1976ApJ...206..777H

THE ASTROPHYSICAL JOURNAL, **206**:777–784, 1976 June 15
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THE ULTRAVIOLET SPECTRUM OF BETA LYRAE. II.

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Received 1975 September 15

ABSTRACT

The far-ultraviolet spectrum of the eclipsing binary system β Lyrae was observed in 1974 with the *Copernicus* Princeton University spectrometers. The observations were primarily made with the U1 spectrometer (slit width 0.05 Å) and the U2 spectrometer (slit width 0.2 Å) at phases 0.0, 0.2, 0.3, 0.5, and 0.8. The results are compared with the U2 spectrometer observations obtained in 1973 at phases 0.0, 0.25, 0.5, and 0.75. The U1 spectrometer results show, among other interesting spectral features, that there is no He II emission contribution to the N II lines at 1085 Å and that there exist variable shortward emission components in the P Cygni type profiles of C III (1175 Å) and N V (1238, 1242 Å). The U2 observations generally confirm and reinforce the 1973 results; the relatively minor variations are attributable to dynamical effects of the mass flow occurring in this system. The far-ultraviolet spectrum of β Lyrae is completely dominated by low-excitation level emission lines of multi-ionized atoms. The binary is surrounded by a high-temperature plasma giving rise to the emission lines which are believed to be collisionally excited. The mass exchange in this system is nonconservative.

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

I. INTRODUCTION

In a recent paper (Hack *et al.* 1975, referred to hereinafter as Paper I) observations of the ultraviolet spectrum of β Lyrae obtained with the Princeton University spectrometer aboard the OAO-3 (*Copernicus*) satellite (Rogerson, Spitzer, *et al.* 1973) during 1973 August and September were discussed. These observations were made at the phases of the two minima and the two quadratures, and only small variations in line intensity and radial velocity were found (see also Hack *et al.* 1974).

In order to obtain additional information concerning possible variations in radial velocity and intensity with one cycle (the orbital period is $12^{\mathrm{d}}908$) and from cycle to cycle, additional observations were made in 1974 September and October (Table 1) at phases 0.0, 0.2, 0.3, 0.5, and 0.8 with both the medium-resolution (resolving power 0.2 Å) and high-resolution (resolving power 0.05 Å) modes. The medium-resolution (U2) observations cover the spectral range $\lambda\lambda$980–1280 and have been corrected for stray and diffuse light and particle background counts with a program prepared by D. York. The reader is referred to Paper I for a complete identification list of lines in the ultraviolet spectrum of β Lyrae and for a discussion of this spectrum. The high-resolution (U1) observations were obtained in order to look for a He II contribution to the N II lines at 1085 Å and to get high-resolution profiles of several prominent lines. The U1 scans cover the spectral regions $\lambda\lambda$1070.8–1074.8 (S IV), $\lambda\lambda$1083.0–1087.7 (N II), $\lambda\lambda$1172.8–1178.5 (C III), and $\lambda\lambda$1235.0–1245 (N V).

The new observations, with a few interesting changes discussed below, confirm the previous ones, i.e., the spectral range $\lambda\lambda$1000–1300 is dominated by emission lines which show very little variation in intensity and radial velocity with phase, indicating that they are mainly formed in an extended envelope surrounding the whole system. Minor changes in the intensities with phase seem to indicate that a subconcentration of this gas may exist around the secondary component which itself is spectroscopically undetected. The P Cygni absorptions indicate expansional velocities ranging from -120 to -170 km s^{-1}. No stellar lines at all are seen in the far-ultraviolet spectrum. This fact is not surprising, since numerous strong resonance and low-excitation lines of multi-ionized elements, typically formed in a circumstellar envelope of this type, lie in this region of the spectrum and mask the corresponding stellar lines, as happens in the visual spectrum for the metastable lines of He I. In addition,

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TABLE 1

OBSERVATIONS

Date (1974)	Phase
September 18..........	0.5
September 22..........	0.8
October 9.............	0.0
October 11............	0.2
October 12............	0.3

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TABLE 2

β LYRAE RADIAL VELOCITIES FROM U1 AND U2 REGION LINES (km s^{-1})

