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AN INVESTIGATION OF β PERSEI (ALGOL) IN THE *IUE* ULTRAVIOLET

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RESUMEN. Un estudio de imágenes ultravioletas de β Persei obtenidas en distintas fases del ciclo orbital, sugiere que en el sistema existen fuentes no térmicas de energía así como, quizás, dos regiones de temperatura electrónica elevada. Esta conclusión es similar a las que derivaran previamente Sahade y Ferrer para AU Monocerotis, y Sahade y Hernández para γ_1 Velorum. El continuo ultravioleta proviene de la componente A del sistema, y todas las líneas del espectro ultravioleta, excepto quizás las de resonancia de C IV, participan del movimiento de esta componente B8 V.

ABSTRACT. A study of ultraviolet images of β Persei secured at different phases in the orbital cycle suggests that there are non-thermal sources of energy and perhaps two regions of high electron temperature in the system, similarly to what Sahade and Ferrer and Sahade and Hernández had previously suggested in the cases of AU Monocerotis and of γ_1 Velorum, respectively. The ultraviolet continuum comes from component A of the system, and all ultraviolet lines, except perhaps the resonance lines of C IV, share the motion of this B8 V component.

I. INTRODUCTION

β Persei [26 Persei = Algol = HR 936 = HD 19356 = SAO 38592 = BD+40°0673 = ADS 2362; $\alpha = 3^h\ 04^m\ 54^s$; $\delta = +40°\ 46'.0$ (1950.0); B = 2.0-3.3 mag.], the first eclipsing variable to be discovered, is actually a triple system. Components A and B form a spectroscopic binary with a period of 2.87 days, and the close system AB and component C orbit around the center of gravity they define, with a period of 1.862 years. The primary eclipse in the spectroscopic pair is a partial occultation, the inclination of the orbit being 81°.2 (cf. Koch, Plavec and Wood 1970).

Component A is the brightest one and its spectral type is B8 V; component C is an Am star that differs from component A by nearly 2 magnitudes (Huang 1957), and component B is some 3 magnitudes fainter than A. Component B is probably a late G or an early K subgiant, that has been spectroscopically detected in the Na I-D lines (Tomkin and Lambert 1978) and is in contact with its inner Lagrangian surface (Guinan *et al.* 1976). The lines of component C are observed during primary eclipse of the system AB, superimposed upon the spectrum of component A (Meltzer 1956 a, b).

The photographic spectrum of β Per displays H emission at quadratures (Struve and Sahade 1957, Sahade 1958, Andrews 1967), thus suggesting that the object AB is an interacting system. Guinan *et al.* (1976) estimated that the circumstellar material *extends to a distance 2.6 times the radius of the hot star and probably fills the Roche lobe of this component.*

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In addition, β Per was found to be a radiosource (Wade and Hjellming 1972) that is strongly variable, particularly in the range of higher frequencies, and displays a very high level of flaring activity (cf. Hjellming 1976). The question as to where the radioemission detected does arise in the system was answered by Ryle and Elsmore (1973), who were able to ascertain that the source of the radioemission was connected with the close pair AB and not with component C.

The radio observations have been interpreted by Woodsworth and Hughes (1976) in terms of two components, namely, a) a thermal component arising from a region of a radius much larger than the size of system AB, and b) *a nonthermal flare component probably associated with the region of mass exchange*.

VLBI observations of a flare at 7850 MHz (3.8 cm) by Clark *et al.* (1976) have suggested that the radiosource associated with the flare *has a size comparable to those of the individual stars of the close pair and is most likely nonthermal in origin.* In addition, Clark *et al.* concluded that *any possible expansion of the apparent size of the radiosource during the decay of the last flare observed had a velocity not greater than about 100 km/s.*

In 1975, β Per was found to be also a soft X-ray source at the 0.15-6 KeV range, with the SAS-3 X-ray observatory (Schnopper *et al.* 1976), and with an experiment on board an Aerobee rocket in the 0.15-2 KeV range (Harnden *et al.* 1977). Harnden *et al.* stated that the X-ray luminosity probably varies in the range $L_X \approx 10^{31} - 10^{33}$ ergs s^{-1} and suggested that the X-ray flux results from accretion of mass from component B to component A, and that *radio flares could be caused by interaction of the streaming matter with regions of strong magnetic field on the B8 star.* On the other hand, Florkowski (1980) has suggested that the location of the nonthermal radio component and of the X radiation is in the region where matter that is lost to the system through the external Lagrangian point L^3 interacts with the system's outer envelope.

