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AN INTERPRETATION OF ε AURIGAE

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ABSTRACT

A model of ε Aurigae has been proposed in order to explain the contradictory behavior of this star found in photometric and spectroscopic observations. This model which consists of a rotating gaseous disk that appears opaque when viewed edge-on resembles the one we have suggested for β Lyrae (Huang 1963). The success of this simple model to explain these two peculiar stars which have defied other interpretations for so long, together with the fact that rotating gaseous rings are frequently associated with the primary component of the Algol-type binary systems (Joy 1942, also Sahade 1960) leads us to a belief that rotating gaseous rings or disks are the result of natural development of gases that are injected into the binary system by its component stars. This belief is further strengthened by our knowledge that such a rotating ring or disk is dynamically or hydro-dynamically feasible (Prendergast 1960, Huang 1964).

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I. INTRODUCTION

The binary ε Aurigae whose period is 27.1 years - one of the longest among eclipsing systems - gives every indication in its light curve of undergoing periodically total eclipses. But the spectrum of the eclipsed component, a F2 supergiant, can be observed persistently during the totality. These two

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seemingly irreconcilable phenomena have puzzled astronomers since the turn of the century. A serious attempt to resolve this incompatibility in the observational results may perhaps be traced to a paper by Kuiper, Struve and Strömgren (1937). They proposed an idea of making the huge eclipsing body - referred to as the I component - so tenuous as to be optically transparent to optical light. However, they argued that the ultraviolet radiation of the F-type supergiant would ionize the crescent-like thin layer of the I component that faces the F-type primary. The scattering by free electrons produced by ionization in this layer would then cut down the light from the F-type primary when the I component is in front, producing the phenomenom of eclipse. Since electron-scattering is frequency independent, the opacity in the crescent-like layer reduces the overall flux of the F component but does not change the spectral nature of the light. In this way, they are able to explain the difficulty we have mentioned before.

While this model has indeed resolved the long-standing difficulty, it introduces several new ones of equal, if not more, serious nature. Some of them have been mentioned in a recent work by Struve and Zebergs (1962).

Although the model by Kuiper et al. has been criticized, the idea of electron scattering as the cause of eclipse has persisted in the latter models by Struve (1956) and more recently by Hack (1961). This same idea has also strongly influenced the directions in which spectroscopic investigations of the star has been made (Kraft 1954).

Both Struve and Hack models may be regarded as modified versions of the original one by Kuiper et al. Struve introduced the idea that both components are surrounded by nebulous gases that fill the respective lobe of the inner contract surface of the system. These nebulous gases are supposed to cause gas streaming from one component to another and vice versa. Struve

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attributed the apparent splitting of lines observed before and after total eclipse to the presence of these gaseous streams. Except for this, Struve's interpretation of this peculiar system follows the same line of thought as in their previous paper. Consequently, the basic difficulties of eclipse by electron scattering are not removed.

Hack's model does introduce a new concept. She proposed a hot secondary star of an effective temperature reaching $20,000^{\circ}K$. According to her, it is this hot star that is responsible for the ionization of gases in the shell or ring around it. The phenomenon of eclipse is then attributed to the intervention of this shell or ring between the primary F2 component and the observer.

It is more convincing to have an O or a B star around to do the work of ionization than an F2 star. But the introduction of a hot secondary meets other difficulties as we shall see in the following ways.

The depth of the eclipse during the apparent totality is about 0.8 magnitudes, which corresponds to an optical thickness of 0.74 over the entire spectral frequencies, if we assume that the eclipse is due to obscuration of the entire F component by the shell or ring. It requires 10^{24} of electrons in the column of unit cross-section and of a length equal to the thickness of the shell or ring. Since hydrogen is the dominant constituent, there will be approximately 10^{24} atoms in each column. Now, how could one explain that these atoms in their ionized states do not impress some additional spectroscopic feature on the light that passes through them? With ionizing radiation coming from a star of $20,000^{\circ}K$ one would expect to observe spectral lines arising from such atoms as neutral or ionized helium, ionized oxygen, nitrogen, etc. that correspond to those found in the early-type supergiant stars. None have been observed. What have been actually observed, such as doubling and strengthening of lines in certain phases during eclipse, only show that the excitation level of the absorbing medium associated with the eclipsing body is not greatly different from that of the primary

F2 atmosphere. Indeed, it has been specifically pointed out in the paper by Kuiper et al. that the lines associated with the secondary component and observed during eclipse are approximately, though not identically, the same as the normal lines of the F2 star.