Ion	No. of Lines	Phase 0.0	0.2	0.3	0.5	0.8	Mean
C II emission	1	+215	+215	+215	+230	+230	+221
C III emission	1	+245	+258	+258	+302	+268	+266
C III absorption	1	−278	−210	−150	(−270)	−230	−224
N II emission	2	+76	+74	+77	+103	+99	+86
N II absorption	3	−160	−160	−152	−154	−154	−156
N V red emission	2	+94	+82	+85	+138	+123	+104
N V violet emission	1	−374	−332	−325	−289	−412	−346
N V central absorption	2	−151	−144	−145	−127	−119	−137
Si II emission	3	+127	+142	+147	+155	+152	+145
Si II absorption	1	−135	−120	−130	−135	−110	−126
Si III emission	4	+124	+133	+152	+167	+155	+146
Si III absorption	2	−165	−180	−154	−147	−165	−162
Fe III emission	5	+64	+81	+96	+109	+85	+87
Fe III absorption	2	−147	−147	−132	−132	−130	−138
S III emission	5	+137	+136	+140	+148	+151	+144
S III absorption	2	−177	−172	−170	−170	−170	−172
S IV emission	1	+48	+52	+64	+111	+124	+80
S IV absorption	1	−168	−173	−168	−163	−160	−166
Mean emission	24	+114	+120	+129	+148	+138	+130
Mean absorption	14	−167	−162	−150	−156	−152	−157

the stellar absorption lines in the far-ultraviolet, if present, should be difficult to detect, since the flux in the continuum is practically zero at $\lambda < 1050$ Å and very low (less than 300 counts) for $\lambda \leq 1300$ Å.

II. RADIAL VELOCITY AND INTENSITY VARIATIONS

Table 2 gives mean velocities averaged over lines of the same ion, over all lines and over all phases.

Figure 1 gives the mean radial velocity, for each ion, of the absorption component, the longward emission component, and, when measurable, the shortward emission component versus phase. In addition, the photographic and visible radial velocities (Flora and Hack 1975) together with the radial velocity curve for the primary star are plotted. All radial velocities are relative to the center of mass of the system.

The P Cygni absorption components in the ultraviolet yield a nearly constant expansional velocity of ~150 km s^{-1} (in the visible spectrum an expansional velocity of ~100 km s^{-1} is given by the circumstellar K line of Ca II and the D lines of Na I). The P Cygni emission features appear to show minor variations with phase. The velocities may be 20–30 km s^{-1} higher at phases 0.5 and 0.8 than at phases 0.0, 0.2, and 0.3. The evidence for any change in the radial velocity–phase relationship between 1973 and 1974 is very marginal and may be due more to intensity changes of the P Cygni absorption components than to actual velocity changes.

The Fe III radial velocities are about 50 km s^{-1} lower than the average velocity for all ions, while the C II and C III velocities are 50–100 km s^{-1} higher. Velocity variations are very similar for all lines. However, for these values to be significant, it would be necessary to reconstruct the whole emission profile, which is partly masked by the P Cygni absorption.

Table 3 gives the peak intensity, width, and normalized area above the continuum for the U2 observations at each phase for all emission lines for which these quantities are measurable. The emission line widths do not vary significantly with phase, while the peak intensities and areas do vary, being generally lower (~15%) at phase 0.5. The N V and C III lines vary most (~30%), and it appears that the degree of eclipsing is correlated inversely with ionization. A similar result was found in 1973, suggesting that the emitting material may have a local concentration in the vicinity of the secondary component. If the secondary component is several times as massive as the primary, then the orbital radial velocity amplitude would be only about a few tens of kilometers per second and would be very difficult to distinguish from other effects such as gas streaming, especially if only part of the gas giving rise to the emission lines is associated with this component.

In addition, the peak intensities of many emission lines tend to be slightly stronger at phases 0.2 and 0.3 than at phase 0.8. This might indicate that the matter was more concentrated near the preceding hemisphere of the primary than near the following hemisphere. However, the opposite behavior was observed in 1973, suggesting that these concentrations are not very stable features, and that most of the observed profile changes may *not* be phase correlated.

The peak emission line intensity relative to the continuum is about 30 percent stronger in 1974 than in 1973. Irregular variations of the emission line intensities have also been observed occasionally in the visible spectrum and are not unexpected, since an extended envelope such as that in which these emission lines are formed is bound to show instabilities.

Continuum intensities were estimated at several line-free wavelengths and were found to vary with phase in a similar way at all of them. The variation is similar to that shown by the emission lines. The

