.63	9.77	5.00	9.00	10.00
t_1	0.00	0.00	0.00	0.00	0.00
r_2	—	4.32	—	2.10	6.50
t_2	—	0.55	—	1.00	0.33
r_3	—	—	—	—	1.65
t_3	—	—	—	—	1.00

REFERENCES.—(1) Huang 1965; (2) Wilson 1971.

bright star, from limb darkening or other sources. All distances were expressed in terms of the radius of the supergiant (*not* the semimajor axis of the orbit), and all angles in degrees.

We first attempted to recreate Huang's 1965 suggestion of a disk seen directly edge-on. The only additional changes we implemented were the ability to tilt the disk somewhat with respect to the direction of motion, and the displacement of the disk's orbit from the center of the star. Huang's initial calculation was purely geometric, and was not actually superposed upon the light curve to determine how well it fit. Further, he was using data from the 1955 eclipse to fix his parameters. Therefore, the numbers we determined to fit the data as accurately as possible (see Table 3) differ somewhat from those given by Huang (1965). However, the differences are not crucial to the model, and Huang himself notes (1974) that numerical values for the dimensions of an eclipsing disk are necessarily underdetermined by mere light curve analysis. As is apparent from Figure 5*a*, this model gives a natural explanation to the flat-bottomed light curve. However, we have already noted that the bottom is not entirely flat; the major difficulty with Huang's model is that there is no possible way to reconcile it with a mid-eclipse brightening. An additional restriction is that the flatness of the light curve is dependent upon the strict rectangular shape of the profile of the disk—if it is really elliptical or irregular, the bottom would be less flat than we observe. By the same token, the twisted or warped disk that has been suggested has similar flaws; there is no way for it to reproduce the mid-eclipse brightening (presumably the warping would prevent us from seeing through a central hole) and the curving shape of the disk makes a flat bottom seem unlikely.

The next model we considered was another thick disk, but this time tilted and featuring a small central hole. This is as if the thickness of the disk decreased from a finite amount at the outer edge to zero a certain distance from the center, but remained opaque over the entire area (where it existed). In both this model and the next, the central hole was offset slightly (0.5 radii of the supergiant) to account for the brightening not being precisely at mid-eclipse (this feature accounts for the asymmetric structure in the theoretical light curve which can be seen at the top of the brightening). The obvious benefit to this model was that the central hole was easily explained. When we began to search for the best fit with this model, we were optimistic that we could reproduce the light curve satisfactorily. However, we found there to be an unavoidable trade-off: if the inclination (i) of the disk with respect to the plane of the sky was near 90°, the central hole was diminished in perspective to so great a degree that it could not explain the mid-eclipse brightening. On the other hand, a smaller value for this angle made the disk more elliptical and failed to agree with the flat bottom (see Fig. 5*b*). The value which was finally decided upon was the best compromise, although it still seemed unacceptable. Comparison with additional photometric data confirms that the true light curve appears significantly flatter than that produced with this model.

The last model attempted was a thin, tilted disk with variable opacity. The thickness of the disk was eliminated to cut down on the number of free parameters, although the real disk probably has a small thickness. This model resembles that of Wilson, with the addition of a small central hole which is completely transparent (and again, offset by ~0.5 stellar radii). Thus, the disk is completely opaque at the rim, has a semi-transparent transitional ring, and a completely transparent center. The adjustable parameters include r_1, the radius of the disk; r_2, the outer radius of the transition region, and r_3, the radius of the central hole; as well as t_1, t_2, and t_3, the transparencies of each region. As is obvious from Figure 5*c*, this model can fit the light curve even more precisely than the precision of the data warrants. Caution must be exercised, however, since the introduction of enough free parameters will allow us to fit anything at all. In addition, the method of obtaining a flat bottom seems contrived, in this model and in Wilson's original; the radii and transparencies of the different regions of the disk must be taken to contribute just the right amount of opacity to completely cut off a constant amount of light during "totality," even though different areas of the different regions are eclipsing the star. Nevertheless, this model is the only one which seems to be able to explain the most coarse aspects of the light curve. In addition, it is in complete agreement with the Hα spectra, which indicate high-temperature hydrogen at the center of the disk. It is also consistent with the suggestion of Lissauer and Backman (1984) that the proposed central binary would heat the surrounding material and make it more transparent. It could be argued that three distinct sharply defined regions of different transparency seem like an unphysical arrangement. Of course, the true situation is more probably a gradual increase in opacity from the center to the outer edge of the disk, or some other function of distance from the center of the disk; however, such a transparency function is impossible to determine more precisely than we have, and its more difficult to numerically model, besides. Lastly, an additional piece of evidence comes from Stickland (1985), who used IR data to compute the ratio of the projected area of the disk to that of the bright star. His value is 6 ± 1, which agrees excellently with our model's prediction of 6.1 (at the time of our computations we were unaware of Stickland's result). Therefore, we present this model as the most feasible configuration for ε Aurigae and its disk.