Although it may be argued that compared with the F2 supergiant component, the hot star proposed by Hack is too faint to be seen in the visible region even during eclipse, it is difficult to comprehend why it has not been detected in the ultraviolet region. All these questions impair the otherwise attractive proposal by Hack.

From what has been said before, we cannot help but conclude that in spite of various modifications and refinements made since its inception, the electron scattering theory of the eclipse of ϵ Aurigae cannot explain this binary system in an internally consistent way.

Other theories of eclipse have been suggested in the meantime, but according to Hack (1961), none of them can explain the spectroscopic behavior of the system. However, it should be noted that Kopal's (1955) theory of attributing the opacity to solid particles did introduce a new conception of a ring structure which has been followed by Hack herself.

II. A PROPOSED MODEL

The success of our interpretations of β Lyrae by the introduction of an opaque gaseous disk rotating around its secondary component (Huang 1963) has led us to examine whether the same kind of model may be used for ϵ Aurigae, because in many respects the two peculiar binary systems show a similar behavior. Their similarities are: (1) The light from the primary component can be seen during the entire duration of eclipse while the spectrum of the secondary component itself has never been observed at any phase. (2) Additional lines appear during eclipse. These lines are, in both systems, displaced towards the red end before the principal mid-eclipse and towards the violet end after mid-eclipse. (3) Light shows fluctuations, especially during eclipse, and (4) both show emission features.

However, there are also differences between these two systems. In the first place, the magnitudes of wavelength shifts of those additional lines observed during eclipse are different. In the case of β Lyrae, the radial velocities corresponding to the shifts are of the order of 100-300 km/sec, while in the case of ε Aurigae the velocities are perhaps of the order of 30-50 km/sec. This difference actually confirms our conviction that the two systems are similar, if we remember that the period of β Lyrae is only about 13 days while that of ε Aurigae is about 27.1 years. Thus, for the purpose of a similarity consideration, we must compare the stream velocities in terms of the respective orbital velocities of the component stars. Then the stream velocities in the two systems are of the same order of magnitude.

Another difference between these two systems comes from the fact that β Lyrae shows a secondary eclipse but ε Aurigae does not. This difference can be readily explained on the basis of our model of an opaque disk, as we shall see presently.

Figure 1 shows the model we propose for ε Aurigae. The obscuration of the primary component by the rotating gaseous disk causes an eclipse which would look, in the light curve, like total but the light from the primary will continuously be seen even at the apparent totality. We suggest that the inclination, i, of this system is very near to 90°. Thus, we see only the edge of the disk; the secondary component itself cannot be seen because it is hidden in the disk. Because of this inclination neither do we receive any radiation from the primary reflected by the disk. As a result there will be no secondary eclipse. On the other hand, we have suggested in the previous paper that β Lyrae has an inclination which differs appreciably from 90° so that we can see the secondary star itself as well as the light reflected by the rotating gaseous disk. Consequently, we are able to observe a secondary eclipse.

Because of the difference in inclination, the shape of minimum differs in these two systems too. In the case of β Lyrae, the projected area of the disk will be an elongated ellipse, resulting in a curved minimum in the light variation. In the case of ε Aurigae, the projected area would be a rectangle (as shown in Figure 1), producing a flat minimum.

The sizes of the primary component and the opaque disk may be determined from the light curve. Let us, for the sake of illustration, assume that the stellar disk of the primary component is uniform in brightness and the edge of the disk we actually face is completely dark. We can now determine the radii, denoted respectively by r_1 and r_2', of both the primary component and the disk around the secondary component as well as the thickness of d_2' of the disk. All these quantities will be measured in terms of the mean separation between the two components of the system.

