IUE OBSERVATIONS OF THE TWO PECULIAR BINARY SYSTEMS BETA LYRAE AND UPSILON SAGITTARII+

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The common peculiarities of these two systems are: a) the companion is a massive object (probably $m_2 \gtrsim 10$) whose spectrum is not observable; b) both systems show evidence, though in different degrees, of mass-transfer and mass-loss; c) both present, in different degrees, hydrogen deficiency; d) ultraviolet observations have shown, in both cases, the presence of lines of highly ionized elements like N V, C IV, Si IV, probably formed in an extended envelope because they do not show orbital radial velocity shifts, and cannot be explained by the effective temperature of the star whose spectrum we observe. The latter property seems to be common to several close binaries, as shown by the ultraviolet observations with IUE by Plavec and Koch (1979); e) both systems present infrared excess, suggesting the presence of an extended envelope (Gehrz et al. 1974; Lee and Nariai, 1967; Humphreys and Ney, 1974; Treffers et al. 1976).

The main characteristics of the two systems are summarized in Table 1.

The IUE observations and their purpose.

Although Beta Lyrae had been observed very extensively with Copernicus (Hack et al. 1975, 1976, 1977) a few problems were left, because the spectral region 1500-2000 A, where the sensitivity of the spectrometer was extremely low, had not been observed. In this region are located two lines, λ 1640 He II and λ 1908 C III] , which are important for deriving the physical conditions of the envelope. During the first run of observations of Beta Lyrae with Copernicus, it was a surprise to observe the strong emission of the resonance lines of N V and

+ Based on observations by the International Ultraviolet Observer (IUE) collected at the Villafranca Satellite Tracking Station of the European Space Agency.

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the apparent absence of λ1085 He II (blended with the resonance lines of N II). A confirmation of the weakness or absence of He II was given by low resolution spectra obtained with an objective prism spectrograph on Skylab by Kondo et al. (1976), and its complete absence was confirmed by IUE observations. This result suggested that the far UV emission lines are not radiatively but collisionally excited.

Table 1 - Properties of the systems

	β Lyr	υ Sgr
P (d)	12.9349	137.9567
f(m) (⊙)	8.73	1.677
K (Km s^{-1})	184.0	49.12
γ (Km s^{-1})	-17.8	-13.29
a sini(Km)	32.7×10^6	9.3×10^7
i (°)	≳75°	47°
Sp.Prim.	B8-B9	B8,F0 Ia
H/He	1/2	1/40
m_1/m_2 (i=90°)	1/1.6 m_1=14 m_2=21.4	
" "	1/6 1.6 11.8	
m_1/m_2 (i=47°)		1/2 m_1=4.8 m_2=9.64
" "		1 17.1 17.1
" "		2 38.6 19.3
Probable type sec.	B0-B5 III-IV or Black Hole	O9 V

The existence of strong emission in the region 1900-2100 A was shown by the low resolution observations obtained by Hack (1974) with experiment S2/68 on TD-1 and by Kondo et al. (1976) with Skylab. Hack attributed these emissions mainly to the strong Fe III lines present in this region. However, a possible contribution could be due to λ1908 C III] whose emission is strong in several Wolf-Rayet stars, symbiotic stars, and chromospheric spectra of late-type stars. This line requires a gas density of 10^{10} cm^{-3} or less (Osterbrok, 1970). Now the IUE observations have excluded its presence, putting the lower limit for the density of the envelope above 10^{10} cm^{-3}.

Upsilon Sgr was also observed with Copernicus, but only in two limited spectral regions (Duvignau et al. 1979) and with very low S/N. The present observations cover the epochs of the two minima and the two quadratures in the spectral range 1170-3200 A. Table 2 gives the list of the observations. All the exposures were obtained with the 3" aperture.

