OAO-2 OBSERVATIONS OF BETA LYRAE AND A PROVISIONAL INTERPRETATION

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ABSTRACT

Six-color ultraviolet photoelectric observations of Beta Lyrae obtained with OAO-2 are presented. These observations, made at 1380, 1500, 1920, 2460, 2980 and 3330 Å, represent the first truly continual coverage of the light changes of Beta Lyrae during one orbital revolution and were obtained in November 1970. The photometric data are supplemented by spectral scans in the wavelength intervals 3800-1800 Å and 2000-1050 Å; the latter interval was scanned at 10 Å resolution once during every OAO-2 orbit, i.e., about 100 minutes. Anomalous features, such as asymmetries and short and long term variations, are present in the light curves. A tentative discussion of solutions of the light curves is given. The problems of combining the photometric and spectroscopic information to arrive at a model of the system are also discussed.

I. INTRODUCTION

This paper reports on ultraviolet photoelectric observations of Beta Lyrae obtained with OAO-2. This eclipsing binary system has been studied extensively both observationally and theoretically during much of this century. The properties of the system have been reviewed by Struve (1958) and Huang (1963) among others. Because of the wide spread interest in this binary system, and also in view of the desirability of concerted continual effort to observe the entire orbital period of the system, an internationally coordinated campaign to observe Beta Lyrae was conducted in 1958-59 and again this year.

II. OBSERVATIONS

The six-color ultraviolet light curves to be discussed in this paper represent the first continual coverage of a single cycle of Beta Lyrae and were obtained in November 1970. During this period, 10 Å resolution spectral scans from 1800-1100 Å were made once during each OAO-2 orbit; the period of revolution of OAO-2 is about 100 minutes, with simultaneous filter photometry measurements at each step of the scan. On alternate orbits the filters used were 2980 Å, 2460 Å, 1500 Å and 3300 Å, 1920 Å, 1380 Å. The filters have a typical half width of 200 Å. One observing sequence consists of about eighty 8-second filter exposures plus a spectrometer scan. Only about 10% of the available observations were utilized in this discussion. In addition, the spectral energy distribution of the system was observed at various phase angles in the wavelength interval 3800-1800 Å with a resolution of about 20 Å; and from 2000-1100 Å at a resolution of about 10 Å.

The light curves shown in Figure 1 were drawn through the observed points, and the flux has been arbitrarily chosen to be unity at maxima. The estimated error of observation was typically less than 0.01 magnitude.

The coverage of the light curves begins at about phase angle -90° and continues for a little more than one orbital period. A number of interesting anomalies are present. Short term variations with a time scale on the order of 5-20 hours and amplitudes of $0^m.01$ to $0^m.05$ occur in all wavelengths. Several of these, particularly the features at phases of about 5°, 220° and 300° occur in several, if not all, of the wavelengths. The maxima also show prominent short term variations. A long term, i.e., on the order of an orbital period or so, variation is prominent at 1380 Å and 1500 Å. The light level decreased by nearly 20% at 1380 Å in about 13 days and decreased by about 9% at 1500 Å between phases 90° and 270°. The 3330 Å light curve shows an increase in brightness of about 5% between phases -90° and 90°. The light curve at 1920 Å has eclipses which are much shallower than those in the other wavelengths. The eclipses are asymmetric in all wavelengths as are the

