THE BEHAVIOUR OF THE ATMOSPHERE OF σ SCORPII

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RESUMEN. La estrella de tipo β CMa, σ Scorpii, ha sido observada espectroscópicamente, cubriéndose dos ciclos. Se ha encontrado que las líneas de absorción que representan distintas profundidades en la atmósfera (excluyendo la región de transición) dan curvas diferentes de velocidad radial; las amplitudes decrecen y los valores de γ se hacen más negativos en las capas más exteriores. Ca II λ3933 tiene una componente cromosférica.

ABSTRACT. The β CMa star σ Scorpii has been observed spectroscopically along two cycles. It has been found that absorption lines representing different depths in the atmosphere (excluding the transition region) yield different radial velocity curves; the amplitudes decrease and the γ's become more negative in the outermost layers. Ca II λ3933 A has a chromospheric component.

I. INTRODUCTION

σ Scorpii (HD 147165; $\alpha = 16^h18^m\!.1$, $\delta = -25°28'$ (1950.0)) is a well studied β CMa star (Huang and Struve 1955, Struve *et al.* 1955, Struve *et al.* 1961). The spectral type is B1 III and the visual apparent magnitude is V = 2.9 mag. The period of the light and the radial velocity variation is P = 5.55 hours; the amplitude of the radial velocity curve is about 100 km/s and the amplitude of the light variation amounts to 0.08 mag (Struve and Zebergs 1955). σ Sco is a member of a close binary system, the orbital period of which seems to be 34.2 days (cf. Batten *et al.* 1978).

Recently Burger *et al.* (1981) have disclosed, from IUE ultraviolet observations, that the resonance lines of Si IV and C IV, that originate in the transition region, yield different accelerations; they estimated a value for the mass-loss of $\dot{\mathfrak{M}}$ = 1.6E-7 $\mathfrak{M}_\odot$/yr.

II. THE OBSERVATIONS

In order to obtain information on the behaviour of lines formed in different atmospheric regions, one of us (A.E.R.) has observed the star at the coudé focus of the 1.5-m-reflector of the Cerro Tololo Interamerican Observatory, in Chile, trying to secure an homogeneous group of good quality plates in acceptable dispersion and with short exposure times. Thirty nine spectra were obtained; exposure times were, on the mean, 3 E-2 times the period; the dispersion, 9 A/mm and the emulsion was Kodak III a-J. Information on the observational material is given in Table 1. The period of 5.5 hours of the radial velocity variation was covered twice, once in one

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night (July 18, 1981); the second coverage was attained through observations on two different nights (July 21 and July 24, 1981). The spectra were analysed with a Grant comparator and the data processed with the FAPES software prepared by Juan M. Fontenla for the IAFE's PDP 11/44

TABLE 1

OBSERVATIONAL MATERIAL

PLATE		J. D. +24448	EXP. TIME (minutes)
D1245		04.4664	7
D1246	a	04.4768	7
	b	04.4844	7
	c	04.4921	8
	d	04.5004	8
	e	05.5093	9
	f	05.5184	9
	g	05.5281	10
	i	05.5385	11
D1247	a	05.5538	9
	b	05.5663	9
	c	05.5788	9
	d	05.5878	10
	e	05.6003	10
	f	05.6086	10
	g	05.6191	9
	i	05.6427	9
D1248	a	05.6566	10
	b	05.6657	10
	c	05.6739	9
	d	05.6829	10
	e	05.6913	9
D1254	a	07.7397	11
	b	07.7501	12
	c	07.7619	10
	d	07.7731	10
	e	07.7842	16
D1258	a	08.7563	21
	b	08.7785	38
D1264	a	10.6228	10
	b	10.6312	10
	c	10.6395	9
	d	10.6485	8
	e	10.6555	9
	f	10.6638	9
	g	10.6707	8
	i	10.6791	8
D1265	a	10.6895	9
	b	10.6971	8
	c	10.7048	8

computer. All radial velocities obtained were corrected for the Earth's orbital motion and for the binary orbital motion. Radial velocities were measured by considering the whole profile except the deepest part of the nucleus (values of Ir < Irmax/2, where Ir = (Ic-II)/Ic, Ic and II being the intensities on the continuum and on the line). The error of a single determination is, on the mean less than 5 km/sec.