It is important to ask, given that this model yields an excellent fit to the data, whether it is physically tenable. If there is a binary at the center of the disk, will the particles in the disk be sufficiently stable in their orbits that the disk remains thin? This question was addressed by van Hamme and Wilson (1986), who argue that the answer is yes. There are actually two effects which would cause the disk to deviate from a thin geometry: self-interaction of the disk material and gravitational interaction with the central binary. A simple estimate of the magnitude of the first effect on the ratio of disk thickness to radius, d/r_1, can be obtained from the ratio of sound speed to circular velocity (Pringle 1981):

$$\frac{d}{r_1} = \left(\frac{RTr_1}{GM\mu}\right)^{1/2} ,$$

where R is the gas constant per mole, G is Newton's constant, M is the mass of the central binary, T is the temperature of the disk, and μ is the mean molecular weight. Therefore, for ϵ Aur this ratio becomes approximately

$$\frac{d}{r_1} = \frac{0.05}{\mu^{1/2}} .$$

If much of the material in the disk is dust and grains, then μ represents the "molecular" weight of a dust particle and would be very high. This forces the disk to be extremely thin, and is thus perfectly consistent with Wilson's tilted disk. The gravitational interaction between the disk and the three stars in the system is harder to calculate. Van Hamme and Wilson explored the question by looking at the motion of a test particle in the potential of a hypothetical three-body system. By performing numerical simulations they found that a disk particle would wander only a very small vertical distance if the inner binary were closely aligned with the wide orbit—within $\sim 1°$. This result, of course, is slightly discrepant with our result that the best fit is obtained with a disk tilted at $\approx 2°.5$ with respect to the wide orbit. However, the discrepancy is not so great that it rules out the model, especially given the uncertainty in the masses and separation of the hypothetical close binary, and the geometry of the entire system. The question of the object at the center of the disk evidently remains open.

Subsequent to the submission of this paper, a relevant preprint by Ferluga (1990) was brought to our attention. This work studies the possible configurations of the eclipsing disk in much the same spirit as our study. Hearteningly, Ferluga has independently reached conclusions which are very similar to ours. The main results of both works are identical: the eclipsing object must be a thin, tilted disk with a transparent central hole and opacity changes across the surface. The only discrepancies involve the specific nature of the opacity changes across the disk; while we find that a region of intermediate transparency between the inner and outer disk suffices to fit the photometric data precisely, Ferluga argues in favor of a transparent gap between two opaque regions (a configuration which superficially resembles the Cassini division in Saturn's rings). Ferluga's disk is also slightly smaller than ours, with a radius of approximately 6 times that of the supergiant, as opposed to our model where the disk is ten times the radius of the supergiant.

Despite these differences, we feel that our model and that presented by Ferluga (1990) are essentially the same. The uncertainties inherent in modeling a disk of varying opacity eclipsing a star with intrinsic pulsations prevent us from unequivocally distinguishing between the two proposals. The physical mechanisms for producing the disk configurations are quite different; a disk which becomes monotonically more transparent near its center can be understood as the result of heating by an energetic central source, whereas a Cassini-like gap could result from resonances with the orbit of a presumed central binary, or the gravitational influence of hypothetical shepherding bodies orbiting within the disk itself. Either way, the issues of the origin and astrophysical significance of the disk remain unaltered.

IV. CONCLUSIONS: A PROTOPLANETARY DISK?

Epsilon Aurigae has been a mystery for over a century, and it will probably remain a mystery into the 21st century. However, we can state at this time what the most likely configuration of the system seems to be. The bright star is an F supergiant. Its companion is a large, relatively thin disk with decreasing opacity near the center. The disk is tilted a few degrees with respect to the orbit. At the center of the disk is a single star (possibly a protostar) or binary which is heating and ionizing the material nearby. The disk material has a low temperature and emits infrared radiation; the central object is hot and gives us the UV emission.