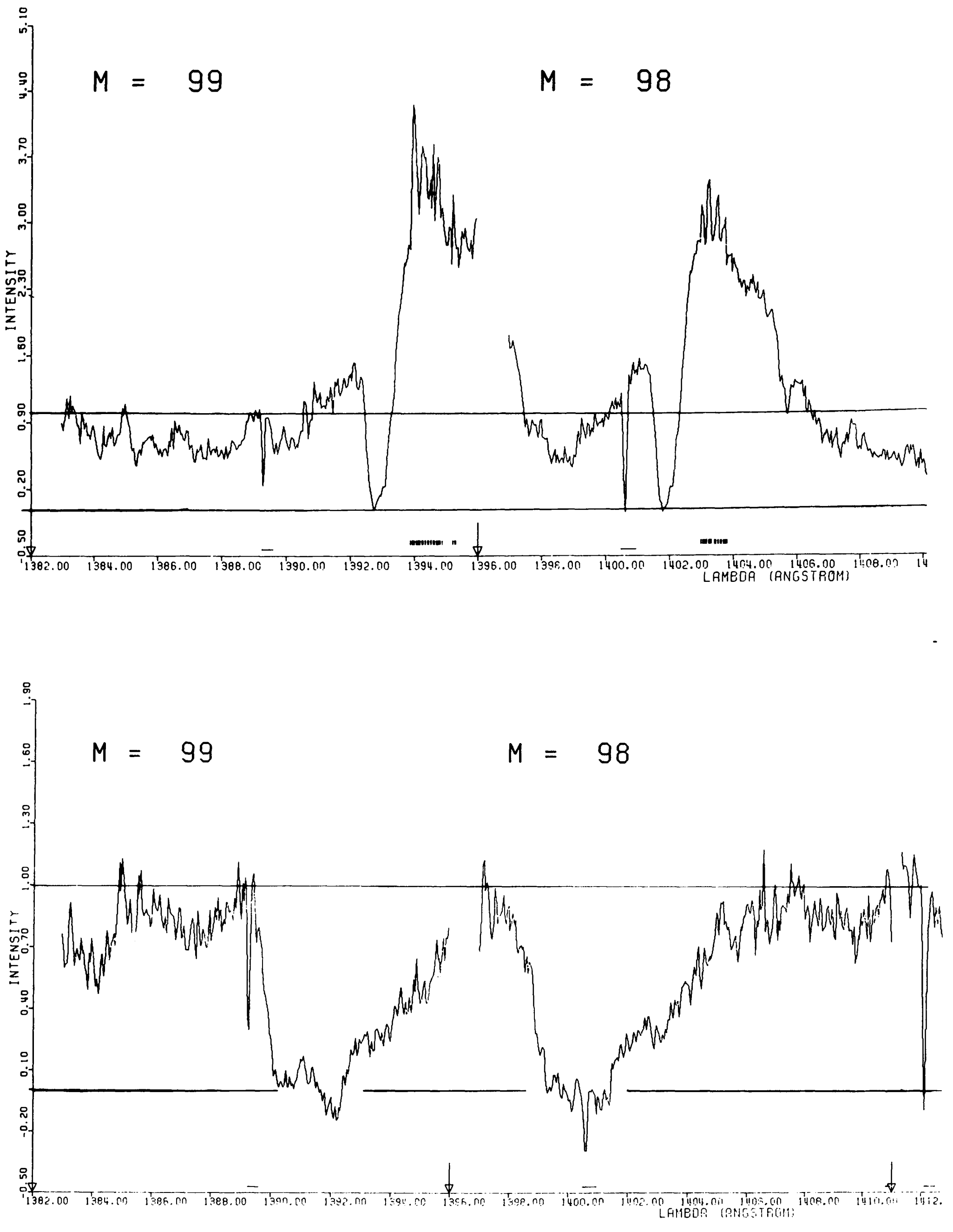

Figure 1. The profiles of the Si IV resonance lines. Top: Beta Lyr (phase 0.51); bottom: Upsilon Sgr (phase 0.02).

Table 2. Observations
(High Resolution, 3" Aperture)

Image	J.D	Phase	Exposure
β Lyr			
	2443		
3.1375	615.87	0.512P	8 min.
2.1328	.91	0.515	4
3.1386	17.90	0.669	2
3.1426	25.78	0.279	2
2.1397	.81	0.281	2
υ Sgr			
	2443		
3.1398	620.72	0.02 P	60 min.
2.1361	.72	0.02	10
2.1528	49.59	0.23	10
3.1592	.63	0.23	60
3.1856	85.50	0.49	60
2.1909	718.47	0.73	10
3.2136	.50	0.73	60
2.1910	.60	0.73	20
3.2137	.62	0.73	75

The line-spectra.

The most conspicuous characteristics of the spectra of the two systems are the following: the far ultraviolet spectrum is dominated by strong ground level or metastable lines of multi-ionized atoms like C II, C III, C IV, N V, Si II, Si III, Si IV, Al II, Al III, and low excitation lines of Fe III. Copernicus observations of Beta Lyr (Hack et al. 1975) in the region at $\lambda < 1150$ A have shown also the presence of N II, S III, S IV, ground level lines of Fe III, and the absence of the lines of O VI.

