THE ASTROPHYSICAL JOURNAL, 208:780–788, 1976 September 15

AN INTERPRETATION OF BETA LYRAE. II. DISK LUMINOSITY, MASS RATIO, AND NATURE OF THE SECONDARY COMPONENT

SU-SHU HUANG AND DEBORAH A. BROWN
Department of Astronomy, Northwestern University
Received 1975 December 5; revised 1976 February 25

ABSTRACT

We have found from an analysis of light curves in different colors that the temperature of the disk surrounding the secondary component of the system is about the same as that of the primary and have thereby been able to show why the disk (or secondary) spectrum has not been detected for certain. From its temperature, the contribution of the disk to the luminosity of the system, formerly uncertain, can now be estimated, thus paving the way for a new estimate of the mass ratio of the system. The secondary mass is found to be 5 or more times that of the primary. However, a detailed analysis shows that the mass ratio is greatly affected by other uncertain factors that are at present not controllable.

The determination of the disk temperature also makes it possible to examine the nature of the secondary component embedded in the disk. It has been found that the secondary has to be an early B star if it is on the main sequence and even earlier if it is below the main sequence.

Finally the sources of emission lines and the evolutionary state of the system are briefly discussed. It is suggested that emission lines arising from some highly ionized atoms may be formed in the corona that exists around the entire system.

Subject headings: stars: eclipsing binaries — stars: emission-line — stars: individual

I. INTRODUCTION

From the distance of β Lyrae determined by Abt *et al.* (1962), it has been possible to settle the dispute about its mass ratio (Huang 1962; Skul'skii 1971; Wilson 1974), in favor of what had long been suspected (e.g., Sahade *et al.* 1959), namely, that the secondary component is more massive than the primary. With this result we have found that it is necessary to introduce an opaque disk surrounding the secondary component in order to explain the otherwise contradictory data from photometric and spectroscopic observations (Huang 1963, hereafter to be referred to as Paper I). This disk model has since been generally accepted (Woolf 1965; Coyne 1970; Alduseva 1974) and has provided a base on which further investigations have been made by several investigators (Devinney 1971; Stothers and Lucy 1972; Kříž 1974; Wilson 1974; Hack *et al.* 1975) whose concern centers mainly on the problem of the nature of the secondary component. The present paper will also deal with the nature of the secondary component but with the difference that it will try first to understand the disk and then infer indirectly the nature of the secondary from the properties of the disk. We follow this procedure because only the disk is directly observable while the secondary component, being surrounded by the disk, is not.

In Paper I we introduced the disk without specifying its physical nature, since at that time there were not enough observational data that could be used to suggest any concrete ideas. However, as a result of OAO-2 observations, light curves of this system have been obtained in several far-ultraviolet regions (Kondo, McCluskey, and Houck 1972). When these curves, admittedly provisional because the observation has not been repeated, are combined with those in the optical region (Larsson-Leander 1969), they provide us with a new avenue for our understanding of the radiative nature of the disk (Huang and Brown 1976, hereafter to be referred to as Paper A). In the present paper we will show that the knowledge of disk radiation derived in this way leads us to the nature of the secondary component as well as an improved estimate for the mass ratio of the system and the various factors affecting it.

II. LUMINOSITY OF THE DISK

Consider the eclipsed area of the projected surface of the disk on the celestial sphere at secondary minimum, which has been denoted by ΔA in Paper A. Radiation from the primary component will fall on ΔA and contribute at least a part of its luminosity. The dilution factor w_1 of radiation of the primary star at the disk is about 0.1. Since the disk has been found in Paper A to be in a state of LTE, incident radiation will most likely be absorbed at the spot of incidence and raise the temperature with the result that the incident area will have a slightly higher temperature (denoted by T_x in Paper A) than the intrinsic temperature T_d of this area, the intrinsic temperature being the one the disk would have if there were no incidence of radiation from the primary.

TABLE 1

TEMPERATURES OF THE PRIMARY, THE DISK, AND THE HYPOTHETICAL MAIN-SEQUENCE SECONDARY

T_1 (K)	T_x (K)	w_x	T_d (K)	"T_2" (K)*
12,000......	12,660	0.490	10,100	25,900
11,350......	11,950	0.490	9600	25,100
10,700......	11,200	0.495	9000	24,300

* Based on $M_v = -3.9$ mag.

The relation between T_x and T_d is given by the condition of energy balance:

$$w_x T_x^4 = w_1 T_1^4 + T_d^4 , \quad (1)$$

where T_1 is the temperature of the primary star while w_x and T_x have been derived from the one-component analysis of the eclipsing depths in Paper A. The purely numerical factor w_x is a correction factor taking care of the fact that the radiative flux may depart from the Planck function (cf. Paper A). We have derived in the previous paper w_x and T_x by assuming three values of T_1, namely, 12,000 K, 11,350 K, and 10,700 K. These results are given in Table 1 together with T_d determined according to equation (1) with $w_1 = 0.1$. It is to be noted that the disk temperature thus derived is close to the primary temperature in all three cases.