Different investigators gave different values for the duration of eclipse, D, and that of totality, d. We shall follow Plaut's (1950) values D = 0.0760 and d = 0.340, which yield after a simple calculation,

$$r_1 = 0.065 \quad \text{and} \quad r_2' = 0.171. \qquad (1)$$

In order to determine d_2' we must use the observed depth of eclipse during the apparent totality. If we denote by α_o the angle subtended at the center of the primary by the two points of intersection, all projected on the celestial sphere, between the boundary lines of the opaque disk and the primary component during eclipse (see Figure 1), the maximum light L_1 and the minimum light L_2 of the system are related by

$$\frac{L_2}{L_1} = \frac{\pi - \alpha_0 - \sin\alpha_0}{\pi} \qquad (2)$$

where

$$\sin\left(\frac{\alpha_0}{2}\right) = \frac{1}{2}\,\frac{d_2'}{r_1} \qquad (3)$$

Since the observed depth of minimum is 0.81 mag., equation (2) gives $\alpha_o = 0.881$ which in turns yields

$$d_2' = .055 \qquad (4)$$

III. Interpretation of the Light Curve

As an illustration that the present model can predict a light curve very much like the one actually observed, we shall consider a central eclipse ($i = 90^o$) of a uniformly bright stellar disk of the primary component by the dark projection of the rotating disk, shown schematically in Figure 1. If we denote by δ the apparent distance between the center of the primary and the center of the opaque disk and if we let

$$\delta_1 = r_1 + r_2', \qquad \delta_2 = r_1 \cos\tfrac{1}{2}\alpha_0 + r_2', \qquad (5)$$

$$\delta_3 = r_2' - r_1 \cos\tfrac{1}{2}\alpha_0, \qquad \delta_4 = r_2' - r_1,$$

where r_1, r_2' and α_o have been determined in the previous section, the light curve predicted on this model is given by

$$\frac{L_2}{L_1} = 1 - \frac{1}{2\pi}(\alpha_1 - \sin\alpha_1), \quad \delta_2 \le |\delta| \le \delta_1 \qquad (6)$$

$$\frac{L_2}{L_1} = 1 - \frac{1}{2\pi}(\alpha_0 - \sin\alpha_0) - \frac{d_2'}{\pi r_1^2}(\delta_2 - \delta), \quad \delta_3 \le |\delta| \le \delta_2 \qquad (7)$$

and

$$\frac{L_2}{L_1} = 1 - \frac{1}{\pi}(\alpha_0 + \sin\alpha_0) + \frac{1}{2\pi}(\alpha_2 - \sin\alpha_2), \quad \delta_4 \le |\delta| \le \delta_3 \qquad (8)$$

where

$$\cos\frac{1}{2}\alpha_1 = 1 - \frac{\delta_1 - \delta}{r_1} \quad \text{and} \quad \cos\frac{1}{2}\alpha_2 = 1 - \frac{\delta - \delta_4}{r_1}$$

For $0 \leq |\delta| \leq \delta_4$, L_2/L_1 has already been given in equation (2).

The light curve according to these equations has been computed with the numerical values given by equations (1) and (4) and is plotted at the top of Figure 1. There is a general agreement between this predicted curve and the actually observed one (Güssow 1936).

It may be noted parenthetically that this interpretation of the light curve of ε Aurigae requires only that the rotating disk is opaque when viewed along the edge. Whether it is transparent or opaque in its vertical direction, does not matter in our interpretation. Indeed, we have no observational means to ascertain the optical depth in its vertical direction.

As has been pointed out by Fredrick (1960), the light curve shows a slight asymmetry. On the basis of our model, the asymmetry in the light curve reflects either an corresponding asymmetry in the thickness of the rotating disk or an additional absorption by gaseous stream above and below the rotating disk. Physically, it is difficult to envisage a permanent asymmetry in the thickness of the disk. Therefore it is most probable that the asymmetry is caused by the gaseous stream. If we assume that there is a gaseous stream flowing out from the primary component through the Lagrangian point into the secondary lobe of the innermost contact surface (Kuiper 1941), the gaseous stream will circulate around the secondary component above and below the main body of the rotating disk. As the gaseous streams circulate around the secondary component in the same sense as the rotation of the disk, which is in turn supposed to be rotating in the same sense as the binary motion, we would expect that they will gradually coalesce into the disk itself as a result of collisions. It is then not difficult to see that at any moment more gas would be found in the rear side than in the front side of the secondary component, giving rise to an asymmetry in absorption in agreement with the observed result. In this respect the behavior of the gaseous streams outside the main body of the rotating disk resembles closely what has been suggested for β Lyrae, which shows an asymmetric primary eclipse, with the decline steeper than the rise. We have attributed this asymmetry also to obscuration of gases just streaming out from the primary component, this obscuration making the eclipse last longer, and consequently show slower decline than would be the case of intervention of a simple disk. According to this interpretation, the light curves of both ε Aurigae and β Lyrae before mid-eclipse are perhaps less distorted by gaseous streams outside the rotating disk than those after mid-eclipse.

