THE ASTROPHYSICAL JOURNAL, **269**:L17–L19, 1983 June 1

THE PARTIAL PHASE OF THE ECLIPSE OF EPSILON AURIGAE

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Received 1982 December 17; accepted 1983 January 27

ABSTRACT

Ultraviolet spectra of the peculiar eclipsing binary ε Aurigae (F0 Ia + ?) were obtained with the *International Ultraviolet Explorer* at pre-eclipse and ingress partial phases. The results show a wavelength dependence of the eclipse in contrast to the grayness (non–wavelength dependence) of the eclipse observed in visible light. From the current results, incorporating previous observations, we suggest that: (a) the obscuration of the light of the F supergiant by the disk proposed by Huang is the result of electron scattering in visible light; (b) the increase in the eclipse depths toward shorter wavelengths observed in the ultraviolet is caused by dust; and (c) the temperature of the disk is in the range from 1000 to 2000 K.

Subject headings: stars: eclipsing binaries — ultraviolet: spectra

I. INTRODUCTION

The eclipsing binary ε Aurigae is one of the longest period eclipsing binary systems known, with a period of 27.1 years. The system has sometimes been classified as a ζ Aurigae system, though current models tend to indicate substantial differences. Ground-based observations of the system are discussed by Wright (1970) and Gyldenkerne (1970). Observations during the 1955–1956 eclipse have been interpreted to support a picture proposed by Struve (1956) and Huang (1965) in which an early F type supergiant primary is losing mass. Some of the material forms a cloud around the supergiant, filling its critical Jacobian lobe. Material from the cloud flows through the inner Lagrangian point and forms an accretion disk around the secondary, which is assumed by these authors to be an early-type main-sequence star.

The eclipse in the system occurs when the supergiant is obscured by the mysterious companion; yet the secondary star, if one exists, is not observable. Presumably the secondary is imbedded in a very large (~ 800 $R_\odot$) accretion disk which is partially opaque.

II. OBSERVATIONS AND RESULTS

The most recent eclipse began in 1982 July. Figure 1 shows the light curve inferred from the Fine Error Sensor (FES) on the *International Ultraviolet Explorer* (*IUE*) using the Holm and Rice (1981) calibration. These data were obtained by ourselves and other observers from records in the public log books. The ingress partial phase lasts for about 6 months, followed by a year-long totality and a 6 month long egress partial phase. Observations of the ultraviolet spectrum of the system have now been made, as part of a program to study the entire eclipse, with the *IUE* at pre-eclipse and ingress partial phases. This *Letter* reports on the two conclusions that can be drawn from a preliminary look at the data.

a) Absorption-Line Spectrum

The general appearance of the spectra before eclipse and during ingress shows relatively little change in the details of the absorption-line spectrum. There are small changes in the relative strengths of a few lines, near to one another in wavelength, in the short-wavelength spectra, and almost no changes in relative strengths in long-wavelength spectra. There are not significantly increased numbers or strengths of absorption lines such as have been observed in ζ Aur (Chapman 1981). The opacity produced by the companion must be almost entirely continuous. If it were pseudo-continuum produced by the confluence of many absorption lines at the shortest wavelengths, one would expect to see some wavelength regions at longer wavelengths where such lines were more or less resolved. Such is not observed in the visible or the near-ultraviolet.

The magnitude of the opacity has been ascertained by comparing the fluxes at several wavelengths in low-dispersion spectra taken in 1982 April, before eclipse, and in 1982 September, during egress (Table 1). The results

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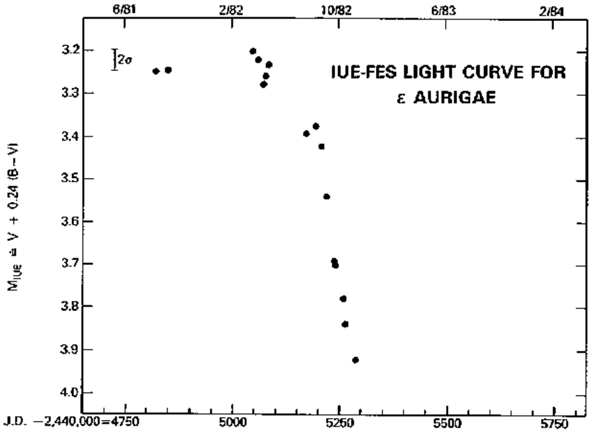

FIG. 1.—The light curve for ε Aur inferred from FES counts from the *IUE* satellite, using the Holm and Rice (1981) calibration. The curve shows the star's brightness before eclipse and during the ingress partial phase of the eclipse.