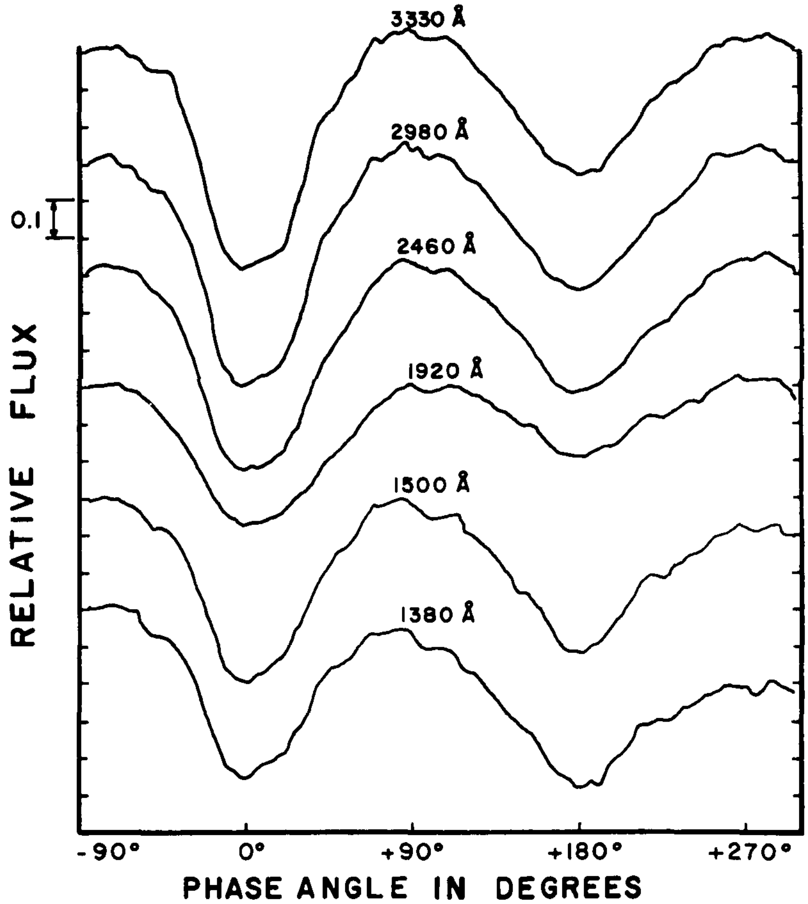

Figure 1.

maxima. Another anomaly is the fact that the depth of the secondary eclipse becomes deeper at 2460 Å, 1500 Å and 1380 Å than it is at 3330 Å, 2980 Å and 1920 Å. It should be emphasized that there is excellent reason to believe that the performance of the OAO-2 provides a high degree of confidence in the reality of the observed anomalies.

III. ANALYSIS AND INTERPRETATION

a) Light elements

An attempt was made to determine the epoch of the mid-primary eclipse from the OAO-2 observations, but difficulty was encountered due to the asymmetry of shape of the eclipse, and the fact that additional observations made with OAO-2 over a two year period are too scattered in time to aid in determining the time of minimum. Consequently, for this preliminary analysis, previously published light elements by Wood and Forbes (1963), which appeared to give a reasonable time of minimum light, were used. The phase zero computed from the above elements is JD2440892.66132 and $P = 12^d.932724$. In order to determine whether or not this time of minimum might be in error, the minimum was arbitrarily shifted by ±3° and ±6°. This generally increased the asymmetry of the primary eclipse and did not improve the situation. The coordinated international campaign on Beta Lyr being conducted this year under coordination by Dr. Batten at the Dominion Astrophysical Observatory is expected to produce an improved ephemeris for this system.

b) Rectification

Rectification was carried out following the technique developed by Merrill (1970). The coefficients are listed in Table 1. The coefficients were determined through 4θ. Sine terms were not negligible. The rectification yielded maximum light which was reasonably constant. However, the eclipses still showed pronounced asymmetries both for the primary and secondary minima. For comparison, ground-based observations in visual light by Wood and Walker (1960) were incorporated into this work. The rectified visual observations also exhibited asymmetries in the eclipses.

c) Discussion

The form of the light curves suggested that the egress of the primary eclipse was anomalous. It was felt, therefore, that taking an average of both branches was unadvisable. Solutions were made separately for the ingress and the egress. Solutions were indeterminate for the 1380 Å, 1500 Å and 1920 Å light curves: this point will be amplified later on. No satisfactory solutions were found for the egress at any wavelength. The resulting solution from the ingress is presented in Table 2. The fit of the solution with the rectified light curve is reasonable. However, the light curve solution is difficult to reconcile with the spectroscopic observations. The spectroscopic observations show only one component of the binary, which we shall herein call the primary component, although variable emission features have been associated with the secondary component by some investigators. The difficulty is that according to the solution, the secondary component contributes some 60-70% to the total light of the system. Normally, a secondary component that contributes this much light to the system should be easily detected on a spectrogram. The spectroscopic observations show that the primary