Other interesting facts found in this system are, according to Güssow (1936) and Fredrick (1960), that the light fluctuation far away from eclipse does not exceed 0.1 mag., that in 3-5 years before and after eclipse the variation may get as large as, but seldom 0.2 mag. and that in totality, the fluctuation may reach 0.3 mag. or even slightly larger. Such a manner of variations in light follows also quite naturally from our model. While the intrinsic variation of light far away from eclipse is expected from the supergiant F2 primary itself, the greater fluctuation in light near and during eclipse only indicates the unsteadiness of gaseous streams on both sides of the rotating disk.

IV. INTERPRETATION OF SPECTROSCOPIC RESULTS

That ε Aurigae shows an H_α emission has long been known (Adams and Sanford 1930). More recently, Wright and Kushwaha (1958) have made an extensive study of the structure of this

H_α line both inside and outside the last eclipse. According to them, the two emission wings are almost equal in intensity outside eclipse. Moreover, the central absorption gives the same radial velocity as the absorption lines of Fe II , Ba II , and Y II in all phases outside eclipse. This result suggests that the material that produces the emission feature moves with the primary.

Moreover, Wright and Kushwaha have found that just before and during ingress the emission wing towards violet is usually stronger than that towards red and during egress, the reverse is true. At the time of totality, the absorption becomes dominant.

The H_α emission is produced by gases moving with the primary component, but we still do not know how they are distributed in space around the primary component. The line profile outside eclipse appears to suggest a rotating gaseous ring like the one observed in many an Algol-type binary system (Joy 1942; also Sahade 1960). However, the behavior of this emission line found in ε Aurigae during eclipse differs from what has been observed in the Algol-type variables. In the latter, the emission wing toward violet decreases in strength when the system enters into eclipse, but in ε Aurigae, the same wing increases in strength. Similarly, in egress, the two cases show variation in the relative intensity of the two emission wings in opposite directions. Two hypotheses as regards the distribution of emitting gases may be proposed to explain the behavior of H_α emission found in ε Aurigae in and out of eclipse. (1) The emission indeed comes from a gaseous ring rotating around the primary but the sense of rotation is opposite to the orbital revolution of components in the system.

(2) Emission is produced by expanding gases ejected from the primary component. It is interesting to note that

Adams and Sanford (1930) did find that H_α showed then as an emission line with an absorption border on its violet edge, indicating outward motion of gases. Consequently, Beals (See Mack 1961) classified it as a P Cygni star.

According to Wright and Kushwaha, the weak emission feature that occurs during totality seems to correspond to the velocity of the system and could be due to the tenuous gases enveloping the entire binary.

While the H_α emission mainly comes from gases associated in whatever way with the primary component, the complicated absorption feature of this line observed during eclipse is due to gases spilled above and below the main body of the disk around the secondary component.

It is reasonable to assume that the distribution of gases around the secondary component is not confined to the disk itself. However, for the same reason that the material density in the galactic plane falls off rapidly in the polar directions, the density around the secondary component must also decrease rapidly with the perpendicular distance. At places not too far away from the main body of the disk, the gaseous distribution would be so rare that it is no longer opaque to the continuous radiation but it may still produce line absorption. Therefore, we should expect to observe it through spectroscopic study. Indeed, according to our model, it is this gas distribution that produces the additional absorption that modifies the profile of H_α continuously with phase during eclipse. Thus, during ingress, additional absorption which occurs in the red side of the normal position makes the emission wing toward violet appear stronger than the other. A similar argument leads to the reverse conclusion at the time of egress. During totality the light from the primary passes through a large amount of gases, resulting in a dominantly absorption line as observed. In this way Wright and Kishwaha's results can be satisfactorily explained on the present model.

Because of the appearance of H_α emission in its spectrum, it has been proposed (Wright and Kishwaha 1958) that the excitation might be due to a hot secondary, since under normal conditions, no emission at H_α appears in the spectra of a star as late as spectral type F of the primary component. As we have seen before, Hack has incorporated this suggestion in her theory in order to explain the ionization of gases in the shell or ring around the secondary. In section I, we have seen that a hot secondary introduces some new difficulties. Now we have found that the H_α emission comes from gaseous distribution associated with the primary instead of the secondary. Hence, the hypothesis of a hot secondary made in order to explain H_α emission becomes even less satisfactory than the case if the emission were associated with the secondary.