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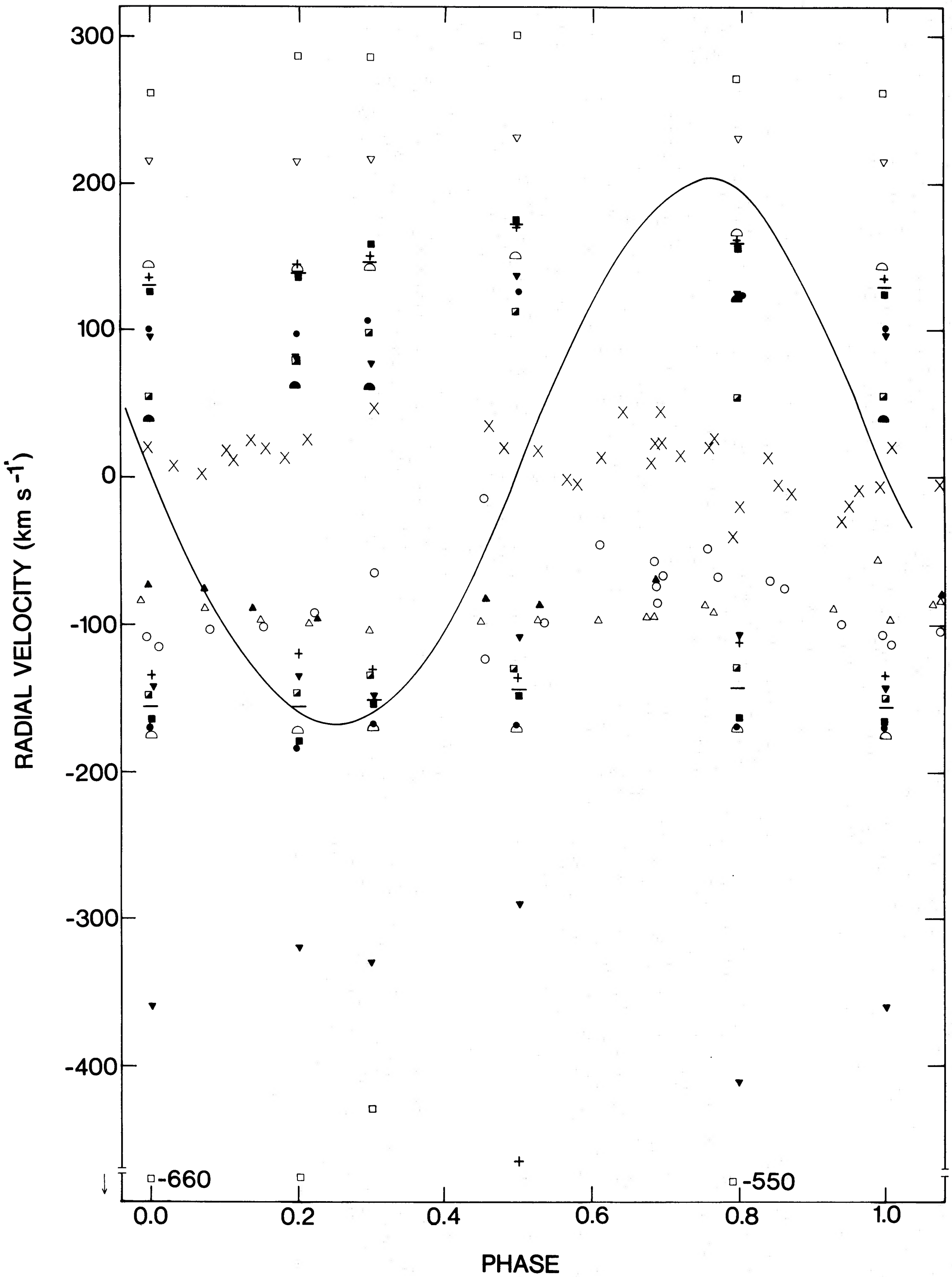

FIG. 1.—Radial velocities from the visual and ultraviolet spectrum of β Lyrae. The smooth curve represents the radial velocity curve of the primary star. The smooth curve and the visual radial velocities are from Flora and Hack (1975). The symbols have the following meanings: Visible: ×, Hα emission; ○, Hα absorption; ▲, circumstellar Ca II; △, circumstellar Na I. Ultraviolet: □, C III; ▽, C II; ▼, N V; +, Si II; ■, Si III; ⌓, S III; ◓, S IV; ◪, Fe III; ●, N II; —, mean value.

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TABLE 3

β LYRAE SPECTROPHOTOMETRY

LINE	$\phi = 0$ P	A	W	$\phi = 0.2$ P	A	W	$\phi = 0.3$ P	A	W
S IV λ1073	1220	1560	436	1220	1650	432	1040	1360	464
S III λ1077	980	680	250	880	580	250	940	580	226
N II λ1084	720	180	99	740	200	109	840	250	113
N II λ1086	2160	2230	318	2240	2150	294	2340	2290	300
Si III λ1109	560	200	166	760	320	165	840	370	170
Si III λ1110	960	440	166	1100	440	140	1080	430	142
Si III λ1113	1120	900	276	1200	960	276	1320	1020	258
Fe III λ1123	1340	860	207	1160	800	237	1320	1040	258
Fe III λ1127	600	260	190	680	230	148	640	230	152
Fe III λ1129	1020	590	196	1220	670	184	1100	590	182
Fe III λ1142	620	...	...	620	...	...	620	...	...
C III λ1175	800	910	364	700	860	412	820	920	384
Si II λ1197	320	170	237	280	115	208	280	55	135
S III λ1202	820	1000	70	840	1040	368	800	850	372
Si III λ1206	880	1170	393	780	1030	399	720	850	370
N V λ1238	740	1520	497	660	1310	481	540	950	426
N V λ1242	520	...	...	460	...	...	420	...	...
Si II λ1260	300	80	108	340	120	130	340	145	143
Si II λ1265	420	280	224	380	270	248	280	160	200
Sum	16100	12440	...	16260	12745	...	16280	12090	...
Continuum (arbitrary units)	...	84	...	...	87	...	...	97	...