If we should assume that the entire surface of the disk radiates in the same way that ΔA would without the added energy due to primary radiation, the bolometric luminosity of the primary, l_1, as a fraction of the combined bolometric luminosity of both primary and disk, $(l_1 + l_d)$, will be given by

$$k = \frac{l_1}{l_1 + l_d} = \frac{r_1^2 T_1^4}{r_1^2 T_1^4 + abT_d^4} , \quad (2)$$

where r_1 is the radius of the primary while a and b are respectively semimajor and semiminor axes of the ellipse that is supposed to be the projection of the disk on the celestial sphere. In writing down equation (2) we have assumed that the limb darkening factor is about the same for the disk and for the primary. The fractional luminosity contributed by the disk to the entire system as observed by the observer on the Earth is of course equal to $(1 - k)$. Wilson (1974) has assumed the disk to be in the shape of an ellipsoid of revolution of semimajor axis a and semiminor axis b_1, and the primary star to fill its Roche lobe. Consequently the size of the primary is given by four parameters instead of the single value, r_1, that we have used here. Since the maximum light occurs at quadrature, we may set r_1 equal to $(r_x r_z)^{1/2}$, where r_x is the mean of his r_1(point) and r_1(back) values and r_z is his r_1(pole) value. The r_1 as given here differs slightly from r_1 used in Paper A, where for an order-of-magnitude estimate we have simply taken an arithmetic mean of the four values given by Wilson. By assuming five values for the mass ratio $q = m_2/m_1$, where m_1 and m_2 are respectively the mass of the primary and the secondary, Wilson (1974) has derived from the light curve in the V color the inclination of the orbit (which is assumed also to be the inclination of the disk), a, b_1 and four radii for the primary component, all in the unit of separation of the two component stars. From these values we derive b according to an equation given in Paper A, and r_1 according to the method just described. Then from a, b, and r_1 we derive k for each given value of T_1. The results are tabulated in Table 2, where three values of T_1 have been assumed. It appears that k does not change much with T_1. The table shows that as seen by the observer on the Earth, the disk contributes about 30–40 percent to the total luminosity of the system at the quadrature. What the system would look like in the direction perpendicular to the plane will be discussed in connection with the nature of the secondary.

III. DISK SPECTRUM

If the disk contributes 30–40 percent to the total luminosity of the system, it would be observable not only during primary eclipse but also at quadrature. But so far most observers agree that no spectrum of the secondary component has been detected. This point presents, of course, one of the well-known difficulties in the interpretation of this peculiar system. Kříž (1974) suggested that the secondary star is in a state of rapid rotation which washes away its own absorption lines. If the disk scatters radiation only, this explanation will be quite satisfactory, because scattering only further broadens the line profile. But we found that the disk is in the state of LTE. Consequently whether the secondary component rotates rapidly or not has no bearing on emergent radiation from the disk. The emergent radiation is completely determined by the disk itself. In

TABLE 2

PARAMETERS THAT ARE USED TO DETERMINE q AND "T_2"

							$T_1 = 10{,}700$ K		$T_1 = 11{,}350$ K		$T_1 = 12{,}000$ K	
q	$m_1/m_\odot$	$m_2/m_\odot$	i	a	b	r_1	k	k'	k	k'	k	k'
2.......	9.56	19.12	90°	.52	.21	.34	.68	.68	.68	.68	.68	.68
3.......	5.04	15.12	89°	.54	.16	.31	.69	.69	.69	.69	.69	.69
4.......	3.36	13.44	85°	.56	.18	.29	.63	.63	.62	.62	.62	.62
5.......	2.48	12.40	85°	.57	.16	.27	.62	.62	.61	.61	.61	.61
6.......	1.95	11.70	85°	.57	.16	.26	.60	.60	.60	.60	.59	.59

other words we should expect to observe absorption lines corresponding to the effective temperature, T_a, of the disk.

That no disk spectrum has been observed may be attributed to two causes. In the first place, the effective temperature of the disk has been found to be very close to that of the primary component, as can be seen in Table 1. That explains why the disk spectrum has not been detected during primary eclipse. Such an explanation is invalid at quadrature because the relative motion of two component stars will make their spectral lines separable. However, we must remember that the spectral lines formed in the disk are broadened by its rotation and thereby could be washed out by rotational broadening.

Rotation of the disk, unlike that of a star, is predictable and can be quantitatively estimated by calculation. This is because the flattened form of the disk is supported by rotation instead of pressure. In other words, the centrifugal force must balance the gravitational force for the matter at the edge of the disk. If we assume that the plane of the disk and the plane of the binary orbit have the same inclination, i, we obtain readily the observed rotational velocity $V_r \sin i$ as follows:

$$V_r \sin i = \frac{K_1}{a^{1/2}} \left(\frac{M_1 + M_2}{M_2}\right)^{1/2} (1 - e^2)^{1/2} \qquad (3)$$

by the two-body approximation, where K_1 is the semiamplitude of the velocity curve of the primary and a the dimensionless radius of the disk (cf. Table 2).