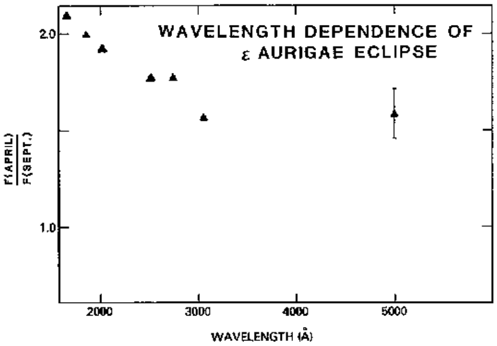

FIG. 2.—The wavelength dependence of the ε Aur eclipse, calculated from the ratios of low-dispersion *IUE* spectra taken on 1982 April 13 and 1982 September 21. The point plotted at 5000 Å was inferred from the FES magnitudes. The points in the ultraviolet region of the spectrum were derived from the ratios of the long-wavelength halves of the long-wavelength and short-wavelength low-dispersion spectra. In both pairs of low-dispersion spectra used to produce the plot, the signal-to-noise ratio in the short-wavelength halves were too small to permit calculation of meaningful ratios.

TABLE 1

ULTRAVIOLET OBSERVATIONS

Image	Dispersion	Exposure (mm:ss)	Mid-Exposure [date (1982): UT]
LWR 13016	low	00:09	Apr 13: 1829
SWP 16755	low	00:30	Apr 13: 1834
LWR 13017	high	10:00	Apr 13: 2034
SWP 16759	high	105:00	Apr 14: 0051
SWP 18045	high	350:00	Sep 21: 0400
LWR 14223	low	00:06	Sep 21: 0831
SWP 18046	low	00:60	Sep 21: 0836
LWR 14224	high	10:00	Sep 21: 0912

are shown in Figure 2. The signal-to-noise ratios in the low-dispersion spectra are sufficient to give meaningful flux ratios only in the long-wavelength halves of both the long-wavelength and short-wavelength spectra. The broad-band flux ratio centered near 5000 Å was calculated from the ratio of FES counts. The expected error is indicated. Past observations of the visible part of the spectrum have led to the conclusion that the eclipse is gray. The results shown in Figure 2 are consistent with that conclusion between 3000 and 5000 Å. However, the opacity increases by about 50% between 3000 and 2000 Å. We agree with the earlier suggestion (Kuiper, Struve, and Stromgren 1937) that the constant opacity longward of 3000 Å is probably electron scattering, while the opacity shortward of 3000 Å may be dust in the vicinity of the secondary object. Wolff (1973) has measured the infrared emission from the system between 2 and 22 μm. The spectral energy distribution is similar to that of a late A or early F type star between 2 and 5 μm. However, longward of 10 μm, the energy distribution is elevated by about a factor of 2. Wolff concluded that the excess radiation comes from the companion and asserts that the temperature of the secondary object is similar to that of the primary. Wolff's suggestion seems to be in conflict with the large size of the companion and its spectral undetectability. On the other hand, the infrared radiation could come from a much cooler object. For instance, if the object were as cool as 2000 K, its surface area (assuming blackbody radiation) would have to be about 25 times larger than that of the primary, in order to account for the infrared radiation longward of 10 μm. A circular object with that area would have a radius of about 1000 $R_{\odot}$, in line with the size inferred from eclipse observations. A simple calculation shows that, at the distance of the secondary, the equilibrium temperature of a dust particle in the radiation field of the F type star is around 1500 K, consistent with the above numbers. The infrared and ultraviolet observations seem to point to a large cloud of dust and plasma around the secondary. The infrared observations could be interpreted as optically thick free-free emission on top of the stellar continuum. However, if there were relatively hot gas around the secondary in sufficient optical thickness to produce the infrared emission, we should see effects in the ultraviolet absorption spectrum. Though there are few clues as yet regarding the nature of the cloud, our observations are not inconsistent with the concept of accretion disks around main-sequence stars (Pringle 1981), that is, a thick disk lying in the orbital plane of the system and obscuring the central star.

