AN INTERPRETATION OF BETA LYRAE

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AN INTERPRETATION OF BETA LYRAE

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ABSTRACT

To explain the β Lyrae system's peculiar spectroscopic and photometric behavior, a model in which the primary component is assumed to be the less massive of the two components has been constructed. Consequently, a theory of emission lines that predicts a redshifted peak superimposed on a broad emission line has been proposed. The observed shift in the γ-velocity of the emission peaks is thereby understood. Finally, the evolution of the component stars leading to the present situation is discussed.

AUTHOR

I. A MODEL OF THE SYSTEM

In the present paper we shall present a model of the β Lyrae system in which the secondary is more massive than the primary component (Gaposchkin 1956; Huang 1962; Woolf 1962). We propose that the system is similar to the Algol-type binaries. The B8 primary, like the secondary in the Algol-type variables, has completely filled its equipotential lobe, while the more massive secondary, like the primary in the Algol-type variables, is comparatively smaller in size and is surrounded by a rotating disk. The rotating disk resembles the rotating rings suggested by Joy (1942, 1947) for the Algol-type stars but is dense and therefore opaque. This disk cuts off a considerable amount of the radiation received from the secondary at all phases and obscures a part of the primary component during principal eclipse. Figure 1 illustrates two views (front and edgewise) of the model proposed here. For reasons that will be apparent later, the inclination of the orbital plane, which is assumed to be identical with the plane of the rotating disk, is not exactly 90°. Thus, when seen from the earth, the surface of the disk is projected on the celestial sphere in a significant area.

As a result of this obscuring disk, which plays an important part in the phenomenon of this system's eclipse, the relative temperature determined by the depths of both primary and secondary eclipse is no longer meaningful. This can easily be understood when we realize that the opaque disk has its own temperature.

It naturally follows from the existence of the opaque disk that the sum of radii $R_1 + R_2$, as derived from the duration of eclipse, no longer represents the sum of radii of the primary and secondary components. Instead, it is the sum of the radii of the primary component and the obscuring disk. Accordingly, we should be able to observe, as we actually do, the B8 component during principal eclipse because the obscuring disk eclipses only the central zone of the stellar disk of the primary component. Thus the light-curve will behave, as regards its duration of eclipses, like a contact binary, while actually it is not. This removes the difficulty arising from the relative sizes of the two components.

Let us now examine the size of the secondary component. Assuming the mass ratio, we can derive the masses of both components from the mass function obtained observationally. If the secondary should be a main-sequence star, we could estimate its radius from the mass. Table 1 lists the values of the radius R_2, estimated in this way for different values of $\alpha = m_1/m_2$ and for two values of the orbital plane's inclination, i. In all cases R_2/a appears to be very near to 0.1.

The radius of the primary component, R_1/a may be derived from the size of the inner contact surface, as all observational results point to the fact that it fills one lobe of the surface (Kuiper 1941). It is also given in the table.

From the relative size of the primary and the secondary components obtained in this way, we must conclude that either (1) the secondary component is actually larger than that we have estimated or (2) the projected thickness of the opaque disk on the celestial sphere is quite large; otherwise we will not obtain a primary eclipse as deep as that observed. This conclusion may not be true if a is considerably smaller than those values listed in Table 1—a situation which we will not consider seriously at present. Then, according to the *first* alternative, the secondary component is not a main-sequence star. The *second* alternative suggests that the inclination, i, differs appreciably from 90°. Both alternatives may be true. We shall return to the nature of the secondary in the last section of this paper.

The projected area of the disk on the sky depends on the extent of the disk itself, as well as on the inclination of its plane. Although we cannot know at this stage the exact size of the disk, it is apparent that it must lie within that lobe of the inner contact surface that surrounds the secondary component. Therefore, the upper limit of the disk's radius,