III. DISCUSSION

We shall consider in our discussion the lines that seemed to be formed in different regions of the atmosphere of the star.

a) The Silicon Lines

From Kamp's (1973) non-LTE calculations for Si III-IV we can select the models for log g = 4 and T = 25 E3 K and log g = 4 and T = 30 E3 K which are the most appropiated ones available to represent σ Sco.

According to Kamp's models, a) Si V λ 4088 A would form deep in the atmosphere, due to the fractional population and the fact that the optical depth of the line center equals unity in a region very close to the region where the continuum at λ 4089 A forms; b) Si III λ 1294 A would originate in the very outer layers of the stellar atmosphere.

b) The Helium Lines

The He I lines at λ 3867 A and at λ 3819 A must arise in a region intermediate to those of Si IV λ 4088 A and Si III λ 1294 A, for three reasons, namely, 1) according to Johnson and Poland (1969) the He I 2 $^2p^0$ level, for T = 2-3 E4 K, is practically in LTE for τ_c(4000 A) $\simeq$ 2 E-2; 2) in the atmosphere, the velocity gradients are small; 3) on account of the Eddington-Barbier relation (cf. Mihalas 1978), and allowing for the differences in population and abundance of Si IV and He I and the values of the gf's, the He I transitions must attain τ = 1 at much shorter distance from the atmosphere's border (the distance would be shorter for λ 3819 than for λ 3867).

TABLE 2

ENERGY LEVELS AND gf'S OF THE TRANSITIONS SELECTED

ION	λ(A)	gf(1)	Xi(ev)	Xl(ev)
SiIII	1294	0.70	33.492	6.51
SiIV	1393	1.08	45.141	0.00
SiIV	1402	0.54	45.141	0.00
CIV	1448	0.38	64.492	0.00
CIV	1550	0.19	64.492	0.00
HeI	3867	0.02	24.587	20.87
HeI	3819	0.19	24.587	20.87
CaII	3933	1.38	11.871	0.00
OII	4075		35.11	25.55
SiIV	4088	1.56	45.141	23.95

Xi=ionization potencial
Xl=energy of the lower level of the transition
(1) gf's values from Morton (1973)

Table 2 lists the lines selected for our analysis. We have included Ca II λ 3933 A because it seems to be associated with the star. The radial velocities obtained from those lines are given in Table 3 and plotted in Figs. 1-4. For each velocity curve, the adopted value of γ is the velocity value at phase Y, which is defined by the expression

$$\int_0^y v_r\, dt + \int_y^P v_r\, dt = 0\ ;$$

for each curve, values of γ, amplitude of the curve and phase of the minimum, are given in Table 4.