Table 1. Fourier Coefficients for Rectification

	1380 Å	1500 Å	1920 Å	2460 Å	2980 Å	3330 Å	5500 Å
A_0	+0.8560	+0.8730	+0.8810	+0.8330	+0.8440	+0.8340	+0.8650
A_1	+0.0061	-0.0092	-0.0596	-0.0304	-0.0242	-0.0180	-0.0311
A_2	-0.1480	-0.1090	-0.1185	-0.1650	-0.1700	-0.1620	-0.1370
A_3	-0.0265	-0.0191	-0.0122	-0.0144	-0.0136	-0.0095	+0.0015
A_4	-0.0160	+0.0070	-0.0015	-0.0010	-0.0000	-0.0200	-0.0030
B_1	-0.0139	-0.0130	-0.0231	-0.0164	-0.0007	-0.0012	-0.0036
B_2	-0.0220	-0.0300	-0.0375	-0.0476	-0.0349	-0.0340	-0.0155
B_3	-0.0079	-0.0069	-0.0181	-0.0138	-0.0066	-0.0011	-0.0022
B_4	+0.0011	-0.0081	-0.0018	-0.0064	-0.0056	-0.0051	+0.0001
C_0	+0.0334	+0.0334	+0.0334	+0.0334	+0.0334	+0.0334	+0.0334
C_1	-0.0061	+0.0092	+0.0596	+0.0304	+0.0242	+0.0180	+0.0311
C_2	+0.0111	+0.0111	+0.0111	+0.0111	+0.0111	+0.0111	+0.0111

Table 2. Orbital Solutions

(Solution for the Ingress: Primary Eclipse is an Occultation)

Geometric Quantities	Photometric Quantities		
		$\alpha_o^{oc}=1.00$	$\alpha_o^{tr}=1.07$
$k = 0.4$		$1 - l_o^{oc}$	$1 - l_o^{tr}$
$r_g = 0.475$	5500 Å	0.300	0.136
$r_s = 0.190$	3330 Å	0.390	0.105
$i = 76\overset{\circ}{.}82$	2980 Å	0.356	0.105
$\theta_e = 40°$	2460 Å	0.318	0.155
$p_o = -1.30$	1920 Å	0.095	0.040
	1500 Å	0.298	0.269(?)
	1380 Å	0.162(?)	0.250(?)

component is the one behind its companion at the time of the primary eclipse. Also, spectroscopic observations give a mass function (Struve, 1958) of about 8.5 solar masses. Table 3 shows the masses of the components for different mass ratios assuming that the light curve solution gave the correct orbital inclination. As seen in the table, unless both components are more massive than about $40M_\odot$, the secondary component, which is spectroscopically undetected, is the more massive of

Table 3. Mass Ratio and Individual Masses

M_1/M_2	M_1 ($\odot$)	M_2 ($\odot$)
0.10	1.1	11.1
0.20	2.6	13.2
0.30	4.7	15.5
0.40	7.2	18.0
0.50	10.4	20.7
0.70	18.6	26.6
1.00	36.8	36.8

the two. OAO-2 observations of the spectral energy distribution of Beta Lyrae show an energy distribution similar to that of Eta UMa, which is a B3 V star (Houck, 1971).

If this ultraviolet spectral energy distribution represents basically the temperature of the primary component, and not hot circum-binary gas, this star should ordinarily have a mass of about $8M_\odot$ or greater. However, in a rapid mass exchange phase (Kippenhahn, 1969; Refsdal and Weigert, 1969; Harmanec, 1970a,b) the evolved star that is losing mass becomes very overluminous for its mass. The absolute visual magnitude for such a star could be as high as -4 to -6, although its mass may have become as small as one to two solar masses or less.

If we accept the light curve solution, the mass function may be written as:

$$\frac{M_2^{\ 3}}{(M_1 + M_2)^2} = 9.2M_\odot$$

If we impose a restricting condition that neither of the components shall exceed its own critical Roche limiting surface, this places an upper limit on the mass ratio. This upper limit is about 0.4 according to the table of dimensions of Roche limiting lobes prepared by Plavec and Kratochvil (1964). Assuming that the relative radius of the larger star, i.e., the more massive secondary, is about 0.5, the Roche lobe will be unable to contain this star if the mass ratio is greater than 0.4. If we impose the condition that the less massive primary component fills its Roche limiting surface, the mass ratio must be about 0.1. With a mass ratio of 0.1, the mass of the primary star is about $1.1M_\odot$ and the mass of the secondary is about $11.1M_\odot$. Absolute dimensions have been computed for this model and are listed in Table 4.