The most striking difference between the spectra of the two systems is the shape of the line profiles. The spectrum of Beta Lyr is characterized by the presence of strong emissions cut by sharp absorption cores shifted shortward by about 150 km/s; the same lines, in the spectrum of Upsilon Sgr, present very broad, asymmetric profiles in absorption, with a sharp edge on the side of the short wavelengths, indicating a terminal velocity of about 700 km/s. (Fig. 1)

These lines do not show appreciable shifts due to orbital motion.

The regions where there are no resonance lines of abundant ions are very similar in the two systems. The Fe II lines, which dominate the region 1600-1700 A, present radial velocity shifts indicating that they are formed in the atmosphere of the primary. In the spectrum of Beta Lyr λ1640 He II is absent. In Upsilon Sgr there is a sharp absorption at λ1640.5; moreover there is a broad depression (missing in Beta Lyr) centered at λ 1640 and extending from λ 1639 to λ 1643. This depression may be due to a broad He II absorption. (Fig. 2)

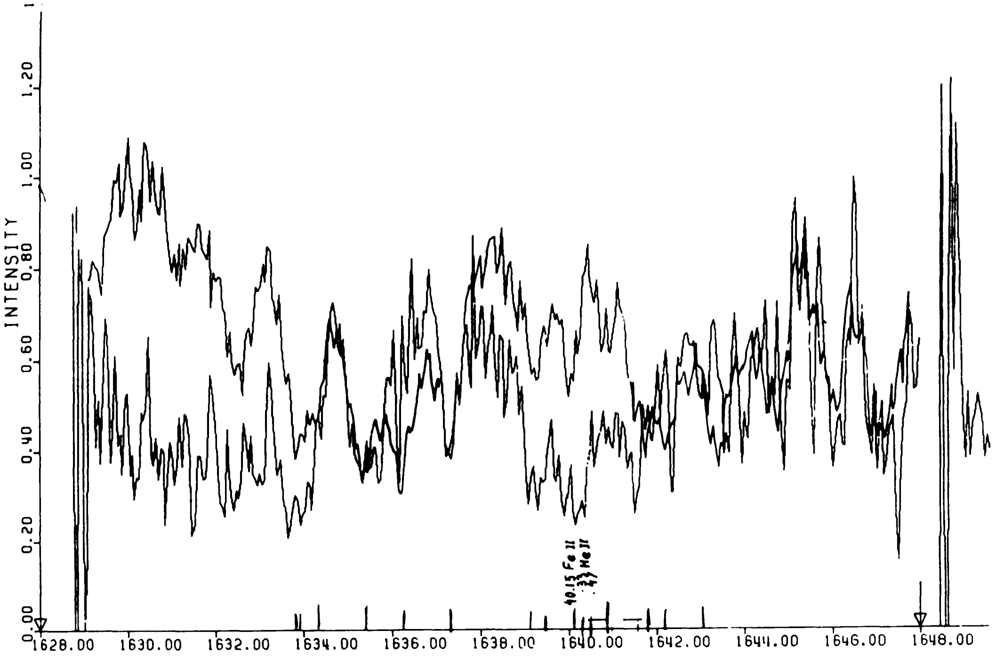

Figure 2. The region of λ1640.5 He II: top Beta Lyr (phase 0.51), bottom Upsilon Sgr (phase 0.49).

The region 1850-2200 A, where many strong lines of Fe III are located, differs in the two systems, because in Beta Lyr the strongest lines of Fe III present P Cygni profiles with rather strong emission lines, while in Upsilon Sgr they are in absorption and fainter than in Beta Lyr. The region 2200-3100 A is dominated by lines of once-ionized metallic atoms (mainly Fe II). The radial velocity shifts clearly indicate that these lines are formed in the atmospheres of the primary stars. The absorption lines of the once-ionized metals are generally stronger in Upsilon Sgr than in Beta Lyr, a fact which can be explained by the lower temperature of Upsilon Sgr, which in the visual range has a metallic-line spectrum very similar to that of Alpha Cyg (A2 Ia), or Epsilon Aur (FO Ia) (Hack and Pasinetti, 1963).