TABLE 3

RADIAL VELOCITIES FROM DIFFERENT LINES IN THE SPECTRUM OF σ SCORPII

	LINES (A)				
PHASE	4026	4075	3933	3867	3819
0.00	40	23	6	49	10
0.04	-	-	-	-	6
0.08	-	-	-	-	-
0.1	-	-	-	-	-7
0.14	-	-	-	-	-9
0.18	-	-	-	-	-16
0.21	-	-	-	-14	-
0.25	-	-5	-	-7	-31
0.31	-	-14	-	-16	-30
0.36	9	-10	-46	-85	-101
0.41	-12	-66	-46	-31	-27
0.46	-19	-31	-25	-24	-32
0.49	-7	-32	-	-23	-33
0.55	-8	-25	-33	-14	-22
0.6	-5	-16	-10	-12	-20
0.62	6	-5	-10	-10	-17
0.72	22	14	-1	27	-
0.77	35	16	-12	18	10
0.81	36	19	-8	25	[illegible]
0.84	49	8	7	27	7
0.88	66	8	20	41	12
0.91	-	12	-13	61	27
0.26	-30	-	-21	-31	-40
0.30	-30	-36	-39	-43	-37
0.35	-85	-41	-28	-28	-41
0.39	-26	-64	-25	-39	-47
0.33	-20	-41	-25	-10	-37
0.42	-25	-40	-35	-35	-40
0.89	36	13	3	52	-
0.93	45	28	-1	48	42
0.96	59	46	2	50	-
0.99	66	54	-1	50	27
0.01	53	20	-1	43	29
0.06	21	-	0	14	13
0.08	-5	-14	-2	7	-5
0.12	7	-3	-1	1	-7
0.16	-	-36	-	-5	-24
0.19	-42	-19	-1	-14	-20
0.22	-11	-28	-10	-12	-36

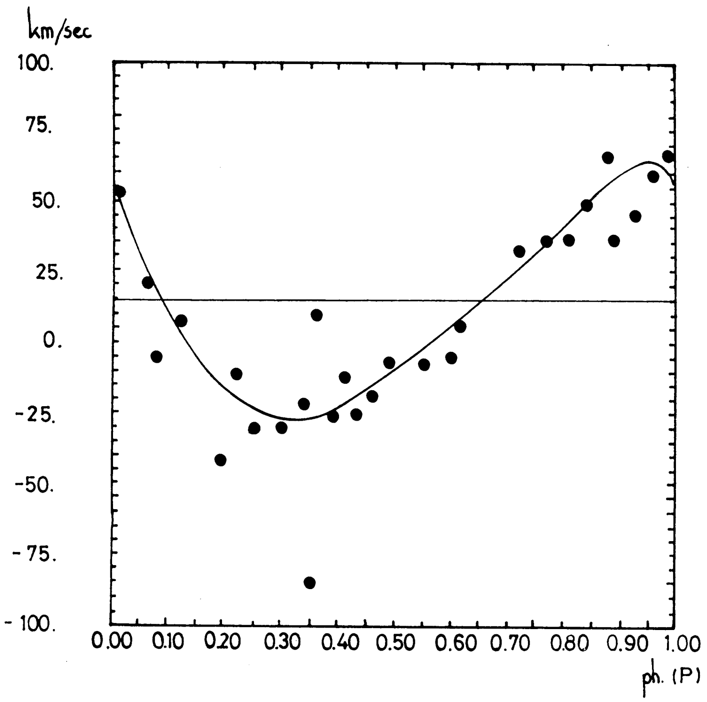

Fig. 1. Radial velocity curve of Si IV λ 4088 A.