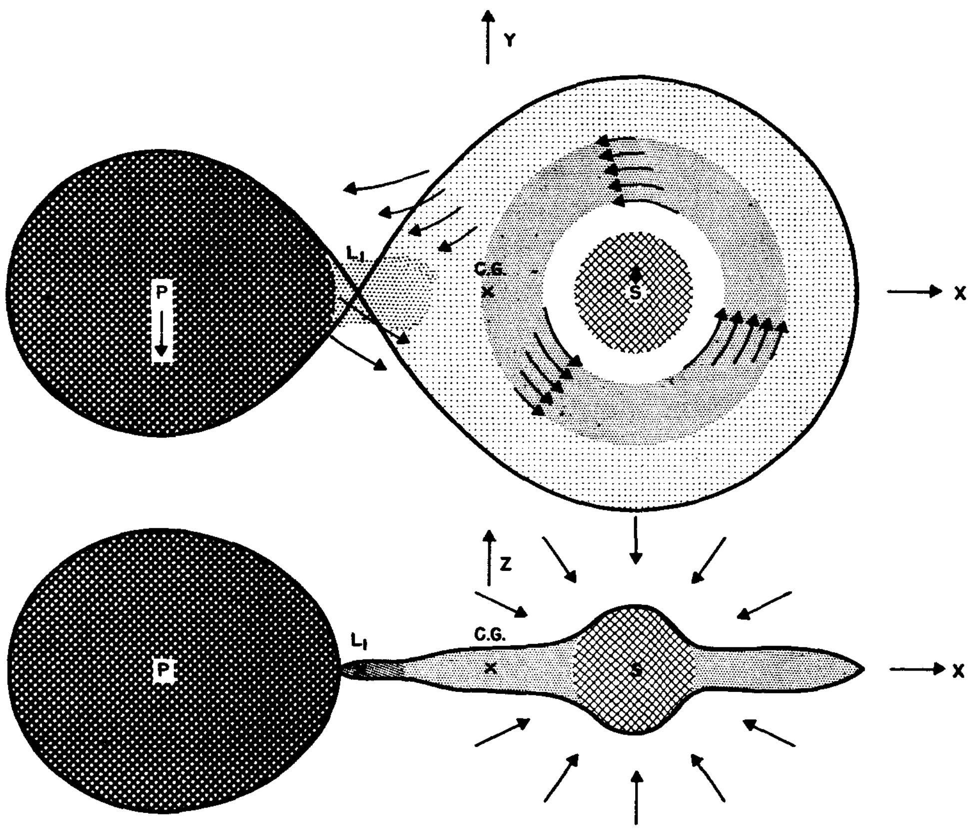

FIG. 1.—Two views of the proposed model of the β Lyrae system. The upper one is a view of the plane of the orbit (the XY-plane), where P and S denote, respectively, the primary and secondary component. The obscuring disk is rotating differentially around the secondary within one lobe of the inner contact surface whose intersection with the plane of orbit is represented by a figure-8 curve in the diagram. The lower one is a side view of the system. The emitting atoms fall into the secondary from all directions. If the inclination of the system is not exactly $\pi/2$, this spherically symmetric distribution of emitting atoms will produce an asymmetric profile of the emission lines, as observed, because of the presence of the obscuring disk.

denoted by R_2', may be obtained from the dimension of the inner contact surface and also is approximately given in Table 1.

Some interesting features of the light-curve obtained for β Lyrae may be understood quite naturally in terms of the present model.

First, the primary eclipse is asymmetric, with the decline steeper than the rise (Stebbins 1916). This is perhaps due to obscuration by those gases just streaming out from the primary component. They provide an opacity in addition to that produced in the gaseous disk. These gases will either join the disk or disperse away, depending on their angular momentum. Consequently, very little is left when we observe the system at phases before principal eclipse.

Second, the depth of principal eclipse varies between 0.8 and 1.1 mag. in blue light, according to Guthnick (1945–1946). This variation was not noticed in recent observations by Wood and Walker (1960); since their observations covered only two consecutive principal eclipses, they suggested that the variation in the depth of principal eclipse noticed by Guthnick might occur over a period of years instead of weeks. If so, the cause of the variation must be stable over a short time, say a few cycles, but unstable over a long period, say a few years or so. It follows from this reasoning that the cause cannot be a star, which should not change in a few years; neither should it be randomly flowing gases, which should change from cycle to cycle. A rotating disk consisting of gases can perhaps fulfil the stringent conditions of semistability deduced from observations. Its intrinsic thickness or its extent may vary over a period of a few years, causing a change in the depth of eclipse.