β Per has been investigated in the ultraviolet, particularly in regard to the behaviour of the resonance lines of Mg II. From observations made with the OAO-3 *Copernicus* satellite, Chen and Wood (1976) found the resonance lines of Mg II to be double *near minimum light*, and Cugier and Chen (1977) found them to have red wings in the phase interval 0.90-0.03 P, such wings being interpreted as arising in a gaseous stream from component B towards component A in the system. On a scan made at phase 0.04 P, a P Cygni profile was detected (Chen, Wood and Barker 1981). Let us mention that the phases quoted were computed by the respective authors by considering two times of minimum estimated from observations at 3428 A, and a value for the period of 2.86740 days (Chen and Wood 1976).

No magnetic field (Borra and Landstreet 1978) nor polarization (cf. Pfeiffer and Koch 1977) have been detected in β Per. Frieboes-Conde *et al.* (1970) have derived a distance of 25 pc for the system.

II. THE OBSERVATIONS

In order to learn more about as interesting a binary as β Per, in particular about its outer envelope, one of us (J.S.) included it on his observing program with the IUE satellite, in December, 1978-January , 1979. The images, that are listed in Table 1, were secured in the high dispersion mode, with small aperture, from the ground observatory at NASA's Goddard Space Flight Center, in Greenbelt, Maryland, U.S.A.

In addition we had at disposal the results of the examination and comparison carried out by one of us (J.S.) at the IUE RDAF, of *selected regions* of the IUE high dispersion images of the star, available at the NASA Goddard Space Flight Center archives. The phases represented on the available images are, in fraction of P, 0.0037, 0.0044, 0.0073, 0.0115, 0.0178, 0.0195, 0.0212, 0.0342, 0.0981, 0.3459, 0.5090, 0.6526, 0.7837, 0.9834, and 0.9954, for the SWP (short wavelength prime camera; range: 1165-2126 A) images, and 0.0059, 0.0059, 0.0193, 0.0193, 0.0212, 0.0322, 0.0964, 0.3364, 0.3442, 0.5103, 0.6685, 0.7849, and 0.9846, for the LWR (long wavelength redundant camera; range: 1845-3230 A) images, if we compute the phases by using the expression for the epoch of primary minimum suggested by Frieboes-Conde *et al.* (1970). A few of these images were used to determine radial velocities, particularly of the resonance lines of Si IV, and, in some cases, of the resonance line of C IV at 1548 A.

The phases we have computed differ from those determined with Chen and Wood's elements by +0.008P to +0.012P, in the sense Frieboes-Conde *et al.*'s phases minus Chen and Wood's phases.

III. THE ULTRAVIOLET SPECTRUM

A. *The Continuous Spectrum.* Because of the fact that all IUE images were taken with small aperture, the continuum of β Per was determined, in arbitrary units, through application of *Cassatella et al.*'s (1981) calibration method for high dispersion by considering E_{B-V}= 0.00 and by shifting vertically the LWR plot. The adoption of E_{B-V}= 0.00 rather than the value of E_{B-V}= 0.06 quoted in Jamar *et al.*'s *Catalogue* was due to the fact that is yielded a better matching between the two IUE regions.

TABLE 1

IUE IMAGES OF β PERSEI

Image*	Start Exposure Time Year	Day	Hour	Min.	Exp. Time (Seconds)	Phase** (P)
LWR 3328	1978	364	19	12	60	0.336
LWR 3329		364	19	45	40	0.344
SWP 3752	1978	364	19	52	80	0.346
SWP 3771	1979	1	17	09	210	0.004
LWR 3349		1	17	16	75	0.006
SWP 3772		1	18	05	150	0.018
LWR 3350		1	18	12	75	0.019
SWP 3774		3	22	48	70	0.784
LWR 3374		3	22	53	30	0.785
SWP 3818		6	00	43	50	0.509
LWR 3398	1979	6	00	48	35	0.510

* The images were taken with small aperture
LWR: long wavelength redundant camera; range: 1845-3230 A
SWP: short wavelength prime camera; range: 1165-2126 A

** The phases were computed from the expression
Princ. Min. = JD 2,434,705.5493 + 2.86732442 x E days (Frieboes-Conde *et al.* 1970), that is, they are counted from the conjunction at which the B8 V star is behind component B of the system.