continuum flux is about the same at the epochs of the minima, while it is 1.4 times higher at phases 0.2 and 0.3 and 1.2 times higher at phase 0.8. In 1973, again like the emission lines, the continuum was stronger at phase 0.75 than at phase 0.25. The correlation between lines and continuum variation suggests that the main source of the continuum in the far-ultraviolet is also the origin of most of the line emission.

III. LINE WIDTH AND PROFILES

In Paper I it was found that the width of the emission lines increases with increasing ionization potential, implying that the lines of higher ionization are formed either (1) where the P Cygni self-absorption is small or (2) where rotational velocities are higher, or both. The 1974 data yield the same relationship as did the 1973 data. Figure 2 gives the radial velocity and mean width versus ionization potential. The radial velocities increase essentially linearly with ionization potential with the exception of N v which has an ionization potential of about 77 eV and a mean radial velocity of about 114 km s^{-1}, the same as for elements with ionization potentials of about 30 eV. The emission line widths also increase linearly with ionization

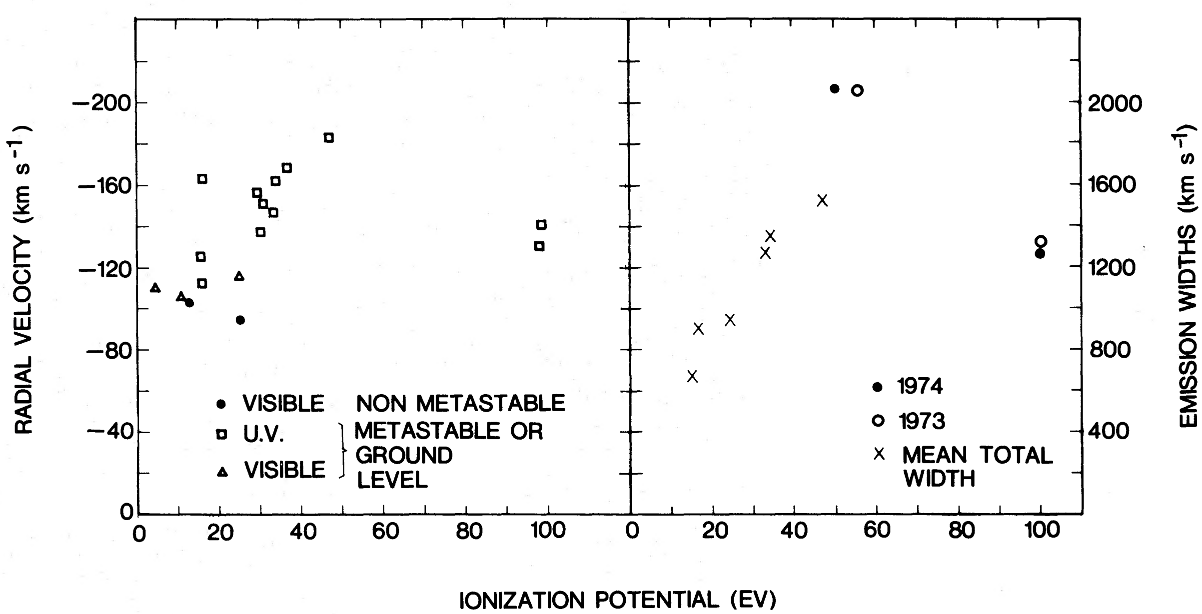

FIG. 2.—*Left*, plot of radial velocity of the visual and ultraviolet absorption lines versus ionization potential. *Right*, plot of emission line width in km s^{-1} versus ionization potential.