Table 3 lists the values of $V_r \sin i$ for different values of q. They are of the order of 300 km s^{-1}. If we should see the disk alone, this amount of rotational broadening would not be enough to wash out completely the absorption lines of the disk, since we observe spectral lines in stars that show $V_r \sin i$ far greater than 300 km s^{-1}. But in our present case there is the primary whose light increases the continuum by a factor of about 2 to 3 and thereby suppresses the absorption lines of the disk to make the latter shallower by the same factor than they would be without the presence of the primary component.

Batten, Diamond, and Fisher (1974) have searched for the K line of the secondary component in high-dispersion spectrograms of the system. From their figure we note that the central depth of the K line of the primary component is about 40 percent (i.e., the residual intensity at the line center is 60%); since the disk and the primary have about the same temperature (cf. Table 1), the line produced in the disk measured against the continuum of the disk and the line produced in the primary measured against the continuum of the primary should be about the same before any kind of broadening. Now we have found in § II that the disk contributes about 30–40 percent of the total light of the system. Let us for definiteness take within this range the ratio of 2:1 for the light from the primary as compared with that from the disk. Consequently, simply as a result of the difference in the continuum of the primary and the disk, the central depth of the K line of the disk as seen in the combined continuum of both the disk and the primary could be one-half of that of the K line of the primary, namely, 20 percent. Now the rotational velocity of the primary is 45 km s^{-1}, but the rotational velocity of the disk is about 300 km s^{-1}. Consequently the central depth of the K line of the disk as compared with that of the primary should be 45/300 because of rotational broadening alone. When we take both the continuum and the rotational broadening together into consideration, it is easy to see that the central depth of the K line of the secondary component is only 3 percent, which cannot be detected with any degree of certainty. Therefore, it is not surprising at all that we have been unable to detect the absorption lines of the disk with certainty. However, knowing the nature of the lines of the disk and knowing the mass ratio of the system more accurately, we may be able to find the disk absorption lines in future studies.

TABLE 3

ROTATIONAL VELOCITY OF THE DISK

q	$V_r \sin i$ (km s^{-1})
2	314
3	291
4	276
5	268
6	265

IV. MASS RATIO

Several methods for estimating the mass ratio of this system have been proposed. A brief review of them has recently been given by Wilson (1974). The most reliable one is still the one based on the Roche limit and used by Huang (1962), but has since been employed by several other investigators, all mentioned in Wilson's paper. Three current developments lead us to reexamine this critical problem. The first is, of course, our determination by equation (2) of k that provides a realistic estimate of the luminosity of the primary component. Second, the relative dimensions of the system are better known as the result of Wilson's analysis of the light curve. Finally, we have now a better value for the bolometric correction (Morton and Adams 1968) than before. Otherwise we follow the same procedure as before and redetermine the mass ratio of the system.

The same idea of Roche geometry may be used to determine the mass ratio without the use of the bolometric correction, as has been done by Wilson (1974) who has used the visual magnitude directly. This procedure depends upon model atmosphere calculations. So we trade the error in the bolometric correction with that in the model-atmosphere calculation. We will apply both procedures in the present investigation.

Let us consider the first procedure, which employs the bolometric correction. We have defined k in equation (2) as the fraction of the bolometric luminosity of the system contributed by the primary component. If k' is the fraction of the visual luminosity of the system contributed by the primary component, then k' and k are related by

$$k' = \frac{l_{v,1}}{l_{v,1} + l_{v,d}} = \frac{k}{k + (1 - k)\,\mathrm{dex}\,[-0.4(\delta_1 - \delta_d)]}, \quad (4)$$

where δ_1 and δ_d are respectively the bolometric corrections of the primary and the disk and consequently are known (Morton and Adams 1968). The reason we have to introduce k' is the fact that what we observe is the visual luminosity of the primary component, from which its bolometric luminosity can be derived by applying the bolometric correction. In reality because the temperature of the primary and the disk are close, k and k' are practically equal, as can be seen in Table 2, where i, m_1, m_2, a, b, r_1, k, and k' are given as functions of q.

It can be easily seen from what has been described that

$$\log \frac{R_1}{R_\odot} = 0.2(-M_v + 2.5 \log k' - \delta_1 + M_{\odot,b}) - 2 \log \frac{T_1}{T_\odot}, \quad (5)$$

where $R_\odot$ and R_1 are the radii respectively of the Sun and the primary component in the absolute measure, $T_\odot$ and $M_{\odot,b}$ are respectively the effective temperature and the absolute bolometric magnitude of the Sun, and M_v is the absolute visual magnitude of the entire system. M_v is equal to -3.9 mag according to Abt *et al.* (1962) and -3.72 mag according to Wilson (1974). We will use both values in our determination in order to see the uncertainty of the mass ratio as a result of the uncertainty of M_v. Equation (5) defines, for a given T_1, a curve that relates $R_1/R_\odot$ to the mass ratio q on which a, b, and r_1 depend (Wilson 1974), and hence on which k, k', and $R_1/R_\odot$ also depend.