The comparison of the continuum for images SWP 3752+LWR 3329 with Kurucz's (1979) LTE model atmosphere calculations, illustrated in Fig. 1, finds its best fit for T_e= 12000° and

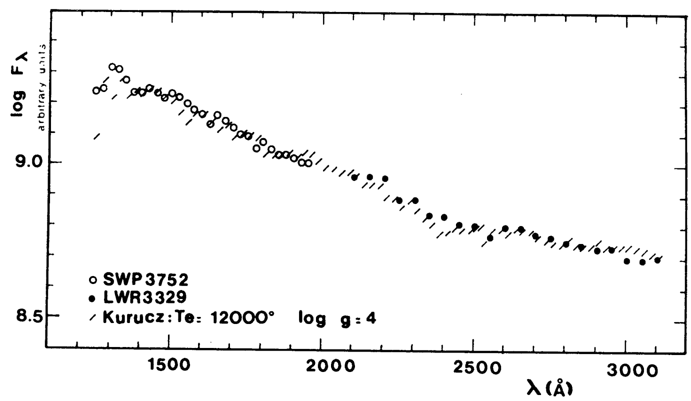

Fig. 1. Ultraviolet continuous spectrum of β Persei compared with Kurucz's LTE model calculation.

log g = 4, parameters which are those of a B8 V star (Böhm-Vitense 1981). Therefore, the ultraviolet continuum corresponds to component A of the system, the component which is eclipsed at primary minimum.

B. *The Line Spectrum*

B.1. Elements and Ions Present. Our IUE spectra of β Per are purely absorption spectra. The elements and ions present are
H*, C I, C II, C III, C IV*, N I, O I, Mg I*, Mg II, Al II, Al III, Si II, Si III, Si IV*, S II, Cr II, Cr III, Mn II, Mn III, Fe II, Fe III and Ni II, a list where the asterisk (*) indicates that only resonance lines are displayed.

It is not certain whether the resonance lines of N V are present, if they are present, their intensity must be very low; at any rate, the feature at λ1243 A is strongly dominated by N I (5).

The resonance lines of Si IV are strong at some phases and we shall refer to them in subsection B.3. As far as the resonance lines of C IV is concerned, they are weak and the feature at 1550 A is blended with Fe III.

The FWHM values are of the order of 0.5 A, although in the case of Si IV they may be a bit larger. There are no sharp lines on our spectra.

Figs. 2 and 3 illustrate the profiles of the resonance lines of Si IV and C IV, respectively.

B.2. Behaviour in Velocity. The behaviour of the lines that are unblended, of O I, Si II, Si III, Al II, Ni II, Fe II and Mg II, velocity-wise, is in keeping with the orbital motion of the B8 V component, and the velocity amplitude that is suggested agrees with the value determined from the measurement of photographic spectra by Ebbighausen and Gange (1963) and by Hill *et al.* (1971), namely, 44 km/s. This statement holds true for the resonance lines of Si IV, while the radial velocities from C IV 1548 are all negative, -21±6.3 (M.S.E.) km/s on the mean, at the six phases that are represented in the measures.

Table 2 lists the derived radial velocities, and Fig. 4 shows separate plots for the average values from all elements and ions, except Si IV and C IV, for Fe II, for Si IV and for C IV.

TABLE 2

RADIAL VELOCITIES FROM ULTRAVIOLET LINES IN β PERSEI

Phase (P) / Element, Ion	0.995	0.004	0.006	0.011	0.018	0.020	0.034	0.098
O I		+22(1)			-13(1)			
Si II	+12(1)	+24(7)			- 4(7)	-25(2)		
Si III		+14(3)			- 2(3)			
Al II		-13(3)			-14(3)			
Ni II		+30(1)			+ 8(2)			
Fe II		+28(20)	+ 8(9)		+ 4(22)			
Mg II			+ 1(4)					
Si IV				-25(1)	-33(2)		-49(2)	-22(2)
C IV		-12(1)			- 5(1)	-26(1)		

Phase (P) / Element, Ion	0.336	0.344	0.346	0.509	0.510	0.653	0.784	0.785
O I			-47(1)	-14(1)			+56(1)	
Si II			-32(6)	+ 3(7)		+15(2)	+59(7)	
Si III			-54(3)	- 7(3)			+50(3)	
Al II			-44(2)	- 1(3)			+52(3)	
Ni II			-43(2)	+ 5(1)			+54(2)	
Fe II	-38(9)	-33(9)	-32(22)	+ 6(20)	+12(9)		+57(22)	+71(8)
Mg II	-36(4)	-34(4)			+12(3)			+67(4)