The Mg II resonance lines in Beta Lyr present a P Cygni contour with an absorption core shifted shortward by 1.4 A relatively to the interstellar absorption line, and a strong emission wing. Upsilon Sgr presents no emission wing but only a strong absorption core in the broad depression in the continuum due to the photospheric lines, which extend from about 2788 to 2810 A. The shape of the depression is very similar to that observed in Epsilon Aur (Hack and Selvelli, 1979) and indicates the existence of a central emission which fills up and distorts the gaussian profile of the photospheric core. The sharp absorption core may be of interstellar or circumstellar origin. To decide which, we have compared the equivalent widths of other interstellar lines in Beta Lyr and Upsilon Sgr. The K line of Ca II and the Na I lines measured at phase 0.22 in Beta Lyr and at phase 0.71 in Upsilon Sgr, when the separation between stellar and interstellar lines is largest, have about the same value. We expect that also the Mg II interstellar components of the resonance multiplet have about the same intensity in the two stars. Since the equivalent widths of the cores in Upsilon Sgr are about two times stronger than in Beta Lyr, we conclude that probably the sharp cores in Upsilon Sgr are a blend of interstellar and circumstellar lines.

A large discrepancy between the equivalent widths of the Mg II cores measured with Copernicus (Duvignau et al. 1979) and with IUE has been found; it is due to the different central depth, which is about 1 in the IUE spectra and only 0.3 in those of Copernicus. This difference depends on the background correction. Since the particle background in the Copernicus data is large in this spectral region, due to the South Atlantic Anomaly, and since the IUE spectra in the Mg II region permit an easy, direct determination of the background, we think the latter to be more reliable.

Radial velocities.

Only relative determinations of radial velocity are possible with IUE. We have assumed rest velocity for the several interstellar lines easily detectable in our spectra, and have determined the stellar radial velocity relative to them. About 20 interstellar lines are well detectable and measurable in the short-wave range, and about another 10 in the long-wave range. They allow us to establish with sufficient accuracy (0.1 A) the wavelength scale over the whole spectral range.

By comparing the plots for different phases one can easily distinguish the stellar lines which present the orbital radial velocity shifts, from the almost stationary lines of the envelope. The results for the photospheric lines are given in Table 3, and compared with the results obtained in the visual range.

Table 3. Radial velocity shifts of the photospheric lines.

$\Delta\varphi$	β Lyrae IUE		σ	Sahade et al. 1959	Flora, Hack 1975
0.67– 0.51	+ 142	SW	11	+ 120	+ 150
0.28– 0.51	– 213	SW	17	– 215	– 185
	– 194	LW	25		
0.67– 0.28	+ 346	SW	18	+ 335	+ 345
	υ Sgr IUE			Wilson 1914	
0.23– 0.73	+ 99	SW	12	+ 95	
	+ 75	LW	9		

Table 4 gives the radial velocity of the absorption cores of the envelope lines for Beta Lyr. Their behavior is strictly similar to that observed with Copernicus in 1973 and 1974 by Hack et al. (1975, 1976) for the lines included in the spectral range 1030–1400 A.

Table 4. Mean radial velocity of the Beta Lyr envelope.

Ion	IP (ev)	EP (ev)	RV ($km\ s^{-1}$)
C II	11.20	0.0	–163
C III	24.28	6.5	–128
C IV	47.67	0.00	–151
N V	77.09	0.00	–163
Mg II	7.61	0.00	–144
Al II	5.96	0.00	–156
Al III	18.75	0.00	–171
Si II	8.11	0.0	–146
Si III	16.27	0.00	–174
Si III	"	6.5	– 98
Si IV	33.32	0.00	–182
Fe III	16.16	3.71	–175
Fe III	"	5.06	–143
Fe III	"	7.8	–128
Fe III	"	8.2	
Fe III	"	8.6	
Fe III	"	8.7	
Fe III	"	9.5	–129
Ni III	18.07	6.8	–144
Ni III	"	7.7	

Table 5 gives the terminal velocity (measured at half intensity relative to the nearby continuum) for the ground-level lines of various ions at different phases for Upsilon Sgr.