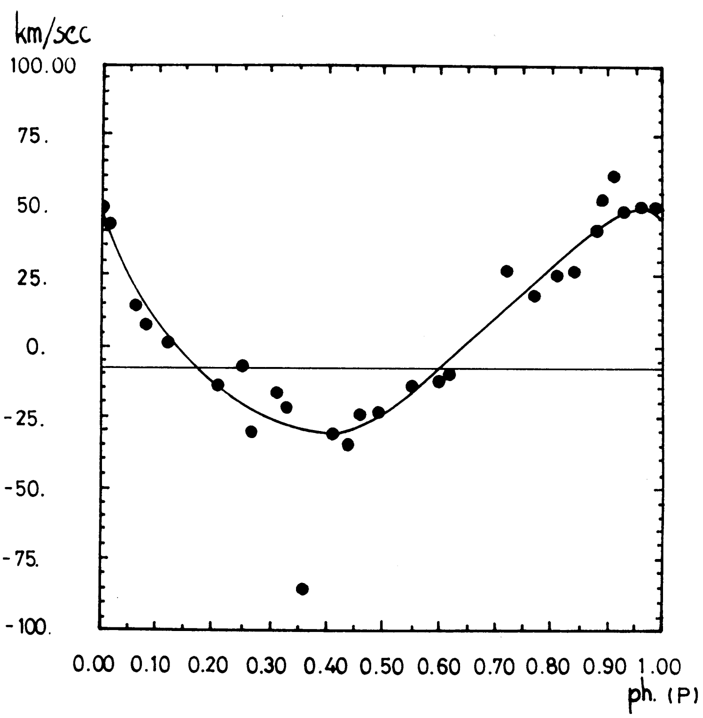

Fig. 2. Radial velocity curve of He I λ 3869 A.

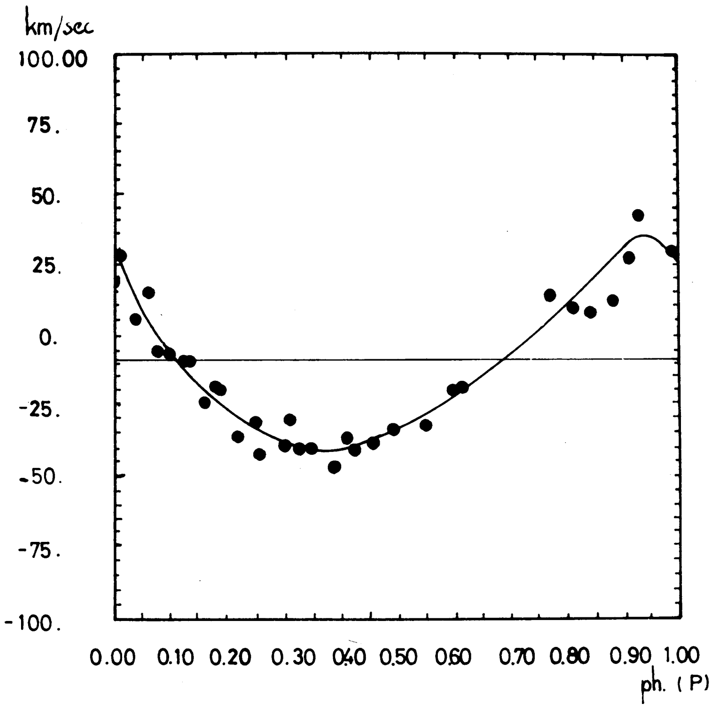

Fig. 3. Radial velocity curve of He I λ 3819 A.

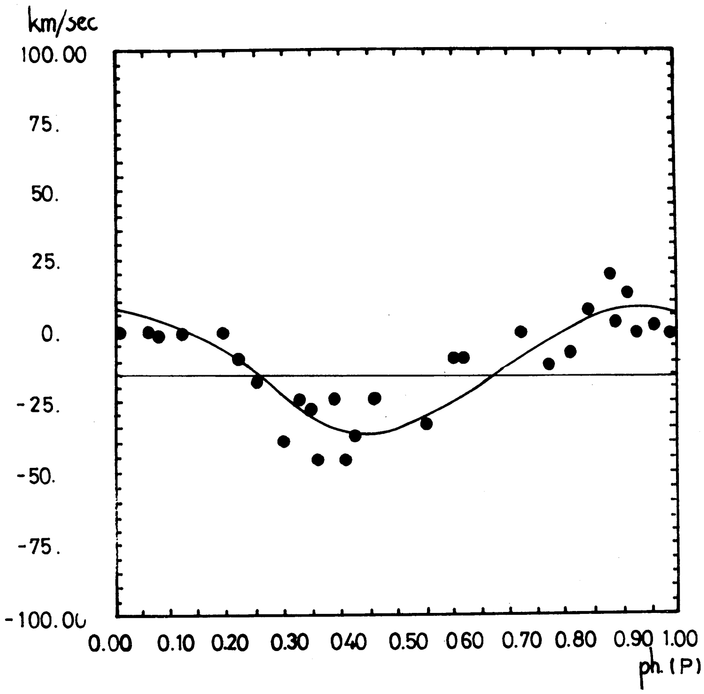

Fig. 4. Radial velocity curve of Ca II λ 3933 A.