TABLE 2 (continued)

Phase (P)	0.336	0.344	0.346	0.509	0.510	0.653	0.784	0.785
Element, Ion								
Si IV			-38(2)			+18(2)	+47(2)	
C IV			-48(1)			-23(1)	-11(1)	

The numbers in parentheses indicate the number of lines measured

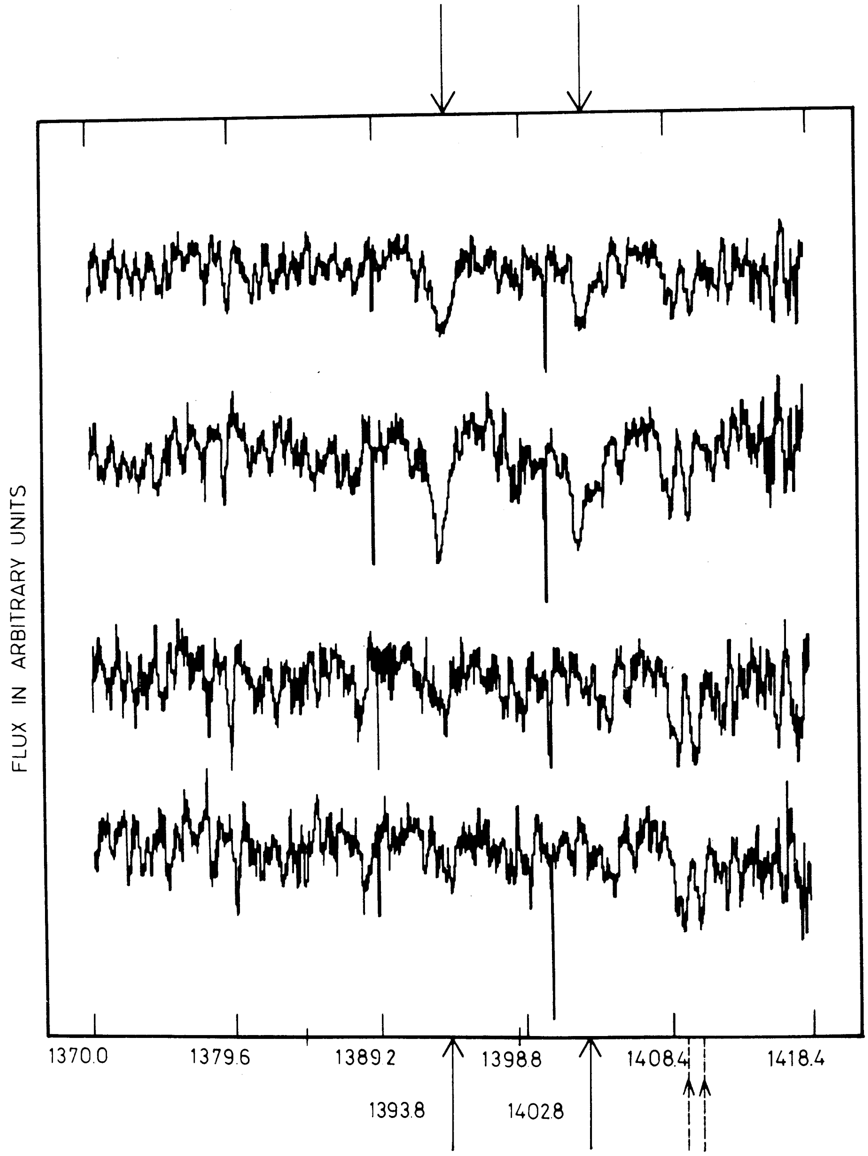

Fig. 2. The resonance lines of Si IV (indicated by full line arrows) and Si II 1409 and Si II 1410 (indicated by broken line arrows) at phases 0.995, 0.098, 0.653 and 0.784 P, respectively, from the top down.