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TABLE 3—*Continued*

Line	$\phi = 0.5$			$\phi = 0.8$			Mean		
	P	A	W	P	A	W	P	A	W
S IV λ1073	960	1260	472	1220	1480	414	1130	1460	450
S III λ1077	800	480	229	860	530	231	890	570	237
N II λ1084	700	200	118	580	130	98	715	190	107
N II λ1086	1980	2130	334	1920	2140	348	2130	2190	318
Si III λ1109	680	280	170	840	220	198	735	280	174
Si III λ1110	820	380	178	1080	420	148	1010	420	154
Si III λ1113	900	670	267	1060	810	273	1120	870	270
Fe III λ1123	980	780	275	1040	760	262	1170	850	248
Fe III λ1127	560	220	179	660	230	153	630	235	164
Fe III λ1129	980	560	190	1220	700	194	1110	620	190
Fe III λ1142	520	...	...	720	...	...	620	...	...
C III λ1175	500	610	444	780	790	340	720	820	388
Si II λ1197	240	100	209	340	200	276	290	130	213
S III λ1202	680	940	336	760	920	418	780	950	376
Si III λ1206	720	970	404	880	1080	373	795	1020	390
N V λ1238	440	590	325	620	850	332	600	1045	412
N V λ1242	320	...	...	440	...	...	430	...	...
Si II λ1260	240	95	143	320	80	116	310	105	128
Si II λ1265	300	210	226	400	210	146	355	225	210
Sum	13320	10475	...	15740	11550	...	15540	11980	...
Continuum (arbitrary units)	...	67	...	...	87	...	...	...	...

Notes.—P is peak intensity above zero in counts. A is area above continuum in Å counts. W is width of feature defined as area/peak (above continuum) in units of km s^{-1} for N v λ1238; no allowance was made for the central absorption in estimating the width of the feature, so they may be 25–50% low.

potential with the exception of C III which is too wide. However, this line consists of a number of unresolved components which complicate the situation. Also, the C III (1175 Å) line is a subordinate line (though in a metastable state), not a resonance line as are the other strong lines.

A shortward emission wing is present only for C III (1175 Å) and N V (1238, 1242 Å). No other emission lines show shortward emission. However, a close examination indicates that shortward emission might be masked by the presence of interstellar lines or by blending with other emission lines. If all emission lines have shortward emission wings, their widths are larger than indicated. Whether or not this is the case, the C III and N V ions produce lines much broader than all the others; moreover C III (1175 Å) is much broader than the two resonance lines of N V, in spite of the higher ionization potential of the latter.

The U1 profiles of S IV (1073 Å), N II (1085 Å), C III (1175 Å), and N V (1238, 1242 Å) are quite interesting. Figure 3 shows the U1 profiles at each phase for N II (1085 Å) and C III (1175 Å), and it is clear that considerable changes occur between each observation.

The presence or absence of He II (1084 Å) is of interest in determining the physical conditions in the circumstellar envelope of gas. The ultraviolet emission line spectrum of β Lyrae is characterized by the presence of zero- or low-excitation (lower level) lines of multi-ionized atoms. In order to understand the mechanism by which the emission lines are formed, it is important to know if the high-excitation lines are actually missing or if they are of low intensity and hence difficult to detect. The 1084 Å line of He II is a high-excitation line of sufficient strength to be detectable if present, and the presence of the lines of N V, requiring an ionization energy of about 77 eV, suggests that the line of He II should be present. Since this line falls only 0.5 Å from the strongest line of N II (1085 Å), we could not decide if He II was present or not on the basis of our 1973 U2 observations. The U1 scans of this spectral region made in 1974 show no trace of the He II line at 1084.95 Å. The observed profile can be synthesized very accurately by a blend of four identical P Cygni profiles of different intensities at the positions of the N II lines. Figure 4 shows the mean U1 profiles for N II (1085 Å) and N V (1238, 1242 Å) and their deconvolution. The profile width for N II is about 1000 km s^{-1} and the absorption shift is -150 km s^{-1}. The intensities are 1084.0 Å (1), 1084.6 Å (2), and 1085.5 Å + 1085.7 Å (5.5). The complexity of the profile puts a high degree of confidence in the conclusion that He II is absent. It is noted that the He II (4686 Å) line is not present in the optical spectrum of β Lyrae either.

Why do we observe the two resonance lines of N V and not the He II line which requires a lower excitation energy? If the emission lines observed in the ultraviolet spectrum of β Lyrae were formed by recombination we should expect to observe all the lines and not only those with zero or low excitation potential. This observational fact suggests that the emission lines are collisionally excited. The kinetic energy which the gas would acquire upon falling onto the disk, presumed to surround the secondary component, might be the source for ionizing and exciting the gas.