Table 5. Terminal velocity (km/s) (Upsilon Sgr)

line	phase							
	0.02		0.23		0.49		0.73	
	v	σ	v	σ	v	σ	v	σ
1334 C II	-434	20	–		–		–	
1548 C IV	-713	19	-636	19	-791	19	-694	19
1238 N V	-726	25	-702	25	-822	:	-678	25
1242 N V	-677	:	-652	:	–		–	
1206 Si III	-821	20	–		–		-746	16
1393 Si IV	-829	21	-678	21	-829	21	-742	21
1402 Si IV	-828	21	-742	21	–		-700	21

We point out one characteristic of the spectrum of Upsilon Sgr shown by past observations in the visual range: sometimes, but not always, at phase 0.5 a violet-shifted component of Hα indicating a velocity of about -300 km/s has been observed; it has been interpreted as evidence of a jet of gas moving from the primary toward the secondary and projecting itself on the stellar disk of the primary. Another red-shifted component, at about +150 km/s, has occasionally been observed (Hack, 1960) and interpreted as due to a jet of gas from the secondary toward the primary. A search for evidence of such jets in the ultraviolet spectrum was made in the short wave range (we had no time to observe the long-wave range at phase 0.5). We have observed: a) a possible component of N V line λ 1238 shifted shortward by about 240 km/s relatively to the terminal velocity of the main component. Nothing can be said about the other line λ1243 which is blended with λ1238.
b) the two resonance lines of Al III show two features longward of the main line, which are absent at the other phases; they could indicate the presence of absorbing gas moving at + 113 km/s.

The continuous spectra.

The continuum was determined by passing through the highest points of the tracings, in positions where no emission contribution is expected. By comparing these well defined "windows on the continuum" on the spectra of Beta Lyr and Upsilon Sgr, it appears that the latter does not present detectable emission lines.

The flux (in erg cm^{-2} s^{-1} A^{-1}) is obtained by the relation $F_\lambda = S_\lambda^{-1}$ N/t, where S_λ is the chromatic sensitivity for the high

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resolution mode (Cassatella and Selvelli, 1979), N the IUE flux number, t the exposure time in seconds. Because of the unknown fraction of radiation occulted by the 3" aperture, the values of the flux are reduced by a factor of 2 or larger (Bohlin and Snijders, 1978) and no information can be obtained about the light variation with the phase.

The continuous energy distribution observed at the various phases is compared with the theoretical models by Kurucz (1979) and with the observations from S2/68 (Jamar et al. 1976). No apparent variation with the phase in the energy distribution curve has been found either for Beta Lyr or for Upsilon Sgr.

Beta Lyr: The best fit of the observed spectrum with the theoretical ones, after normalization at λ 2500, is found for T_e = 13000 K; the dependence on the gravity is negligible. However, the observed spectrum presents a flux higher than the theoretical one in the region 1800-2200 A where many strong and moderately strong lines of Fe III are situated.(Fig. 3)

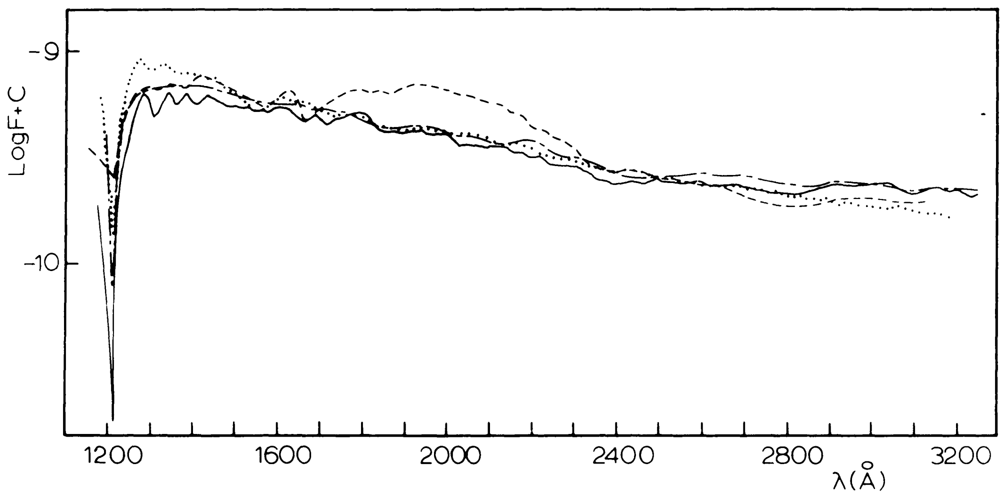

Figure 3. The logarithm of the flux (in erg cm^{-2} s^{-1} A^{-1}) for Beta Lyr (mean of three far UV and two near UV images) versus the wavelength (dashed line) and comparison with Kurucz models (——— T_e = 11000, log g = 3; — - — T_e = 13000, log g = 2.5; ••••• T_e = 15000 log g = 3). The curves have been arbitrarily normalized for 2500 A.