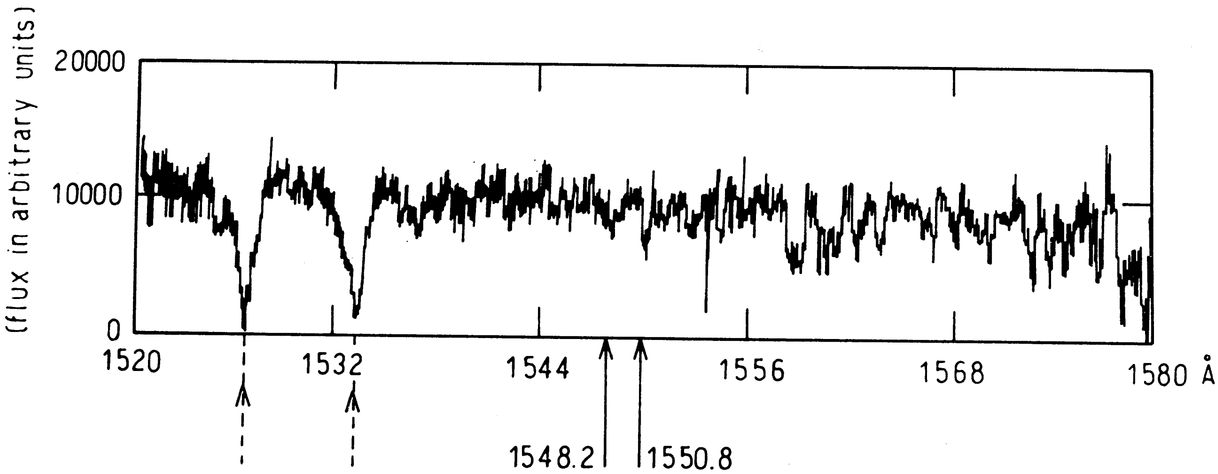

Fig. 3. The region of λλ 1520-1580 A in the spectrum of β Persei where we have indicated with full line arrows the position of the resonance lines of C IV, and with broken line arrows the Si II lines at 1527 and 1533 A. The spectrum corresponds to phase 0.011 P.

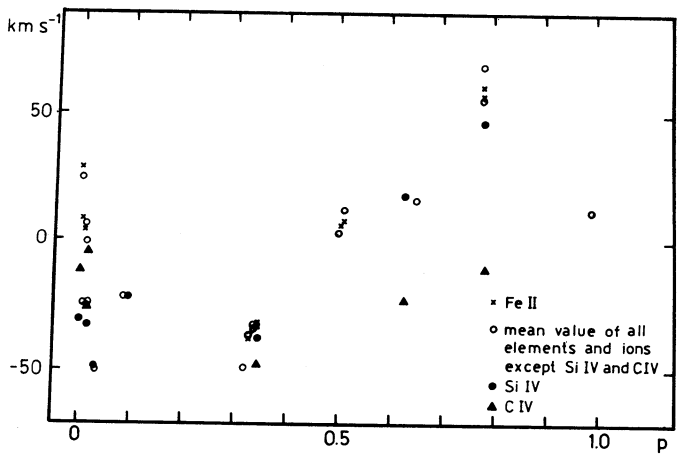

Fig. 4. Radial velocities from unblended lines in the ultraviolet spectrum of β Persei.

B.3. Behaviour in Intensity. The work done at the IUE RDAF, which, as we mentioned, refers to only selected spectral regions, permits us to conclude that there are variations in line intensity in the ultraviolet spectrum of β Per. The variations that we were able to detect can be summarized as follows:

1) The resonance lines of Si IV are stronger at around principal minimum;

2) The lines of Si II of multiplet 13.02, at 1409 and 1410 A, appear to vary in antiphase with the resonance lines of Si IV, while the Si II lines of multiplet 2, at 1527 and 1533 A, which arise from zero or very low energy levels, do not seem to show any changes;

3) The resonance lines of C IV do not appear to undergo noticeable changes in intensity.

B.4. Profile variations in the resonance lines of Mg II. On the IUE long wavelength material, which comprises thirteen images, the resonance lines of Mg II display variations which are illustrated in Fig. 5. The profiles seem to follow the following trend, namely,

a) in our phase inverval 0.501-0.985 P, the profiles are normal;
b) in our phase interval 0.019-0.032 P, the lines are unsymmetrical and their central cores suggest that they are double;
c) on our images at phases 0.096, 0.336 and 0.344 P, the central core is broad.

The behaviour reported in b) agrees with Chen and Wood's (1976) observations, and our interpretation of the double lines is that we are observing the Mg II line from component C, as it is true at Mg II 4481 during minimum. The assymetries appear to be right for the expected radial velocity of component C.

As for profiles described in c), they might indicate some kind of a turbulence on the advancing hemisphere of component A.