The U1 profiles of C III and N V differ in an interesting manner. Both show variable shortward emission

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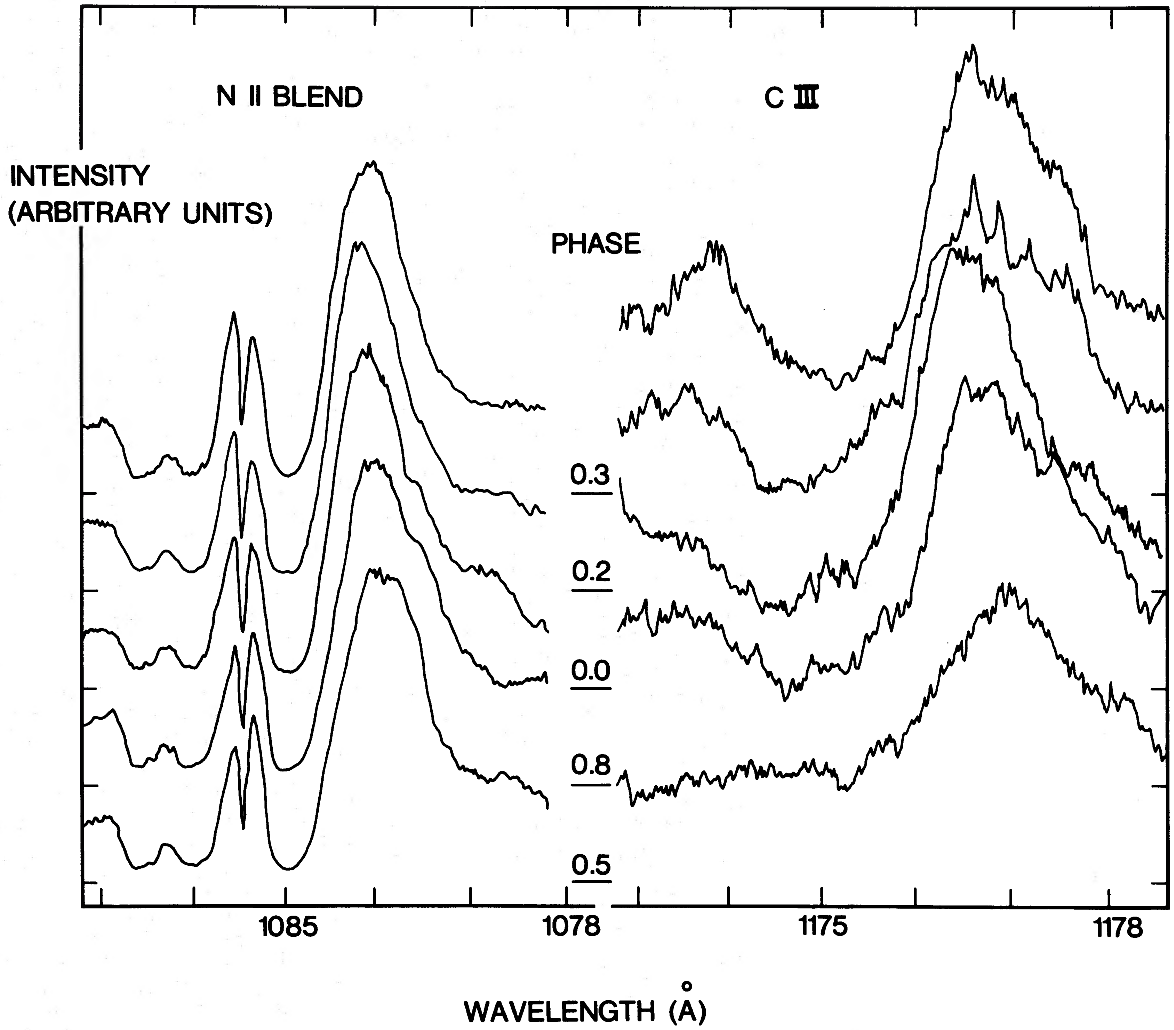

FIG. 3.—U1 profiles of the N II and C III lines at each observed phase

(or variable absorption width) which vanishes at phase 0.5 and is strongest at phases 0.2 and 0.3. The C III shortward emission is also nearly absent at phase 0.0. This absence of shortward emission is probably caused by additional absorption seen at these phases. The matter causing this absorption could be moving through the L_2 and L_3 points.

The N V feature is remarkable in that the emission center is shortward of λ_0, the laboratory wavelength, for any reasonable reconstruction of the line profile. The C III emission lies close to λ_0. The ionization potential–width relationship also breaks down for the N V lines in the sense of their being narrower than expected. A simple ad hoc explanation which does not require a new model is that the N V emission is formed close to a photosphere or a region of high line opacity. This essentially occults the whole of the back (receding) part of the emission, giving a shortward-shifted and narrower line. A blend of two such profiles (integrated over the facing hemisphere of a shell) is very close to the observed mean profile. Figure 5 shows some calculated profiles and blends. The best representation of the observed N V blend lies close to the lower two blends on the right side of the figure. The weakening of the shortward part of the emission at phase 0.5 in both 1973 and 1974 implies that part of the emission is formed closer to the secondary than the distance separating the two stars.