At the same time $R_1/R_\odot$ can also be derived directly from the primary radius r_1 in the unit of the separation, the semiamplitude of the velocity curve K_1, and the period P of the binary motion:

$$\frac{R_1}{R_\odot} = r_1\left(\frac{1 + q}{q}\right)\frac{PK_1}{R_\odot}\frac{(1 - e^2)^{1/2}}{2\pi}\frac{1}{\sin i} \quad (6)$$

where e denotes the eccentricity of the orbit and may be set equal to zero for the β Lyrae system (Sahade *et al.* 1959). Equation (6) defines another curve that relates $R_1/R_\odot$ to q, since K_1 is known from the spectroscopic data (Sahade *et al.* 1959) and i from the photometric data (Wilson 1974). The relation according to equation (6) is presented in Figure 1 as the solid line while that according to equation (5) is represented by two broken lines. The upper broken line corresponds to $M_v = -3.9$ mag and the lower one to $M_v = -3.72$ mag. Both are computed with $T_1 =$ 11,350 K. The intersection between a solid and a broken line determines the mass ratio for the case concerned. For comparison we have indicated by an open circle in the figure for each of two cases ($M_v = -3.72$ mag and $M_v = -3.9$ mag), the values that $R_1/R_\odot$ and q would have if the secondary should be completely dark (corresponding to $k = k' = 1$).

Before we discuss these results, we will make another determination of q without using the bolometric correction. The ratio of the visual luminosity of the primary $l_{v,1}$ to that of the Sun $l_{v,\odot}$ is given by

$$\frac{l_{v,1}}{l_{v,\odot}} = \frac{R_1{}^2 f_v(g_1, T_1)}{R_\odot{}^2 f_v(g_\odot, T_\odot)}, \quad (7)$$

where $f_v(g, T)$ denotes the flux emitted in the visual region by a star of surface gravity g and effective temperature T. The meaning of g_1, T_1, and $g_\odot$ and $T_\odot$ are self-evident. Thus if we should know the ratio $f_v(g_1, T_1)/f_v(g_\odot, T_\odot)$, $R_1/R_\odot$ could be computed because $l_{v,1}/l_{v,\odot}$ is known. However, there is no empirical data for the visual flux emitted by stars of different effective temperatures and surface gravities. This forces us to use the theoretical values obtained from model atmosphere calculations with all the uncertainties arising from the various assumptions made in these calculations.

We have interpolated the required $f_v(g, T)$ values from the tabulation given by Carbon and Gingerich (1969) and thereby obtained another set of curves of $R_1/R_\odot$ from equation (7) as a function of q. They are plotted as the dotted lines in Figure 1. In the main figure the upper one assumes $M_v = -3.9$ mag, and the lower one assumes $M_v = -3.72$ mag, both with $T_1 = 11{,}350$ K. For comparison, q and $R_1/R_\odot$ determined by this procedure in the case of $k = 1$ are shown by two dotted circles (for $M_v = -3.72$ mag and -3.9 mag) in the figure. In any case, the result of $R_1/R_\odot$ derived in this way is perhaps no better and no worse than that derived from equation (5) with the use of the bolometric correction. But the errors in the two determinations come from different sources. Consequently the fact that the two determinations (based on the same T_1 and M_v) do not differ greatly means that errors arising from the bolometric corrections or from the model atmosphere calculation are not large.

In order to bring out the effect of a change in T_1 on the determination of q, we have illustrated in the inset of Figure 1 three sets of a broken curve and a dotted curve each. From top to bottom, each set corresponds to $T_1 = 10{,}700$ K, 11,350 K, and 12,000 K, respectively. The broken and the dotted curves are drawn in the same way as those in the main figure but all with $M_v = -3.9$ mag. Hence the middle set is identical to the upper dotted and upper broken curves in the main figure. The solid curve in the inset is of course the same as in the main figure. There are