Probably the continuum we have traced is too high, passing through several faint emission wings. This is confirmed by the fact that the line blocking appears larger in this region than in the contiguous region

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2300-2400 A. After having corrected this first approximation continuum, the fit with the models for T_e = 13000 K is very good from λ 1200 to λ 3100. This result agrees with the data obtained with Copernicus (Hack et al. 1975), where the observations fit an energy distribution intermediate between B6 and B8 in the range 1200-1400 A; however it was found that at λ<1150 the spectrum better fits a distribution curve corresponding to B5.

A determination of the interstellar extinction for normal spectra can be made by using the relation given by Thompson et al. (1978) for B-type stars: $E_{B-V} = 0.40\ (m_{1565}-m_{2740}) - 0.60\ (m_{1565}-m_{2365})$. Since the continuous spectrum of Beta Lyr in the range 1565-2740 can be considered normal, being fitted very well by models with T_e = 13000 K, we have applied this relation and found $E_{B-V} = +0.02$.

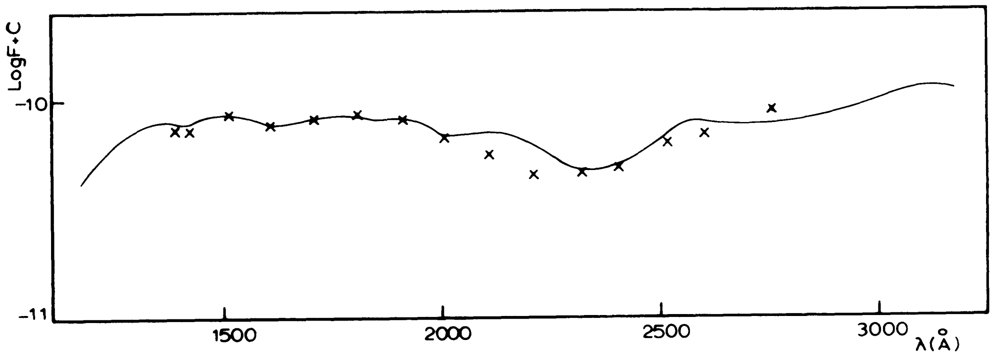

Figure 4. The logarithm of the flux (in erg cm^{-2} s^{-1} A^{-1}) for Upsilon Sgr (mean of four far UV and three near UV images) versus the wavelength) (continuous line). The crosses represent the logarithm of the flux observed for Zeta Oph reduced by a factor 35 plus the flux observed for Alpha Cyg and reddened by E_{B-V} = 0.31 (S2/68 observations)

Upsilon Sgr: The average spectrum is compared with several theoretical models. No one of them fits the observations, and it is clear that two different models, one for $T_e \sim 8000$ K and another for $T_e \gtrsim 11000$ K are necessary to fit the whole spectrum. The spectrum presents a slight depression at 2100-2300 A, giving evidence of appreciable interstellar extinction. (Fig. 4)

Discussion.

A model for Beta Lyr has been extensively discussed on the basis of the data obtained with Copernicus (Hack et al. 1977) and the present observations generally confirm it. The lower limit for the envelope density, which was above 10^8 cm^{-3}, because of the absence of forbidden lines in the spectrum, is now raised above 10^{10} because of the ascertained absence of λ 1908 C III].

A point which needs further discussion is the stratification of the ions in the envelope. By considering all the observations of the radial velocity and rotational broadening of the lines formed in the envelope in the visual and ultraviolet range, we can infer that the expansional velocity is not regularly increasing with the distance from the photosphere of the primary star.