The C III profile is consistent with a rotating, expanding shell, with a variable high-velocity expansion limit, and without the high degree of occultation required by the N V lines. The P Cygni nature of the lower excitation lines is consistent with this formation at greater distances where recessional velocities are higher. The phase where the shortward peak emission intensity occurs is that at which the presumed stream of gas emanating from the primary is seen against the secondary and may be the one at which outward expansion from the secondary appears somewhat suppressed.

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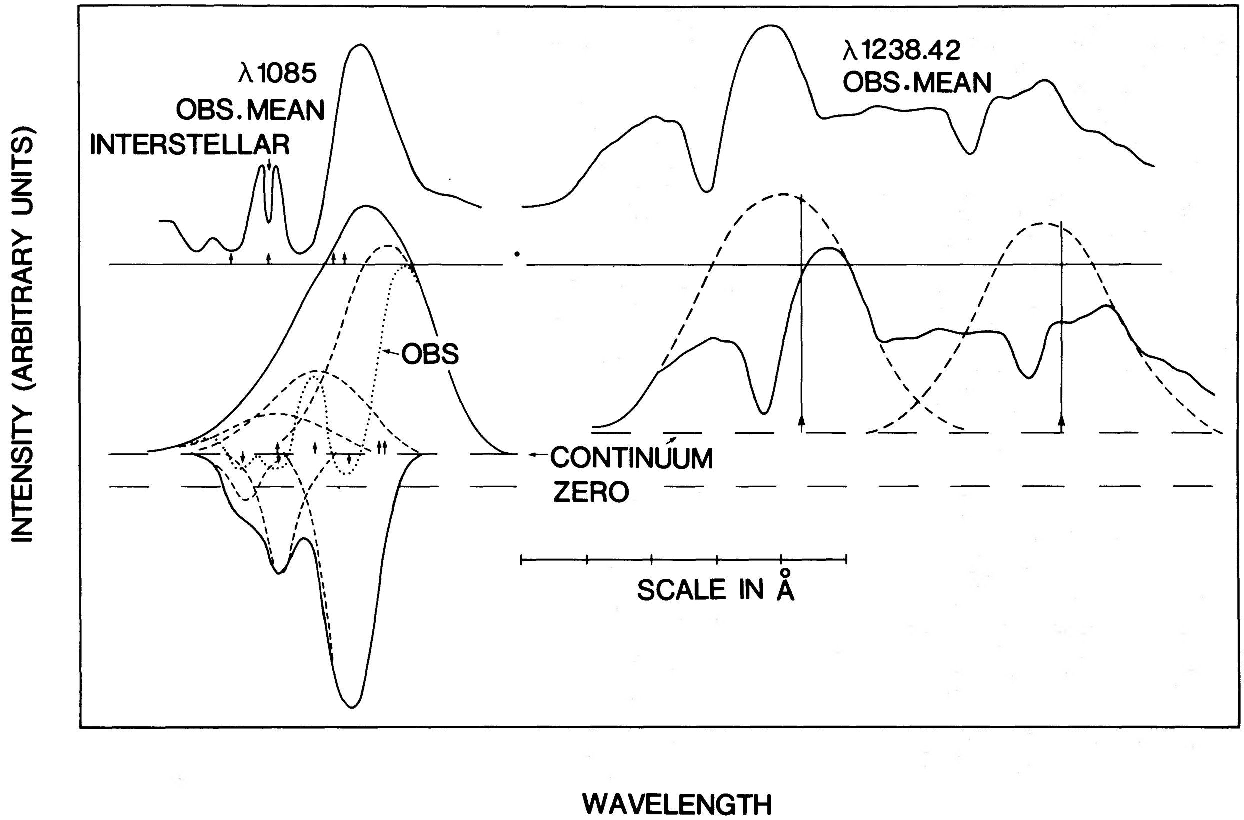

FIG. 4.—*Upper*, mean U1 profiles, averaged over phase, for N II (1085 Å) and N V (1238, 1242 Å). *Lower left*, proposed constitution of the N II blend with four similar P Cygni profiles of different intensities. The dashed curves show the emission and absorption contribution of the 1083.990, 1084.580, and 1085.546 + 1085.701 Å components of the N II blend. The solid curves give the combined emission and absorption of these four lines. If these are added to give the net profile, the result agrees closely with the observed profile shown by the dotted curve, indicating the lack of any significant contribution to the line profile by He II (1084 Å). *Lower right*, proposed emission contribution (*dashed curves*) from the N V lines showing the shift shortward of the rest wavelengths. Solid curve is the mean profile. Rest wavelengths are indicated by vertical lines and arrows.