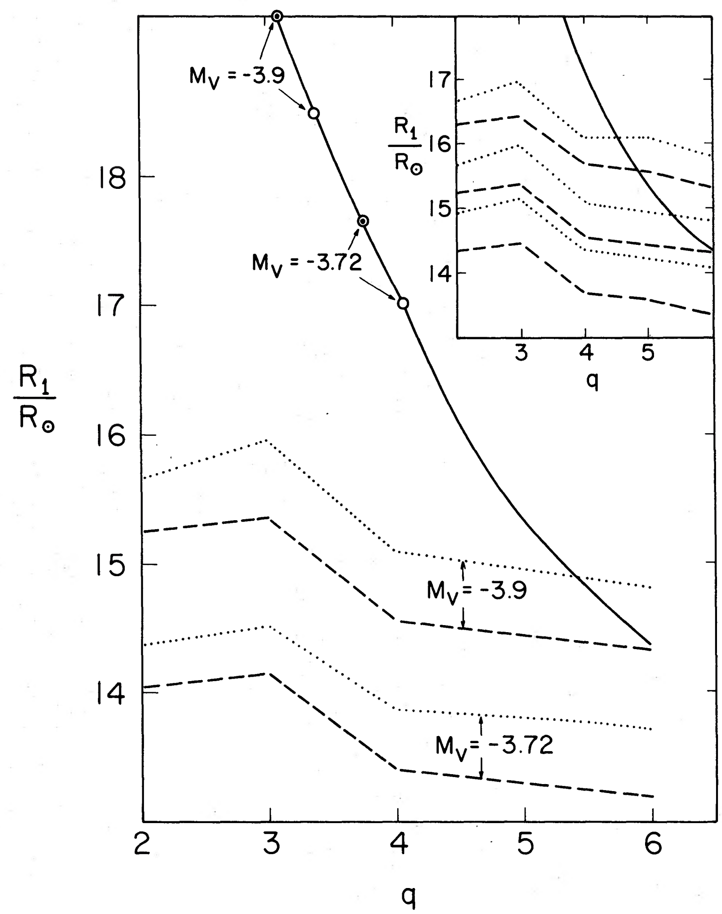

FIG. 1.—Determination of the mass ratio. The mass ratio is determined for each of four different cases by the intersection of the solid curve given by eq. (6) and each of four jagged curves given respectively by eq. (5) (*broken lines*) and eq. (7) (*dotted lines*). The four points on the solid curve represent the corresponding cases if the secondary star (or the disk) is completely dark. A temperature of T_1 = 11,350 K for the primary is assumed for all cases. More detailed explanation is given in the text. In the inset the corresponding determination has been carried out from top to bottom for T_1 = 10,700 K, 11,350 K, and 12,000 K with M_v = −3.9 mag. Each temperature corresponds to one pair of a broken and a dotted curve, both having the same meaning as the main figure.

several sources of error which make the determined value of q uncertain. First, the value of k is very critical. From $k = 1$ to an estimated value of k as given by equation (2), the change of the determined value of q is very large. While the error in k as determined by equation (2) may not be small, what is more serious is the error in assigning values to M_v and T_1. Both produce a large error in q. Figure 1 indicates that q lies perhaps between 5 and 6 if M_v is −3.9 mag, and if T_1 = 11,350 K. But if we should adopt M_v to be −3.72 mag without even changing T_1, q may or may not have a solution, as can be easily seen from the figure where the scale of q ends at $q = 6$. There is no analysis of the light curve based on values of $q > 6$. Needless to say, an analysis of the light curve based on $q > 6$ is desirable. Similarly a change of T_1, as shown in the inset of Figure 1, creates a large change in q. Indeed, for T_1 = 12,000 K the procedure of determining q by the use of the bolometric correction may not even have a solution.

From what has been said we may conclude that the exact value of q cannot be determined at present. Probably it is equal to or greater than 5, but it is by no means certain because of the uncertainties in M_v, T_1, and to a smaller degree k. The purpose of this investigation is to show how different factors can affect the value of q rather than to give an exact value of q.

Huang (1962) has suggested that if we assume that the primary component should rotate in synchronization with its orbital motion, the observed rotational velocity of 45 km s^{-1} (Mitchell 1954; Struve 1958) would suggest that $q > 6$. Indeed, if we plot $2\pi R_1 \sin i/P$ (where P = orbital period) against q by using equation (6) the curve never goes below 45 km s^{-1}. Hence either rotation of the primary is not synchronized (e.g., Huang 1966) or observed rotational velocity is greater than 45 km s^{-1}. In view of our result that the disk contributes 30–40 percent of light to the system, the rotational velocity of the