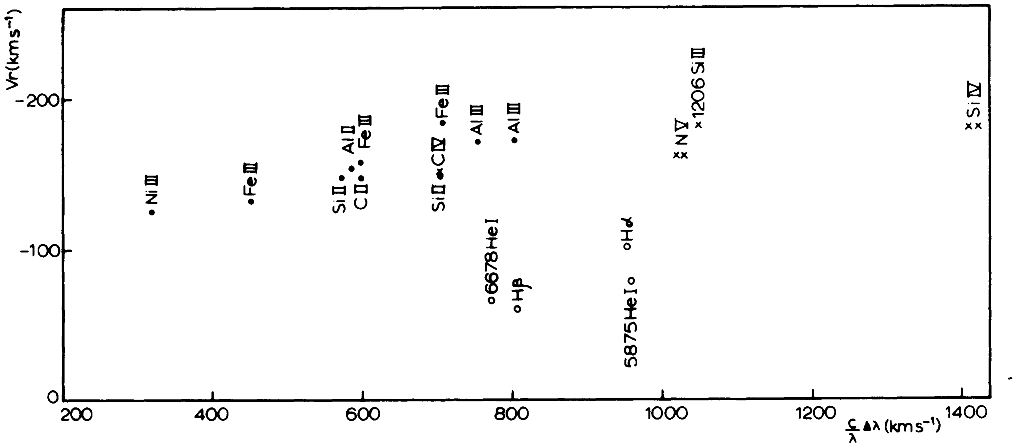

Figure 5.Lines formed in the Beta Lyr envelope: expansional radial velocity versus the rotational broadening. Dots and open circles: low ("chromospheric") ionization lines in the UV and visual range respectively; crosses: high ("coronal") ionization lines.

In fact, if we plot the expansional velocity of the absorption cores versus the width of the whole line (emission wings and absorption core) measured on the continuum (in km/s) we find the curve of Figure 5. We observe that the lines of lower ionization are grouped in the region of lower rotational velocities, while the lines of multi-ionized atoms have generally higher rotational velocities. This suggests the existence of two regions, one at $T \sim 10^4$ K, $N_e \sim 10^{12}$ cm^{-3} (as indicated by the strength of the metastable lines of He I), that we will call "chromosphere", and another at $T \sim 10^5$ K, $N_e \sim 10^{10}$ cm^{-3} that we will call "corona". The lines of Ni III, Fe III, Al II, Si II, C II, Si III, Al III, He I and H I are formed in the "chromosphere"; the widths increase from Ni III to Hα and 5875 He I. When several lines of the same ion, originating from different low excitation levels, are

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measurable (as is the case for Fe III) the expansional velocity decreases with increasing excitation potential.

Since we can reasonably expect that the largest optical depth in this region is at Hα and 5875 He I, we can deduce that the linear rotational velocity increases with the distance from the primary, and therefore that the expansional velocity at first increases with the distance, reaches a maximum and then decreases again.

In the "corona" the C IV lines have lower rotational velocities than the N V lines. It seems improbable that the optical depth in the corona is lower in the C IV lines than in the N V lines, because of the larger abundance of carbon, its lower ionization potential and the comparable gf values. It is reasonable to think that the rotational velocity in the extended envelope follows a keplerian law, decreasing outward; in this case the expansional velocity is also slowly decreasing outward, from -180 (Si IV, Si III) to -160 (N V) and -150 km/s (C IV).

The radial velocities in the "chromosphere" and "corona" at the epoch of the second quadrature are generally less negative by 20 to 30 km/s than at the epoch of the first quadrature (a fact already observed in the visual range by Flora and Hack, 1975, and with Copernicus by Hack et al. 1976, 1977), probably because of the presence of streams or condensations in the vicinity of the primary.

The resonance lines of Ca II and Na I do not present the slight radial velocity variations shown by the other envelope lines, but indicate a constant expansional velocity of -80 km/s relatively to the primary, suggesting that they are formed in a cooler outward circumstellar envelope.

A different behavior is that of 1175 C III, which probably has a component associated with the invisible companion, and was discussed by Hack et al. (1977).

While the envelope profiles of Beta Lyrae are explained by a shell rotating at about 300 to 400 km/s and expanding at about 150 km/s, those of Upsilon Sgr are not easily explained. In order to understand, at least qualitatively, the broad asymmetric absorption profiles of the lines due to multi-ionized atoms in the far ultraviolet spectrum of Upsilon Sgr, we have compared them with the theoretical P Cyg profiles computed by Castor and Lamers (1979). These profiles are computed for spherical envelopes surrounding a single star, and neglecting collisional excitation. Hence we can expect only a very rough indication of the properties of the envelope in our particular case.