IV. DISCUSSION

The 1974 observations of β Lyrae confirm and reinforce the results of Paper I. No major changes occurred in the spectrum between 1973 and 1974. The relatively minor changes which took place are not to be unexpected in a dynamical situation such as that involving mass exchange, mass loss, and the existence of a circumstellar envelope, all of which are present in β Lyrae.

The absence of the He II line in the presence of other lines requiring higher ionization energies, such as N V, strongly suggests nonradiative processes. The observations indicate that different emission lines arise in different regions of the circumstellar cloud. The reason for the existence of such regions may also be related to the fact that the emission lines are collisionally excited. It may be that the electrons have different characteristic energies in different regions of the gas cloud surrounding β Lyrae. This will give rise to excitation of those emission lines whose collisional excitation cross sections are optimized at these electron energies: hence, different regions are characterized by different emission lines. Of course, such regions are not very clearly segregated from each other. Both physical considerations and the observations indicate substantial overlapping of such regions. The small intensity variations and the structure of the N V emission features indicates that a local concentration of emitting gas exists in the neighborhood of the secondary component.

The observations show very clearly that the mass exchange in β Lyrae is not conservative; the system is losing mass as a whole. We are in great need of theoretical studies of the evolution of close binaries with nonconservative mass exchange. Further high-dispersion observations of C III (1175 Å), medium-dispersion observations in the mid-ultraviolet (2000–3000 Å) and high-dispersion observations of Mg II (2798 Å) are being made to provide additional information on the nature of the circumstellar envelope in β Lyrae.

It is a pleasure to acknowledge the competent support we received from the Princeton University *Copernicus* telescope project team—especially Dr. Lyman Spitzer, Jr., the principal investigator, and Drs. D. G. York and T. P. Snow, who oversee the Guest Investigator Program.

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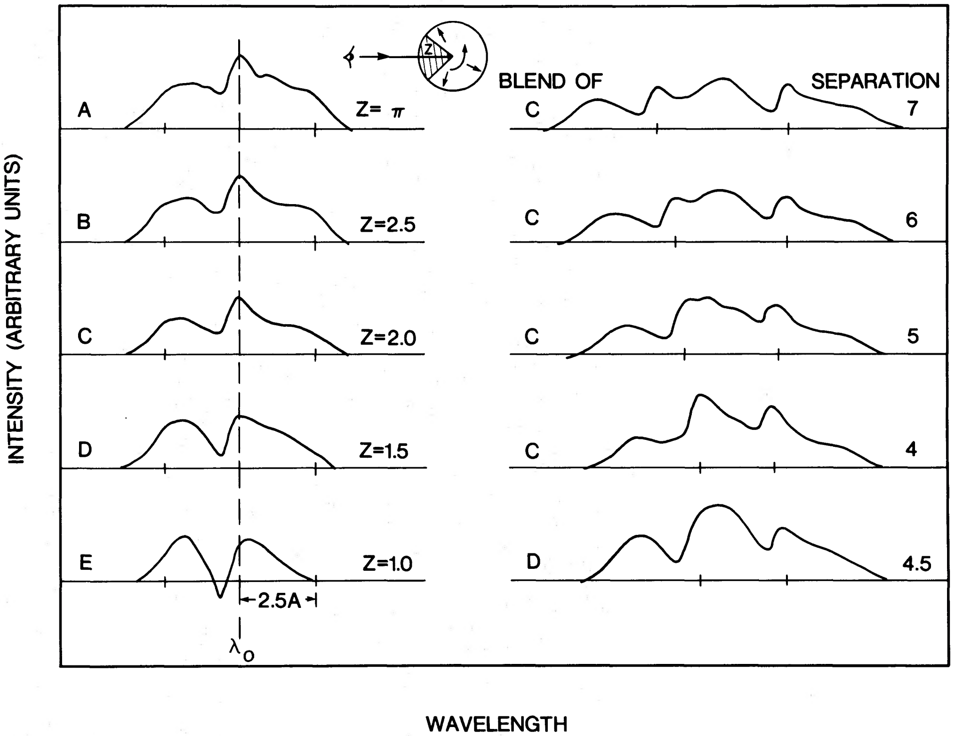

FIG. 5.—Calculated profiles for the N v blend. Line profiles were calculated for a spherical shell rotating at 600–900 km s^{-1} and expanding at 150 km s^{-1}. The integration was carried out from $2R_*$ to $3R_*$, where R_* is the distance from the center of mass of the system. *Left*, line profiles showing the effect of absorbing material occulting differing fractions (Z radians) of the rear part of the shell, showing the shift to shorter wavelengths. *Right*, synthesis of the observed blend, using different separations (or rotational velocities) and models from the left side of the figure.

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