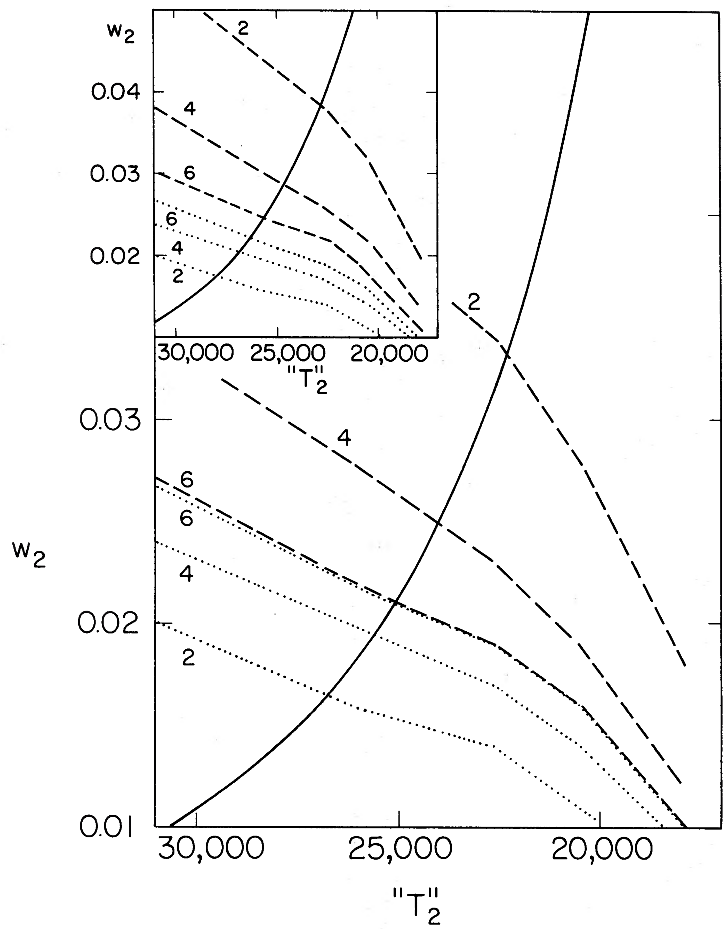

FIG. 2.—Determination of the temperature of the secondary component. The temperature of the secondary component is determined from the temperature of the disk that envelops the secondary by assuming that it is a main-sequence star. The actual temperature is obtained by noting the convergence of the intersecting points respectively of a broken curve and a dotted curve of the same q (by which the curves are labeled) with the solid line. The curves are plotted for $T_1 = 11{,}350$ K, $M_v = -3.9$ mag. More detailed procedure is given in the text. In the inset similar curves are plotted for $T_1 = 12{,}000$ K and $M_v = -3.9$ mag. The temperature thus determined will serve as a reference point if the secondary is not a main-sequence star.

primary component may not be well determined. Consequently the problem of synchronization is by no means settled.

V. EFFECTIVE TEMPERATURE OF THE SECONDARY COMPONENT

Since according to our interpretation the secondary component is embedded inside the disk, it cannot be observed directly. Its nature can, however, be inferred from the luminosity of the disk. We have seen (in Paper A) that the disk is in the state of LTE, and it appears that there is no evidence of a varying brightness over its edge surface. If we assume that the temperature of the disk, T_d, determined previously, is due entirely to the illumination by the secondary star, we may set

$$w_2 T_2^4 = T_d^4 , \qquad (8)$$

where w_2 represents the dilution factor which is roughly equal to $(r_2/a)^2$ along the edge of the disk. Since T_d is determined and is given in Table 1 for different assumed values of T_1, equation (8) gives a relation between w_2 and T_2, which is shown as the solid line in Figure 2 for the case of $T_1 = 11{,}350$ K.

Now if the secondary component were a main-sequence star, we could compute w_2 from $(r_2/a)^2$. For a given value of q, a has been determined by Wilson. For a given spectral type of the secondary star we may infer from the table given by Morton and Adams (1968) its radius in the absolute measure, R_2. Since we already know the radius of the primary component both in the absolute measure R_1 and in the relative measure r_1 for a given q, r_2 can be derived by $r_2 = R_2 r_1/R_1$. We may derive R_1 by the use of either equation (5) or equation (6), and therefore obtain two possible values of r_2 for each combination of T_1, q, and M_v. If we take $M_v = -3.9$ mag, $T_1 = 11{,}350$ K, we obtain for each value of q two curves of w_2 versus T_2 which are shown in Figure 2 for $q = 2, 4, 6$. For each q one line corresponds to r_2 determined from equation (5) (*dashed*) and another corresponds to r_2 determined from equation (6) (*dotted*). The intersection of the solid curve and the broken (or dotted) curve determines "T_2" which would be the temperature of the secondary component if the latter is a main-sequence star. As we shall see later, we could still use "T_2" as a reference point if the secondary component is a star away from the main sequence.

In general two curves (broken and dotted) corresponding to the same value of q do not intersect the solid curve at the same point. But the two intersections are very close, indicating that "T_2" determined in this way is not critically dependent on which of equations (5) or (6) is used. As q increases the two intersecting points slowly converge to a place that corresponds to "T_2" = 25,100 K. The figure shows that "T_2" is not very sensitive to q. In the inset we have plotted curves similar to those in the main diagram except with T_1 = 12,000 K. The intersections of the broken and dotted curves corresponding to $q = 6$ with the solid curve in the inset appear to converge near "T_2" = 25,900 K. Similarly if we should set T_1 = 10,700 K, "T_2" would be 24,300 K (not shown in the figure). All these "T_2" values are listed in Table 1. Furthermore, it may be pointed out that "T_2," unlike q, is not sensitive to M_v of the system. Thus the effective temperature of the secondary component would be in the neighborhood of 25,000 K, which corresponds to a spectral type near B0.5 if it is a zero-age main sequence star and if it is the source for the disk luminosity. If we accept the value of q to be between 5 and 6 as has been found in § IV, the secondary mass would be of the order of 12 $M_\odot$, which corresponds to an early-type main-sequence star. Considering the preliminary nature of the analysis which was advanced in Paper A and on whose result the present study rests and considering the approximateness of w_2 as given by $(r_2/a)^2$ we find that the temperature and the mass are reasonably consistent, if we assume that the secondary component is a star on or close to the main sequence—a view taken also by Stothers and Lucy (1972).