b) Mg II *Emission*

Figure 3 shows the change in the Mg II resonance doublet between pre-eclipse and mid-egress. The flux levels of the tracings have been adjusted to reflect the

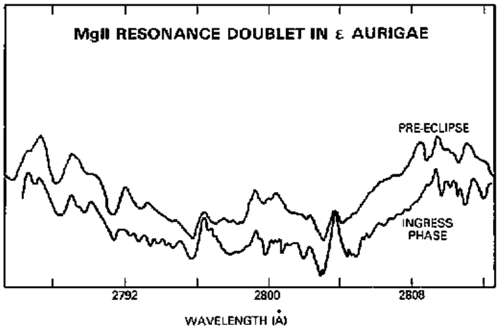

FIG. 3.—The Mg II resonance doublet in ε Aur. The ordinate on the plot is the relative flux in the spectra. The two tracings have been adjusted vertically to account for the differences in exposure times: the vertical displacement is a reflection of the dimming of the star between the two epochs (1982 April 13 and 1982 September 21). It is noteworthy that the two Mg II emission peaks in the broad stellar Mg II absorption remain equally intense as the stellar background decreases in flux level. It is clear that the source of the Mg II emission is not being significantly eclipsed.

relative change in brightness of the star between 1982 April and September. The spectrum decreases in flux level, with little change in appearance, except for an emission peak in each line of the doublet: the emission peak remains constant in flux. This observation shows that there is plasma hot enough to emit Mg II (~ 10,000 K) located in the system in such a way that it is largely unobscured by eclipse. Normal early F type supergiants tend not to show significant Mg II emission (Stencel, Worden, and Giampapa 1981; Parsons 1983). This emission may come from the cloud around the secondary. Similar Mg II emission is observed in ζ Aur (Chapman 1981), arising from the K star's wind. A search of the spectrum has so far not turned up any lines which indicate the presence of plasma hotter than that which will emit the Mg II resonance doublet. The dimensions of the putative disk, derived from the eclipse geometry (Huang 1965), indicate that its area projected on the plane of the sky is at least as large as that of the F supergiant, and it may be 50% larger. This result, coupled with the undetectability of the spectrum of the secondary, also suggests that the temperature of the supposed disk is substantially below that of an F0 supergiant (~ 8000 K). The mid-ultraviolet spectrum of ε Aur longward of 2000 Å is consistent with that of an F0 supergiant (Castelli, Hoekstra, and Kondo 1982).

III. CONCLUSIONS

The current ultraviolet results confirm that the eclipse of the F0 supergiant primary in ε Aur can be interpreted as being caused by an object whose dimensions are greater than those of the primary, whose characteristic temperature is in the range from 1000 to 2000 K, and which scatters light from the F star by electron scattering in wavelengths between 3000 Å and at least 5000 Å. The *IUE* observations support a new factor: the absorption by dust shortward of 3000 Å. Judging from the efficiency of the opacity that becomes effective in the mid-ultraviolet, the average grain size is likely to be comparable to the wavelength of the mid-ultraviolet light; that is, the size is smaller than the 1 μm range usually assumed for interstellar grains. In this connection, we refer to Sitko, Savage, and Meade (1981) who have reported a continuously increasing extinction in the mid-ultraviolet to far-ultraviolet region in the star AB Aur, which they attribute to the dust shell surrounding this B9-A0 variable star.

In addition, there exists in ε Aur a region of Mg II emitting gas, which appears to be associated with an extended region, judging from the observational evidence that it is little affected by the eclipse of the primary star by the secondary object.

Finally, we have thus far not detected any evidence for the existence of a hot star or a hot spot in the secondary. We note that Castelli, Hoekstra, and Kondo (1982) found that the mid-ultraviolet ($\lambda \geq 2000$ Å) spectrum is entirely consistent with that of the F0 supergiant. Judging from the unobservability of a companion star, either the companion is of low (1000–2000 K) temperature, or it is imbedded in a thick disk in such a way as to be completely occulted. We would like to reiterate that the conclusions of this *Letter* are based on a preliminary analysis of the early eclipse observations of the system. A more detailed analysis of the complete eclipse data set should allow us to greatly increase our understanding of the system.

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