This interpretation means that the primary component is a star near the end of the phase of fast mass exchange and may well be in a very luminous pre-white dwarf stage. In the mass exchange phase, the less luminous of the two becomes more massive. If we accept this model, the secondary component will have to be a very unusual star that is large enough to occult the primary component, contributing a substantial amount of light to the total light of the system, yet producing no detectible spectral features except possibly some unusual emission lines. (This difficulty may be partially overcome by stipulating that the total light of the system consists of three contributing sources, i.e. the primary component, the secondary component, and the light from the emitting [and reflecting] hot gas cloud that surrounds the system as a whole. If we assume the preceding, then we will have to abandon the solutions from the light curves since the unknown extent of the contribution from circum-binary gas cloud makes

Table 4. Absolute Dimensions of Beta Lyrae

M_1/M_2	a (10^6km)	R_p (10^6km)	R_S (10^6km)
0.10	37.17	17.66	7.06
0.20	40.55	19.26	7.70
0.30	43.93	20.87	8.35
0.40	47.31	22.47	8.99
0.50	50.69	24.07	9.63
0.70	57.44	27.28	10.91
1.00	67.58	32.10	12.84

the solution indeterminate.) It is at this point appropriate to comment that no calculation has been carried out to estimate the dimensions and temperature for the star gaining the mass during the mass exchange. Consequently, we do not know if the secondary spectrum should be visible. Hall (1971) has suggested that the secondary component is disk-shaped and has not yet reached a post mass-exchange equilibrium state. Such a secondary component, if it has a low surface temperature, could account for the observations, but no quantitative work has been done and the details are yet to be worked out.

Huang (1963) has suggested that the secondary component is imbedded in a disk of gas which is opaque and thus explains the invisibility of the secondary component. However, the formation and maintenance of such a disk, particularly at a temperature low enough so that it does not produce spectral features which are not observed, seems as difficult to explain as the problem of the secondary component itself.

One might assume the presence of a collapsing neutron star inside a relatively low temperature gaseous shell which may be either spherical or disk-like. This model has the advantage of being able to contain a massive secondary component without heating the surrounding mass. Also, since the collapsing neutron star does not require large dimensions, the gaseous shell may assume a smaller diameter which reduces the heating problem due to the primary component. However, here too, the initial acquisition of the gaseous shell must be explained.

Perhaps, in this case, a hot gas flowing in from the primary component has had the time to cool off. The principal problem in this model is avoiding the disruption of the binary in a supernova explosion, which is, according to the currently accepted theories of stellar evolution, required for formation of a collapsing neutron star. Exact physical conditions of a supernova explosion are not well understood: however, work by McCluskey and Kondo (1971) shows that if only a small fraction (several percent) of the mass is lost from the exploding star, the system may remain bound. The orbit, if originally circular, would acquire a small eccentricity (a few hundredths). A similar model was recently suggested for ε Aurigae by Cameron (1971).

An attempt to find a solution was made assuming that the primary eclipse is a transit. However, no satisfactory solution was found to fit the rectified light curves.

The change in light levels for the maxima at 1380 Å and, to a lesser extent, at 1500 Å may be attributable to a contribution of light from the emitting gas cloud which is variable. The shallowness of the eclipses at 1920 Å may be explained in terms of the influence of the strong emission feature adjacent to it, if we assume that the emission originates primarily from the circum-binary hot gas cloud. The asymmetry of the eclipse might also be accounted for by assuming the existence of an additional hot gas cloud at or near the Lagrangian triangular point preceding the primary component in the sense of its orbital revolution. Such an effect will raise the level for the egress in the primary eclipse and the ingress in the secondary eclipse, which is what the light curves appear to show. This interpretation may be partially justified on the ground that it is the ingress in the primary eclipse that renders a shape relation more amenable to solution. The apparent increase in the relative depths of the secondary eclipse as compared with the depth of the primary eclipse, at 1380 Å and 1500 Å, must also be explained. Here one might assume that the side of the secondary (or the circum-secondary gas cloud) that faces the primary component is heated by the latter in such a way that the effect is more pronounced in the shorter wavelengths. Or, one might assume an anomalous reflection effect which is more enhanced at shorter wavelengths. However, we do not know of a specific physical process that will produce such an effect.

Our interpretation admittedly is, to an uncomfortable extent, qualitative. Photoelectric and spectroscopic observations are hard to reconcile with each other. Perhaps, when techniques are developed to investigate, more quantitatively, the qualitative models, the choice of the model may be narrowed down. Also, infrared observations might provide data that will enable us to discriminate among various models.

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