Of course, that does not mean that the secondary is necessarily a main-sequence star. If the secondary star is a giant, then w_2 as directly computed from $(r_2/a)^2$ would be larger than that computed for a main-sequence star of the same T_2. Hence the broken curves would be displaced upward, making the intersection with the solid curve in the figure correspond to smaller values of T_2. From the light curve we expect that r_2 cannot be greatly larger than b (cf. Paper A). If it is not, then w_2 has an upper limit of about 0.16, making the secondary component a star of spectral type no later than B7. The result of this analysis is within the estimate made by Kříž (1974) and Wilson (1974), even though they take a quite different approach to the problem.

If the secondary component is below the main sequence, r_2 would be smaller than shown in the figure. The broken curve should then be displaced downward, making T_2 greater than what would be the case for a main-sequence secondary. While the secondary could be a main-sequence star, we have used the hypothetical main-sequence secondary only as a reference point. We have no intention of concluding in this paper whether the secondary is or is not a main-sequence star. But whether it is on the main sequence or not, its spectral type has to be B or O in order to satisfy the energy balance, unless the energy of the secondary component is dissipated through corpuscular radiation instead of electromagnetic radiation (or if in general the emission of the secondary is nonthermal). Anything that goes beyond this statement would require more observational data.

Next let us examine the geometrical nature of the secondary. Looking in directions near the equatorial plane, we cannot distinguish a highly flattened ellipsoid of revolution from a bona fide disk structure which is in the state of LTE, because both the ellipsoid and the disk produce nearly the same kind of projection on the celestial sphere. This is why Wilson's (1974) parameters derived from the light curve can be interpreted on the basis of either of the two models. However, if the system should be viewed in directions along or close to the normal to the orbital plane, the two models would present two distinguishable kinds of projection on the celestial sphere. The projection of the ellipsoid will be either a circle or an ellipse of low eccentricity. The projection of the disk will be the same with the exception that the central star will be clearly seen. Hence the projection of the system will be a luminous circle or an ellipse with a bright spot in the center. Therefore, if we were able to take a look in the normal direction to the orbital plane, there would be no difficulty in distinguishing the two possible cases. Being limited by our position in space, we cannot decide purely on the basis of the light curve which one is correct.

We are inclined to maintain the view that the secondary component itself is a star—whatever its nature is—surrounded by a disk whose lateral extent far exceeds its thickness. We are not sure whether a star can assume the form of a highly flattened ellipsoid of revolution with the ratio of the major to minor axis exceeding 2. In the case of the Roche model the critical equilibrium configuration is not greatly flattened, both in the case of free rotation (e.g., Jeans 1928) and in the case of synchronized rotation in the binary system (e.g., Moulton 1914).

The equilibrium configuration of homogeneous bodies which has been extensively studied by various investigators from Newton to Chandrasekhar (1969) can assume highly flattened form. But this is not the case that we are interested in at present. Calculations for the equilibrium configuration of rotating bodies composed of a compressible fluid have been carried out mostly for a polytropic gaseous sphere by Chandrasekhar (1933, 1969), and more recently by James (1964) and by Hurley and Roberts (1964). For any reasonable polytropic index that can be fitted to a real star, no equilibrium configurations with the ratio of the major to the minor axis equal to or exceeding 2 have been found. However, there is a possibility which has not been quantitatively studied, and that is a spherical or nearly spherical star surrounded by an envelope which is optically thick enough to be in the state of LTE and which assumes the shape of a highly flattened ellipsoid of revolution as a result of rapid rotation.

VI. SOURCES OF EMISSION AND SUGGESTION OF A CORONA

Unlike the absorption line, the emission line of a star can be formed anywhere in the neighborhood where tenuous gases are present. In the β Lyrae system where an extensive gaseous medium practically envelops the stars and where further complications arise from the gaseous streams and the rotating disk, each emission line must have its own dominant source, and different emission lines could arise from gases located in different regions of space and moving in different ways. Consequently it is very difficult to pin down their exact source or sources in general. However, from both optical and more recently far-ultraviolet studies, we must conclude that a part and perhaps a major part of line emission must have come from an expanding stream of gas. This is especially true for the emission that is associated with the P Cygni profile found in the ground-based spectra as well as in the far-ultraviolet region obtained aboard spacecraft (Hack *et al.* 1975). Hence the picture of such a stream partly moving away from and partly rotating around the entire system as described by Struve (1941, 1958) and Kuiper (1941) is still valid, even though we do not know for sure whether such a rotating-expanding stream is limited to a region only in and near the orbital plane or whether it encloses the system in all directions. The absorption velocities seem to differ somewhat from ion to ion, indicating stratification, as has been suggested by Hack *et al.* (1975), who have further found that the emission velocities are practically identical at phases 0.25 and 0.75. This latter finding is consistent with an expanding-rotating stream around the entire system, although other interpretations are also possible. What we find difficult is to attribute the source of P Cygni profile to the gaseous motion associated with the secondary component.