It is useful to examine the absolute dimensions of the system. To do so, we will assume the bright star has absolute magnitude $M_v = -8.0$. With an interstellar absorption of $A_v = 0.84$, this implies a distance of 1057 pc. We know that the temperature is ~ 7800 K (Castelli 1978). The bolometric correction for an F0 supergiant is 0.14, so we have $M_{\rm bol} = -8.1$. With $L_\odot = 3.84 \times 10^{33}$ ergs s^{-1} and the relations

$$M_{\rm bol} - 4.72 = -2.5 \log (L/L_\odot) ,$$

and

$$L = 4\pi R^2 \sigma T_e^4 ,$$

we find $L = 5.2 \times 10^{38}$ ergs s^{-1} and $R = 1.40 \times 10^{13}$ cm = 200 $R_\odot$ = 0.93 AU. The disk thus has a radius $R_d \approx 2000$ $R_\odot \approx 9.3$ AU. Let us also assume that the mass of the supergiant is 15 $M_\odot$, which is consistent with a distance of 1000 pc and Castelli's value of log (g) = 1. (Of course, a different mass or distance would require recalculation of these dimensions; however, a rough estimate is still beneficial.) Then the mass function of $f(m) = 3.12$ $M_\odot$ (Morris 1962) and orbital inclination near 90° implies a secondary mass $M_2 = 13.7$ $M_\odot$. Kepler's law leads directly to a semimajor axis of 27.6 AU = 5930 $R_\odot$. Thus, while the disk is close to its Roche limit, the supergiant is well inside. If we assign radii of 150 and 1500 $R_\odot$ = 7.0 AU and masses of 1.3 and 5 $M_\odot$ to the supergiant and the disk, as Eggleton and Pringle (1985) have suggested, then the semimajor axis is 16.7 AU. Again, the primary is much smaller than its Roche lobe.

The question of the origin of the disk remains to be answered. The usual explanation for disks in eclipsing binaries is accretion of matter from the other component, and this is plausible in the low-mass model for ϵ Aur. Further, Hinkle and Simon (1987) argue on the basis of $^{12}C/^{13}C$ ratios in the disk that gas has been accreted from the primary. However, the size of the disk and the large distance between the supergiant and its Roche Lobe (see Fig. 6) suggest that, in the context of a high-mass model, this scenario is less likely. Therefore we suggest that Kopal's (1971) suggestion that the disk is protoplanetary be given serious consideration.

Objects which are believed to be protoplanetary disks have been recently discovered around β Pictoris and other stars. These consist of extensive, cool disks of solar system dimensions surrounding recently formed stars. The disks are thought to contain grains in the process of accreting into planets. Comparison of the tilted, semitransparent model advocated in this paper with the picture which has been constructed, in the last few years, of protoplanetary disk systems allows us to approach this possibility more knowledgeably than ever before.

The size and age of the disk are consistent with the protoplanetary hypothesis. Protoplanetary disks appear to be common

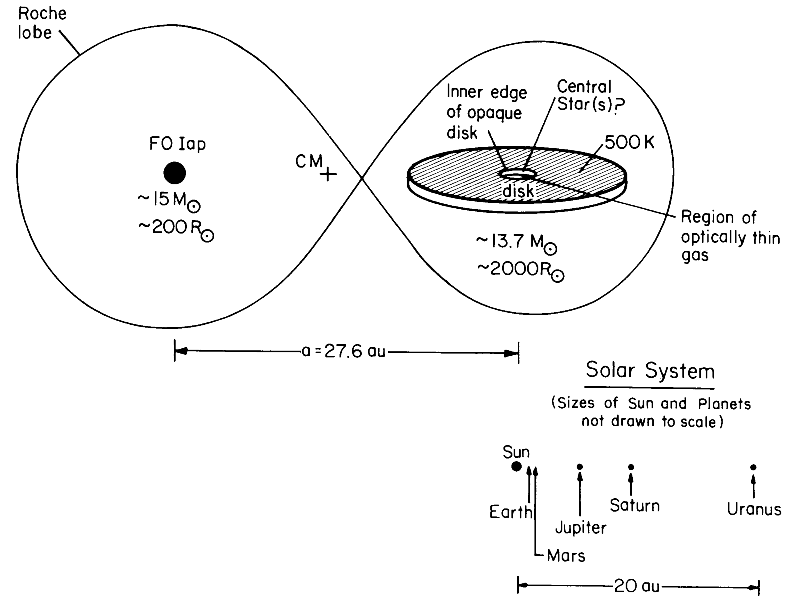

FIG. 6.—A scale model of the ϵ Aur system showing the relatives sizes of the star and disk. We used the parameters obtained from the thin disk model with varying opacity, and assumed a mass for the supergiant of 15 $M_\odot$. For purposes of comparison, the solar system is drawn to the same scale.