TABLE 1

POSSIBLE DIMENSIONS OF THE SYSTEM

α	R_1/a	R_2'/a*	$V_r \sin i$† (km/sec)	$i=90°$			$i=75°$		
				m_2 In $m_\odot$	a In 10^{12} cm	R_2/a‡	m_2 In $m_\odot$	a In 10^{12} cm	R_2/a‡
0.20	0.24	0.49	53	12.2	3.95	0.096	13.6	4.09	0.101
.24	.25	.48	57	13.1	4.08	.098	14.5	4.22	.102
.28	.26	.47	62	13.9	4.21	.099	15.4	4.36	.103
.32	.27	.46	67	14.8	4.34	.100	16.4	4.49	.104
.36	.28	.45	71	15.7	4.47	.102	17.4	4.63	.106
.40	.29	.44	75	16.7	4.61	.103	18.5	4.77	.107
.44	.30	.43	79	17.6	4.74	.104	19.6	4.91	.108
0.48	0.30	0.42	83	18.6	4.87	0.105	20.7	5.04	0.109

* The listed values in this column give the upper limit of the lateral extent of the opaque disk.

† The listed values in this column denote the projected rotational velocity of the primary component if rotation is synchronized to orbital motion.

‡ The listed values in this column represent the ratio of the radius of the secondary to the separation under the condition that the secondary be a main-sequence star.

While the basic structure of the rotating disk does not change from cycle to cycle, it is reasonable to expect that there are minor fluctuations, in the density as well as in the extent, along the edge of the disk. Such fluctuations may be the cause of minor irregularities in the light-curve observed from cycle to cycle.

To test the hypothesis of the disk, we may suggest observations of the light-curve in the infrared region, where radiation emitted by the disk itself may reveal its existence.

Assuming the secondary component to be more massive, can we understand the system *without* introducing the obscuring disk? An extended scattering atmosphere that fills up the lobe of the inner contact surface around the secondary may explain the fact that the light from the primary can be seen during principal eclipse, even though the secondary is larger than the primary. But it is difficult to see how an extended scattering atmosphere can be supported by a star whose light we do not even observe. Also, there is no spectroscopic evidence of the presence of a scattering atmosphere.

II. INTERPRETATION OF SPECTROSCOPIC RESULTS

Spectroscopically, Struve's (1941) interpretation can easily be incorporated into our disk model. The violet-shifted lines seen immediately after the conjunction during principal eclipse show the ejection of mass from the primary. We are able to see these lines, in spite of the presence of the disk, because the inclination of the orbital plane differs from 90°. However, the redshifted satellite lines seen immediately before the conjunction cannot be said to be coming from the secondary, which, according to our model, does not fully fill the equipotential surface. We suggest that this system of spectral lines is connected with the rotating disk around the secondary. What we observe may be either the rotating stream that is spilled over the main disk or a stream that is diverging from the disk to return to the primary.

It is interesting to note here that, within the range of mass ratios assumed in Table 1, the spectroscopic data lead to rotational velocities for the disk of the order of 200–400 km/sec at points near the inner contact surface. These values are comparable with the radial velocities of the two systems of satellite lines during principal eclipse, as the violet-shifted lines indicate radial velocities of 80–360 km/sec and the redshifted lines 120–200 km/sec (Struve 1957). We can easily understand why the redshifted lines should cover a smaller range of velocities than the violet-shifted lines. While the ejection of gases naturally spreads a wide range of velocities, the gaseous particles will somewhat equalize their velocities through collisions when they move around the secondary. Furthermore, according to the present model, the stream corresponding to the redshifted lines must be weaker than the primary stream just ejected from the primary, since some of the primary stream may coalesce with the disk or be dissipated in other ways in the course of a revolution around the secondary. This prediction also agrees with observations (Struve 1941).

As regards the B5 spectrum observed in this system, the introduction of the rotating disk around the secondary introduces no complication into Struve's (1941, 1950, 1957, 1948) interpretation of a shell around the entire system.

Because of the closeness of the two components, we would expect axial rotation and orbital revolution to be synchronized. But, if we should follow the conventional model of a more massive primary, we would immediately see that synchronization could not be the case (Struve 1957), as the observed rotational velocity of the primary component is only about 45 km/sec (Mitchell 1954; Struve 1958), while, according to a previously accepted value of $m_1/m_2 = 1.5$, the synchronized rotational velocity should be of the order of 180 km/sec.