One striking characteristic of our profiles is that the intensity left at $v = v_{term}$ is almost zero, and this indicates a high value for the total optical depth of the envelope. But the higher the total optical depthis, the higher the expected intensity of the emission wing; but this is missing on our spectra. The effect of collisional excitation is to increase still more the intensity of the emission. The only way out is to admit that a strong absorption stellar line is present. The theoretical profile computed on this hypothesis explains our observations. But what are the implications of this assumption? The photospheric lines neutralizing the envelope emissions cannot be formed in the primary, whose temperature is lower than 10^4 K. Only supergiants earlier than B5 or main sequence stars earlier than B1 present absorption profiles of N V (Snow and Jenkins 1977). Hence the photospheric lines of N V, C IV and Si IV must be formed in the hot companion. Its spectral type can be inferred from the distribution of the continuum, taking into account the need to correct for interstellar extinction. Hence we have attempted to fit the observed continuum by combining spectra of early type stars with those of A-F supergiants observed with S2/68 (Jamar et al. 1976). A very good agreement with the observed spectrum (average of spectra at different phases) is obtained by adding the flux of Alpha Cyg (A2 Ia) reddened for E_{B-V} = +0.31 and the flux of Zeta Oph (09.5 V, E_{B-V} = +0.31), reduced by a factor of 35. Hence if the primary is an A-type supergiant, M_V = -7 or -8 (as indicated by the visual spectrum and by the width of the central emission in the Mg II lines), the companion should be an 09 dwarf which at λ1500 has about the same luminosity as the primary, but in the visual is about 100 times less luminous than the primary.

The absorption lines of the highly ionized elements are deeper at phase 0.5, when the secondary is in front, than at the other phases, confirming that the contribution of the spectrum of the secondary is more important at this phase.

The lines formed in the photosphere of the primary star have on the average lower central depths in the far UV than in the near UV; this fact can be explained by the presence of the continuum of the hot companion which fills up the lines of the primary more efficiently at the short than at the long wavelengths.

The terminal velocity of the envelope lines is systematically lower at the quadratures than at the epoch of the minima, suggesting a flow of matter through the lagrangian points L2 and L3.

A model for Upsilon Sgr was discussed by Duvignau et al. (1979). The present data give for the primary M_V -7 and M_{bol} -7.3; for the secondary M_V -2 and M_{bol} -5; R_1 and R_2 are equal to about 120 $R_\odot$ and 3 $R_\odot$ respectively. Since the semi-axis of the orbit of the primary is about 170 $R_\odot$ the system is almost in contact, $(R_1 + R_2)$ / a being about 0.7. The hydrogen deficiency of the primary indicates that it has lost a large amount of mass, and this has been transferred to the companion, producing the thick envelope indicated by the profiles of

C IV, N V, SI IV. If this envelope is associated with the secondary, we should observe the orbital radial velocity shifts in the lines. However, if the two stars have comparable masses, or if the secondary is the more massive one, the shift is too small ($<$0.4 to 0.7 A) to be observable on such broad lines, with such a complex structure.

As discussed by Duvignau et al. (1979), it seems probable that Upsilon Sgr is an example of case C evolution, i.e. the primary reaches the Roche lobe at the end of central He burning.

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COMMENTS FOLLOWING HACK, FLORA AND SANTIN

de Loore: I understand that you invoke case C evolution in order to explain the large helium-hydrogen ratio. However, in my opinion it is possible to explain the evolutionary system by a case B of mass transfer as well, (starting with initial mass of $40M_\odot$ and $10M_\odot$ or masses of $27M_\odot$ and $7\ M_\odot$ with separation of $250R_\odot$ and $500R_\odot$ respectively). Such binaries, considered now at the end of the Roche lobe overflow or having just finished, can explain the circumstellar material and the large He-abundance. Since the probability of case B mass transfer and exchange is so large, one should also think about a case B solution for this case.

Hack: Maybe yes--I was thinking of case C because of the large H-deficiency and the rather long period, $\sim$133 days.

Guinan: During May through November, 1978 Hα wide- and narrow-band and uvby photometry of υ Sgr was done on about 90 nights. The observations were obtained at Biruni Obs., Shiraz Iran by J.D. Donnen, I. Siah, and myself. I hope that all this data will be reduced by September.

Did you obtain data during the light minimum? Were there any changes in the line strengths?

Hack: Yes, I obtained data at the two minima and the two quadratures. The envelope lines are all deeper at phase 0.5. The primary photospheric lines do not show appreciable change events, but just RV-shifts.

Nariai: υ Sgr shows violet-shifted Hα line which corresponds to the velocity of about -200 km/sec for certain phase. What is the relation between this flow and the high-speed flow you have just shown with the far UV spectra?

Hack: The high speed flow ($\sim$800 km/s) is probably wind from the hot O9 companion (and is present at all phases), while the violet-shifted Hα component which is sometimes observed at and near phase 0.5 only is due to a gaseous stream from the primary toward the secondary, projecting itself on the primary disk.