IV. DISCUSSION

In β Per we find, as it was the case in AU Mon (Sahade and Ferrer 1982) and in γ_1 Vel (Sahade and Hernández 1984) and it seems to be true in all interacting binaries, the presence in the ultraviolet spectrum of the resonance lines of Si IV and C IV; whether they are in absorption or in emission might be connected with the dimensions and/or the opacity of the responsible regions. Since these lines imply the existence, in the gaseous envelope around the systems, of regions with electron temperatures of the order of 10^5, and such temperatures cannot be accounted for by the stellar radiation field -which, in the ultraviolet, is essentially that of the primary component- we have to conclude, here again, that in β Per there are sources of nonthermal energy. This conclusion is further strengthened by the fact that β Per is an X-ray emitter.

One question that immediately arises concerns the location of the high temperature regions.

In β Lyrae, the combination of the photometric (analyzed by Kondo *et al.* 1976) and spectroscopic ultraviolet observations led Hack *et al.* (1976) to conclude that the resonance lines of C IV and Si IV form in the neighborhood of the secondary component of the system. On the other hand, N V would arise in the outer envelope of the binary.

In the case of AU Mon the different profiles of the resonance lines of N V, C IV and Si IV led Sahade and Ferrer (1982) to suggest that C IV originates close to the primary component of the system, while Si IV and N V would arise farther out in the extended envelope. A similar interpretation was advanced by Sahade and Hernández (1984) for γ_1 Vel.

What can we say in the case of β Per?

Our observations cover several phases in the orbital cycle. This fact has allowed us to describe the behaviour of the ultraviolet spectrum from the point of view of the radial velocities, as we have reported in subsection B.2. According to the results depicted in Fig. 4, we can conclude that in β Per the ultraviolet lines, including the resonance lines of Si IV and excluding the resonance lines of C IV, originate in regions that share the motion of component A of the system and should be located not very far from the star itself.

Regarding C IV, its behaviour velocity-wise would appear to suggest that the resonance lines of this ion would form in a region of the extended envelope that surrounds the whole system.

In consequence, our IUE observations of β Per would seem to provide evidence, through the behaviour in radial velocity of the resonance lines of Si IV and C IV, that in the gaseous envelope in which the spectroscopic system is embedded, there exist two distinct regions