From Table 4 we readily see that Si IV λ 4088 A displays the most positive γ, the largest amplitude and the phase of the minimum is the earliest.

TABLE 4

PARAMETERS OF DIFFERENT RADIAL VELOCITY CURVES

LINE ION	LINE λ(A)	γ KM/SEC	A KM/SEC	PHASE OF MINIMUM (P)
Si IV	4088	12	47	0.29
He I	3867	7.5	42	0.38
He I	3819	-8.5	37.5	0.38
Ca II	3933	-15	22.5	0.45

If we establish a sequence of the radial velocity curves in order of decreasing γ we are led to conclude that the phase of the minimum of the curve is a function of γ and that the amplitude of the velocity curve is a function of γ, as shown in Figs. 5 and 6. The examination of Fig. 7, where we have represented all radial velocity curves together, and Table 2, permit us to verify that the sequence Si IV λ 4088 A, He I λ 3867 A, He I λ 3819 A and Ca II 3933 A (a

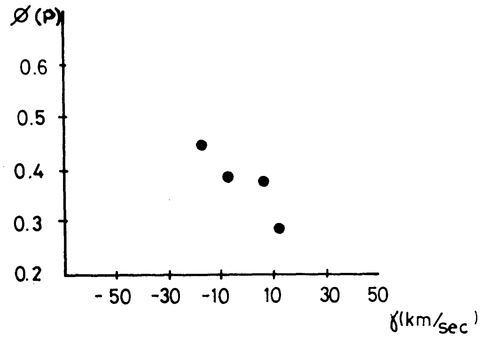

Fig. 5. Phase shift as a function of γ.

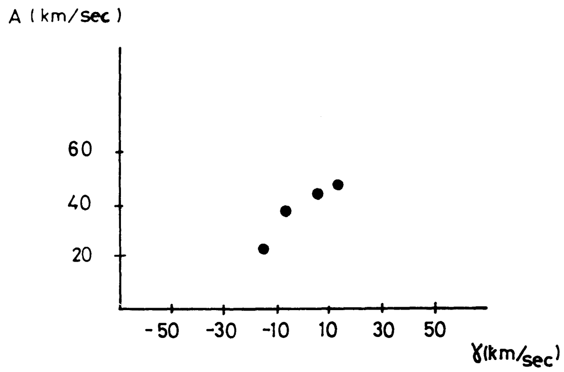

Fig. 6. Amplitude as a function of γ.

sequence in decreasing γ) bears also a relation to atmospheric depth, the deepest region being represented by Si IV λ4088 A. The lines that are formed in the atmosphere, Si IV λ 4088 A, He I λ 3819 A and He I λ3867 A yield, as other authors have noted before, radial velocity curves with a pointed maximum. And we see that the radial velocity curve obtained from the line originating outside the atmosphere, Ca II λ 3933 A, presents a rounded top. From these observations we conclude that a) in the atmosphere, the expansion velocity increases from the inner boundary to the outer boundary; b) in the transition region, the expansion reaches the highest values; c) the shape of the radial velocity curves suggest that there is a discontinuity in the motion, at the outer border of the atmosphere. At this outer border of the atmosphere, the expansion velocity implies a steady mass outflow which comes out to be of the order of 1.E-7 $M_\odot$/yr.