If the gases spilled over the disk give rise to absorption that cuts into H_α emission, we would expect during eclipse the appearance of lines belonging to other elements than hydrogen. Indeed, the indication of such an additional absorption has long been known. According to Kuiper et al, the spectral lines of many elements become asymmetric during ingress by the presence of a strong core on the red side. The degree of asymmetry increases, reaches a maximum at second contact and then diminishes until mid-eclipse when each line becomes symmetric as it is outside eclipse. However, the intensities of lines at mid-eclipse are somewhat stronger than those outside eclipse. After mid-eclipse, the lines become asymmetrical again, but with a strong core on the violet side this time. This asymmetry increases rapidly until it reaches third contact. The asymmetry is obviously due to the presence of a double structure (Adams and Sanford 1930) and indicates the additional line absorption by gases spilled over from the disk. The sense of the Doppler shift of these lines agrees again with what one would expect from gaseous streams rotating in the same sense as the orbital revolution.

In the previous section we have attributed the asymmetry of the light curve also to gaseous streams which are located perhaps closer to the disk than those giving rise to absorption lines. We have suggested that the gaseous streams must be more complicated and extend a larger region in the rear side than in the front side of the secondary. Accordingly, we would expect the structure of absorption lines observed after mid-eclipse to be more complicated than that observed before mid- eclipse. Struve and Pillans' (1957) observational results appear to bear this prediction out. They have found that at the very end of totality, the absorption lines show a remarkable amount of structure not previously observed in the star. Some lines are triple, while others show a double structure, indicating gaseous streams, just coming out from the primary before collision which would have erased the velocity differences of the streams.

V. THE F2 SUPERGIANT ATMOSPHERE, ITS MASS EJECTION AND TURBULENT VELOCITIES

Finally, we may say a few words about the atmosphere of the F2 supergiant primary. Whatever is the mass ratio of the system, it is reasonably certain that the size of the primary component derived in Section II must be small compared with the innermost contact surface (e.g. Kuiper 1941), which will be referred to hereafter as the S_1 surface. Indeed, the light curve outside eclipse does not indicate any distortion due to ellipticity. On the other hand, both spectroscopic and photometric results indicate that mass is continuously flowing out of the primary lobe of the S_1 surface into the secondary lobe. It follows that at the photospheric surface, the star must steadily eject matter to keep the flow of gas from the primary lobe to the secondary lobe of the S_1 surface. Since the photosphere is well below the S_1 surface, the effect of its comparison must be small. Consequently, mass ejection at the stellar surface (i.e. photosphere) must be intrinsic to this F2 supergiant primary and should not be attributed to the interaction within a binary.

Thus, between the photosphere and the corresponding lobe of the S_1 surface, the vast volume must be filled with a tenuous atmosphere. Its extension must be several times the stellar radius; through the extended atmosphere the primary is losing its mass. The picture thus derived agrees completely with what Deutsch (1956, 1960) has found in many red giant and supergiant stars and confirms the general belief that a supergiant -- whatever is its spectral type -- is always ejecting mass.

Violent motions have always been found in atmospheres of supergiant stars (e.g. Huang and Struve 1960). This is especially true in the primary of ζ Aurigae (Wright and van Dien 1949; Hack 1959). However, the nature of the observed motion has never been clearly understood, although frequently but rather vaguely we have attributed it to some kind of prominence activities. With the conception of mass ejection by the supergiant star reasonably established, we can now understand why violent motion should always be associated with its atmosphere. Indeed, the mass ejection from the stallar surface, presumably due to convective currents below, acts as a stirring mechanism of the atmosphere over the photosphere. The ejection creats a velocity field in the atmosphere which also makes the latter very extended.

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LEGEND

Figure 1

A schematic diagram of our model for ε Aurigae and the resulting light curve during eclipse. It is assumed that we observe this system edge-on. Consequently, the rotating gaseous disk around the secondary component will appear like a dark rectangle which obscures the primary component during eclipse. The light curve at the top of the figure is derived by assuming a uniform stellar disk.