However, that does not mean that no emission comes from the gas in the outer fringe of the disk around the secondary component. Kříž (1974) has suggested that the double emission peak, characteristic of a gaseous ring (Struve 1931) of Hα, could arise from emitting atoms revolving around the secondary component. If so, they very likely form the outer edge of the rotating disk around the secondary. Kříž's suggestion seems to agree with the result that a broad Hα emission varies in radial velocity 180° out of phase with the primary. However, the latter result has not been confirmed by Flora and Hack (1975). This only shows that a definite disentanglement of emission from different sources in the system is not an easy task.

The β Lyrae system has also been found to be a variable radio source at centimeter wavelengths (Wade and Hjellming 1972; Hjellming, Wade, and Webster 1972). Jones and Woolf (1973) have attributed the radio source to plasma waves in the gaseous stream moving from one star to the other, but have not attempted to explain the variation in the radio flux. We believe that like the optical emission lines, radio noise might be generated in different regions in the system, as there is no lack of energy supply in and around the system for producing radio emission. However, a definite pinning down of the radio source perhaps requires more detailed observational data than are available now.

It is very likely that enveloping the entire β Lyrae system there exists a corona in the same sense as the solar corona surrounds the Sun. Such a corona will be another source of emission lines. The effective temperature of the Sun is 5800 K, but the coronal lines correspond to an ionization temperature of a million kelvins or so. The energy in the solar corona is supplied by hydrodynamic motion in the hydrogen convection zone underneath the atmosphere. Consequently it would be a great surprise to us if β Lyrae does not possess a corona in spite of the extensive and likely turbulent flows in the system that could be the source of heating mechanisms. A stellar corona, for example, has recently been suggested by Gerola *et al.* (1974) in β Gem, and coronal lines have actually been observed in AS295 (Herbig and Hoffleit 1975). Therefore we are inclined to consider some emission lines of highly ionized atoms (Hack *et al.* 1975) found in β Lyrae as coming from the lower part of its corona or the upper region of its chromosphere. Other emission lines of even higher degrees of ionization might be found in this system if the sensitivity of observation were improved.

The exact structure of the corona around β Lyrae, of course, may not be identical to the solar corona for two reasons. First, the sources of energy are different. While the convection zone under the solar atmosphere is relatively shallow (compared with the solar radius), the extent of hydrodynamic flow in β Lyrae is large compared with the stellar radius. Second, β Lyrae is a binary while the Sun is a single star. In what way these two kinds of differences affect the resulting structure of their respective coronae is an interesting question that has yet to be solved. Whether the expanding gaseous stream that is associated with the P Cygni profile forms a part of the stellar wind resulting from the corona expansion is not clear either.

VII. EVOLUTIONARY STATE OF THE SYSTEM

In Paper I we have assumed that originally the primary component was more massive than the secondary component. But because of evolution the primary has lost a great deal of its mass, some of which has been added to the secondary, making the latter now more massive than the primary. According to this view the secondary is at present close to the main sequence or at least not in any collapsed stage, because the evolutionary stage of the originally less massive secondary must be behind that of the originally more massive primary. There are a number of investigators who adhere to this view explicitly or implicitly (Stothers and Lucy 1972; Kříž 1974; Wilson 1974). The present investigation shows that indeed the effective temperature and the mass of the secondary component are internally consistent with this view. However, we must add that an internal consistency does not necessarily mean that it must be correct.

The other point of view is that the secondary component is in a collapsed state (Devinney 1971; Hack *et al.* 1975). This state can be reached when the secondary was originally more massive than the primary. So the former has already reached the collapsed state while the latter is still in the supergiant stage. Such a view is as plausible as the other one. However, there is the problem of the energy supply to the disk, if one takes this view. Hack *et al.* (1975) have mentioned X-rays produced by the infalling matter from the disk as the source of energy for the disk. However, quantitatively it has yet to be shown that the energy thus derived can explain the nature of the eclipse light curves from which the disk luminosity can be estimated as in Wilson's (1974) paper and in Paper A. In the present paper we have solved this energy problem according to our view to satisfaction.

In either case the scenario of evolution has been described only in generality. Specifically, what exact shape β Lyrae was in the past is not an easy question to answer, because it depends critically on the rate of mass loss, $dm/dt = f(t)$, where $m = m_1 + m_2$, as well as the rate of angular momentum loss, $d\Omega/dt = g(t)$, of the system in the course of evolution, in addition to the transfer of mass $dm_2/dt = h(t)$, from one star to the other. At present no reliable estimate for these three functions can be made from either observational or theoretical considerations. What makes the problem even more difficult is the fact that the values of these functions $f(t)$, $g(t)$, and $h(t)$ at a later time are themselves dependent on the values of these same functions at earlier times. Because of this and other factors the problem of finding the exact original configuration of the system, much like that of finding where water in Lake Michigan, say, comes from, is not unique. This is to be expected since the binary star is not a conservative system, and evolution, just like water flowing downhill into a lake, is an irreversible process. Perhaps this is a point that should be kept in mind by all those who have an interest in studying stellar evolution of close binaries.

The present investigation is supported by National Aeronautics and Space Administration.

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DEBORAH A. BROWN and SU-SHU HUANG: Dearborn Observatory, Northwestern University, Evanston, IL 60201