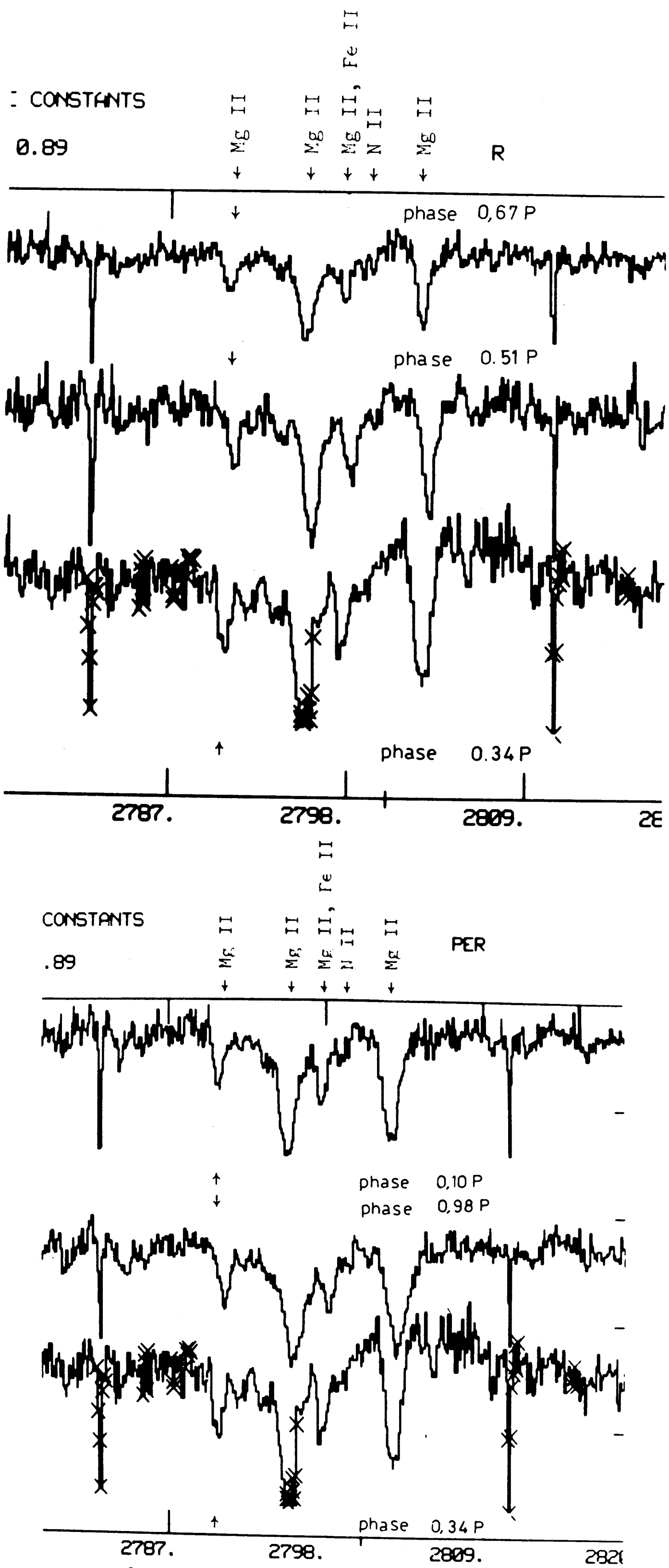

Fig. 5. The spectrum of β Persei at the resonance lines of Mg II, at different phases in the orbital cycle.

characterized by high electron temperatures. This would confirm very nicely the interpretations proposed by Sahade and Ferrer (1982) and by Sahade and Hernández (1984) for the existence of two high temperature regions in the gaseous envelopes of AU Mon and γ_1 Vel.

Unfortunately, this apparent confirmation rests heavily upon the only two radial velocity values we have in the second half of the orbital cycle, from 0.5P to 1.0P, and, therefore, a better coverage of this phase interval with ultraviolet observations is urgently needed to ascertain the conclusion that seems to arise from our material.

Does the behaviour in intensity of C IV and of Si IV add anything or is it in keeping with the conclusion about two high temperature regions? As we have mentioned in subsection B.3, C IV does not seem to vary in intensity throughout the orbital cycle and this would mean that the layers of the gaseous envelope where C IV form have an homogeneous density all around the system. On the other hand, the behaviour of Si IV seems to suggest that the number of absorbing Si IV ions is larger in the region between the two components of the close pair.

The behaviour of C IV intensity-wise, would seem to lend strong support to the conclusion that comes out from the consideration of the behaviour in radial velocity, but here again it would be desirable to have a better coverage of the second half of the orbital cycle.

The nonthermal radio component of β Per and the X radiation are probably associated with, at least, one of our two high temperature regions.

In regard to the question of the origin of the high temperature regions, Sahade and Ferrer, in their paper on AU Mon, suggested that they would result from the dissipation of shock waves produced when the gaseous stream from component B interacts with the ring or disk that surrounds component B (cf. Lubow and Shu 1975, Shu 1976), and when the matter that is being lost to the system interacts with the outer envelope (cf. Florkowski 1980). The same explanation appears to be valid for the case of β Per, particularly in view of the fact that X emission is produced. Since component A is a B8 V star and we do not have any compact object in the system, accretion does not seem to be a mechanism that could produce the necessary temperature. Moreover, if one high electron temperature regions is located in the outer layers of the extended envelope, the dissipation of shock waves appears to be a more likely mechanism to account for it.

We shall not attempt to deal with an interpretation of the behaviour of the Si II lines until we are able to analyze the behaviour of the rest of the Si II lines in the spectrum of β Per.

V. CONCLUSIONS

The ultraviolet observations we have analyzed in the present investigation allow us to conclude that

1) β Per is another interacting binary for which the ultraviolet spectra give evidence for the existence of nonthermal sources in the system;

2) All the IUE ultraviolet lines, except perhaps the resonance lines of C IV, are produced within the gravitational domain of the B8 V component, which is also the source of the ultraviolet continuum;

3) β Per, through the behaviour of the radial velocities and line intensities with phase, seems to provide evidence for the existence of two regions of high electron temperature in the system, thus supporting the models proposed in the cases of AU Mon and γ_1 Vel;

4) The high electron temperature regions probably result from the dissipation of shock waves.

A better coverage of the second half of the orbital cycle (0.5P to 1.0P) with ultraviolet observations is badly needed to ascertain conclusion 3). An attempt will be made to secure such observations.

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