In order to explain this contradiction, Kopal (1959) suggested that synchronization had been disrupted by the star's rapid rate of evolutionary expansion. According to Kopal, axial rotation and orbital revolution are indeed synchronized before the primary departs from the main sequence. As the star expands, however, rotation slows down as a result of conservation of angular momentum.

Since the adjustment time of a stellar envelope to an external field is shorter than the orbital period, tidal bulges will move in such a way that they are always pointing to the companion star. Such a tide will perhaps induce a rotation of the surface layer not greatly different from that to be expected from the state of synchronization in a relatively short time. Therefore, it is hard to reconcile the observed rotational velocity of only 45 km/sec to the synchronized velocity of 180 km/sec, even with the assumption of evolutionary expansion. Only a reversal of the relative masses of the two components can reduce this serious discrepancy to a reasonable situation, as can be seen from Table 1, where the projected rotational velocity of the primary, $V_r \sin i$, under the condition of synchronization is given as a function of α.

From the luminosity of the star we have concluded that α perhaps lies between 0.26 and 0.44 (Huang 1962). Now, if we accept 45 km/sec as the observed rotational velocity, we find from Table 1 that the deviation from synchronization is within reasonable limits and may be due to several factors. The mass ratio may be even slightly less than the suggested limit of 0.26; the observed rotational velocity may be underestimated, or, in view of rapid evolution, a slight deviation from synchronization may be intrinsic.

III. A THEORY OF EMISSION LINES

The density of material, although high in the equatorial plane, must decrease rapidly on both sides of the disk as we move away from the plane. Thus gas away from the plane is rare but extends a large volume. Seen from the earth, it is projected either on the opaque disk, which must be at a temperature much lower than that of the B8 component, or on the dark sky. Hence we propose that the emission lines are produced mainly by the material in this volume. Those particles that stray from the main disk most likely have small components of angular momentum in the plane of the disk; as a result, they will eventually fall into the secondary component. When the atoms depart from the disk, they have low excitations corresponding to the temperature of the disk. Once high above the main disk, they are exposed to, and consequently excited by, the radiation coming not only from the primary but also from the secondary. Thus these excited atoms will eventually emit radiation that we see as emission lines. Since atoms are excited at places high *above* the disk, emission takes place dominantly when the atoms are falling down toward the secondary star.

To derive the profile of the emission lines, let us first consider an ideal case, in which the emitting atoms have a spherical symmetry with respect to the secondary star and fall to the star with a constant speed V. We choose the center of the secondary component as the pole of a spherical co-ordinate system with the polar axis in the direction of the line of sight, and we assume that the natural width of the emission line is infinitesimally narrow, so that the broadening of the line is solely due to the Doppler effect. As the radial velocity of an emitting atom at any point (r, θ, φ) is $v = V \cos \theta$, which is independent of φ, it follows that the intensity of emission line between v and $v + dv$ should be given by

$$I(v; V)dv = A dv \int d\varphi \, , \tag{1}$$

where A is a normalizing factor and the wavelengths are expressed in terms of velocity.

Since the inclination of the orbital plane, and consequently of the opquae disk, has been assumed to be different from 90°, we observe only one half of the emitting atoms, the other half being obscured by the opaque disk. Of course, if the radius of the opaque disk is not much larger than the radius of the sphere in which the emitting atoms are confined, we can still see part of the other half. However, in a binary system like β Lyrae, where the primary component is continuously and energetically ejecting mass, the equatorial plane must be populated with absorbing material even outside the opaque disk. Perhaps the equatorial plane outside the opaque disk is transparent to continuous radiation, but the opacity at wavelengths inside spectral lines is most likely appreciable. Therefore, it is reasonable to assume that only the emitting atoms located on this side of the obscuring disk impress their mark on the photographic plates. Thus the limits in the integral in equation (1) can be found easily in terms of θ or v. A simple geometrical consideration shows that for $0 < \theta < \theta_1$, where $\theta_1 = \pi/2 - i$, the integral extends from $\varphi = 0$ to $\varphi = 2\pi$. As θ becomes greater and greater, the range of the integral diminishes continuously and finally vanishes at $\theta = \pi/2 + i$. In this way we derive the broadening function as follows:

$$I(v;\,V)\,dv=\frac{dv}{V}\qquad (V\cos\theta_1\le v\le V)\,, \tag{2}$$

$$I(v;\,V)\,dv=\frac{dv}{\pi V}\left\{\pi-\cos^{-1}\left[\frac{v\tan\theta_1}{(V^2-v^2)^{1/2}}\right]\right\}\qquad (0\le v\le V\cos\theta_1)\,, \tag{3}$$

$$I(v;\,V)\,dv=\frac{dv}{\pi V}\cos^{-1}\left[\frac{-v\tan\theta_1}{(V^2-v^2)^{1/2}}\right]\qquad (-V\cos\theta_1\le v\le 0)\,. \tag{4}$$