in young stars with an age of at least 10^7 yr (Strom *et al.* 1989*a*, *b*), which is compatible with the adopted mass and luminosity of the supergiant in ϵ Aur. Specifically, evidence has been found for extremely large disks around nearby main-sequence, A-type stars such as α Lyrae (Vega), α Piscis Austrinis (Fomalhaut), and β Pictoris (Smith and Terrile 1984; Paresce and Burrows 1987). The disk in ϵ Aur, while large, is comparable to the size of the solar system (Fig. 6) and smaller than the 400 AU disk around β Pic (Smith and Terrile 1984). Presumably the ϵ Aur disk could have been much larger if not for the constraint of the Roche lobe.

The evidence from the recent eclipse for a transparent central hole is intriguingly reminiscent of protoplanetary disks. Backman, Gillett, and Witteborn (1990) have deduced from IRAS, ground-based IR (5 μm), and multiaperture photometry that the β Pic disk possesses a dust-free central hole. In addition, recent infrared studies of pre–main-sequence stars by Skrutskie *et al.* (1990) indicate that $\approx$10% of sampled stars with disks have central holes. Skrutskie *et al.* suggest that these holes could be produced by the formation of relatively massive planets, which keep the inner disks clear of significant amounts of matter. Alternatively, energy from the pre–main-sequence star or the boundary layer region could heat the inner regions of the disk, evaporating or blowing away the particulate matter. Paresce and Burrows (1987) showed that the disk around β Pic is composed of grains larger than 1 μm, the typical size of interstellar grains. This would be consistent with a semitransparent region without significant optical absorption lines.

Finally, spectroscopic evidence emphasizes the similarity between ϵ Aur and protoplanetary systems. Observations of young pre–main-sequence stars with disks indicate large outflows (winds) as well as infalling matter, jets, and bipolar molecular flows (see Snell and Edwards 1981; Black and Matthews 1985). Also, excess continuum ultraviolet and optical radiation have been discovered from these objects and have been interpreted as arising from the inner regions of the disk, where matter is accreting onto the central star (Hartigan *et al.* 1990). Epsilon Aurigae shows evidence of mass outflows from the P Cygni-type line profiles seen in its spectrum; however, this is characteristic of luminous supergiants. On the other hand, we previously noted an increase in Hα absorption near mid-eclipse. The additional absorption appears to arise from gas in the central regions of the disk. We might imagine that this gas is flowing out of the central region of the disk, analogously to the outflows observed in pre–main-sequence stars.

We must emphasize that, while the evidence for a resemblance between ϵ Aur and protoplanetary systems is suggestive, it is not airtight. Although the existence of a large disk with central hole parallels the structure of β Pic, T Tauri stars, and related systems, it does not exclude other scenarios which could result in similar configurations. More careful analysis of protoplanetary disks and that in ϵ Aur should resolve this question.

Still, we believe the protoplanetary scenario is promising, which makes ϵ Aur an even more important system than was previously believed. Great strides toward understanding the nature of protoplanetary disks and planet formation become possible with the discovery of an eclipsing binary with such an object. This possibility serves to emphasize that continued monitoring of this system is necessary, including outside of eclipse. The system is expected to be near quadrature in 1990–1991, which would be an ideal time to determine the radial velocity of the secondary by looking for CO lines in the radio or near infrared. This would allow unambiguous determination of the masses in the system, which should resolve the puzzle of its evolutionary state. Also, a detailed abundance analysis, such as carried out for several high-latitude supergiants by Luck, Bond, and Lambert (1990) would help to determine the evolutionary state of the bright star. The next important event will be the predicted secondary eclipse in ~1997, however, there is uncertainty in the exact date (of perhaps a few years) due to uncertainty in the eccentricity and orientation of the orbit. We do know that primary eclipse will be in 2009. We may hope that the future will see us solve the mysteries of this perplexing system.

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