Figure 2, *A*, illustrates the profile of this broadening function for $V = 1$ and $\cos\theta_1 = 0.98$, which corresponds to an inclination of about 78°5.

The broadening function just derived shows the basic feature of the emission lines observed in β Lyrae, namely, a positively shifted emission peak superimposed on the broad background emission (Sahade *et al.* 1959).

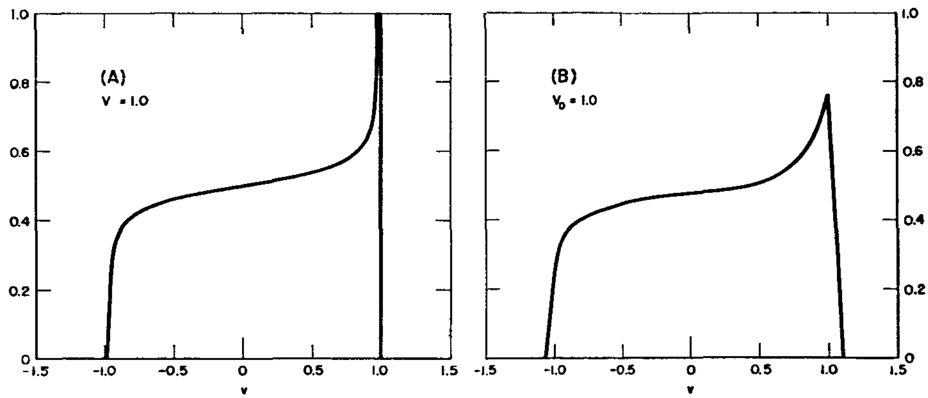

FIG. 2.—Profiles of emission lines according to the proposed model. The emitting atoms have (*A*) a uniform speed of $V = 1$ toward the secondary and (*B*) speeds of falling toward the secondary distributed according to eq. (5) with $V_0 = 1$ and $n = 1.1$.

The previous calculation represents only an oversimplified model for the formation of emission lines. In reality, the emitting atoms do not fall into the secondary component with the same speed. The line profile given by equations (2)–(4) should be further broadened by the non-uniformity of falling speeds of emitting atoms.

Since the time for a particle of speed V to travel a distance ds is ds/v, the distribution function of V should be $1/V$. If the cutoff speeds at both ends are V_0 and nV_0, respectively, where n denotes a numerical factor greater than 1, the normalized distribution function of V will be

$$f(V)\,dV=\frac{1}{\ln n}\,\frac{dV}{V}\,, \tag{5}$$

and the profile of emission will now be given by

$$I(v)dv = dv\int I(v,\,V)f(V)dV\,. \tag{6}$$

Evaluating the integral in equation (6) after equations (2)–(4) have been substituted, we obtain the final profile, which can be represented in six intervals of v by six different expressions.

We have computed the profile with $V_0 = 1$, $n = 1.1$, and $\cos\theta_1 = 0.98$ according to the six expressions and have presented the result in Figure 2, *B*. The profile shows a broad feature and a peak shifted toward the long wavelength, as observed (Houziaux 1958). However, the computed peak is not so high as the observed one. Since it would be unreasonable to assume that $n < 1.1$ and since the predicted profile will have an even lower peak if $n > 1.1$, we have to admit that the simple model of a spherically symmetric distribution of emitting atoms cannot quantitatively explain the observed emission peak, although it is adequate to account for the broad emission feature that moves with the secondary component.

To understand the emission peak, we should remember that the infalling emitting atoms must be more densely distributed near the plane of the disk. It can be seen easily that this asymmetry in distribution of emitting atoms tends to increase the intensity of the emission peak.

According to our model, the shift of the emission peak is always toward the long-wavelength side and depends on the velocity of infalling atoms. Since the shift persists in all phases, it reflects in the shift of γ velocity, as observed. The exact value of the radial velocity corresponding to the emission peak, however, depends on several factors: (1) the motion of the secondary component, (2) the velocity distribution of the falling atoms, and (3) the deviation from spherical symmetry. Consequently, its velocity variation may not be a good measure of the orbital motion of the secondary component. The radial velocity estimated from the center of the broad emission feature is not affected as sensitively by the second factor, as can be seen from Figure 2, *B;* but it is difficult to measure its position in practice because of the absorption line or lines that cut into it.

That the emission lines move in phase with the secondary component suggests that the secondary component is much smaller than its corresponding lobe of the inner contact surface. Otherwise, there will be no space in which to put the emitting material. A natural deduction from this suggestion is that the secondary is smaller but more massive than the primary.

IV. EVOLUTIONARY SIGNIFICANCE

Why should the primary component, which is less massive and therefore evolves more slowly, have reached the giant stage, while the more massive secondary component is underluminous? Sahade (1958; also see Struve 1958) suggested that, as a result of more rapid evolution, the more massive secondary component had already passed the giant stage and had now assumed a position on the H-R diagram below the main sequence. In addition to Sahade's interpretation, we venture to propose here two more possibilities for the sake of further investigation.

1. The angular momentum of the pre-stellar material that finally condensed to become the secondary component may be extremely large and therefore retard the process of its contraction, as a star had to dissipate the angular momentum first before successful contraction. Consequently, the secondary component has, to begin with, a long lag in evolution. The rotating disk we have proposed, in order to explain various observational results, may represent the remnant of the prestellar gases of high angular momenta.

2. Originally the mass of the primary is larger than the secondary. When the primary has reached the giant or supergiant stage (e.g., Schwarzschild 1958) and starts to eject mass through the inner contact surface, the secondary is still on the main sequence because of its relatively slow rate of evolution. The ejected mass of the primary falls into the secondary, as would be expected. Since the primary is more massive to begin with, a mass transfer in this way renders the separation between the two components smaller and smaller (Huang 1963)—a process which, when combined with the effect of change in mass ratio of the two components, makes that lobe of the inner contact surface around the primary shrink fast and therefore further enhances the ejection of mass from the primary. For this reason, the time scale of a close binary in this mode of mass exchange is necessarily short; this explains why β Lyrae is an unusual object in the Galaxy.

The shortening of the separation will stop only when the masses of two components become equal. After this point, a further transfer of mass from the primary to the secondary will reverse the trend and widen the separation. This is the present situation of β Lyrae. Perhaps the absolute dimension of the lobe of inner contact surface around the primary does not change greatly at this stage, as the effect of increase in separation is compensated for by that of the change in mass ratio. Therefore, according to our interpretation, the phase of drastic exchange of mass between the two components is now over. Soon (astronomically) there will be no transfer of mass and consequently no increase in period or widening of separation. Actually, this tendency is already shown incipiently in the equation of observed times of light-minima (e.g., Sahade *et al.* 1959), from which we can see that, while the third term definitely indicates the increase in period with time, the rate of increase is slowing down because of the negative sign in the fourth term.

This kind of mechanism of mass exchange between the two components of a close binary was first suggested by Crawford (1955) and by Kopal (1955) for explaining the characteristic properties of the Algol-type binaries, although Kopal (1959) has since reversed his stand. For whatever merit the mechanism has for explaining the Algol-type binaries, we consider that this mechanism is what is happening to β Lyrae right now.

Because of the mass accretion, the secondary is perhaps in a stage of gravitational contraction the of accreted mass and therefore is underluminous with respect to its present mass. This explains, in addition to the obscuring disk, why we do not observe light from the secondary even during principal eclipse. However, when its thermal state is adjusted to a level corresponding to its new mass, it will become a main-sequence star. Eventually it will evolve to the giant stage and perhaps eject mass. A transfer of mass from the secondary back to the primary will start a new cycle of change in the period, as well as in the separation, in the manner we have described.

Long before that, the secondary component would be more luminous, and the names of primary and secondary components would have to be interchanged in the astronomically not distant future. Therefore, in β Lyrae we obtain a situation in which the brighter component always fills the equipotential lobe and ejects mass toward the fainter component.

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