Another interesting result is related to the behaviour of O II λ 4075 A. The velocity curve from this ion is shown in Fig. 8, where the values that correspond to one cycle are indicated with dots, while the values that correspond to another cycle are represented with crosses. We readily see that on the first cycle, a) the positive semiamplitude is smaller, b)

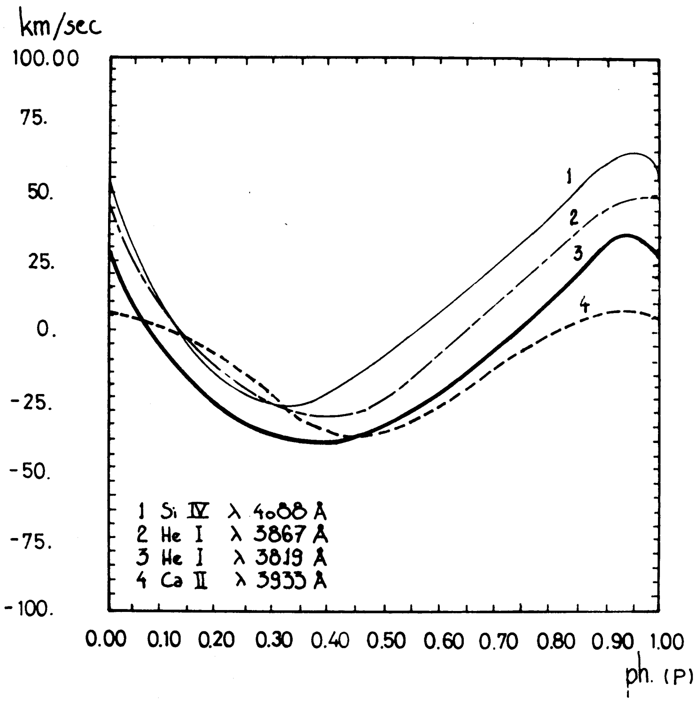

Fig. 7. Sequence of radial velocity curves in order of decreasing γ.

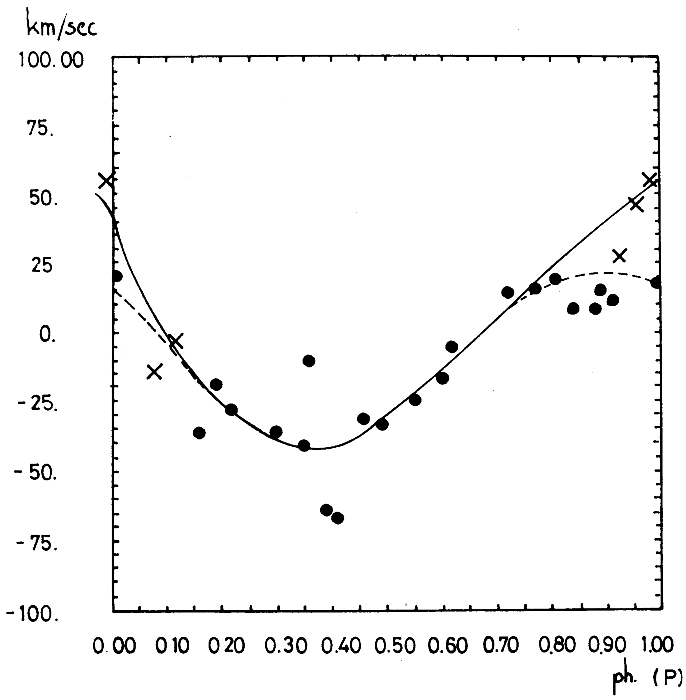

Fig. 8. Radial velocity curve of O II λ4075 A.

the curve is similar to the curve of Ca II λ 3933 A. This would mean that the pulsation, once in a while, breaks down in the contraction phase and the region of line formation behaves like the layers outside the classical atmosphere.

There is still a third point; if we represent the depth of the lines in units of the continuum as a function of phase, we obtain Figs. 9a and 9b, which show the relation for He I λ 3819 A and Si IV λ 4088. In the first case, the result is in keeping with Struve's conclusion (Struve 1955), in the sense that the depth of the absorption lines increases in the ascending branch of the radial velocity curve. In the second case, that of λ 3819 A, it is not evident

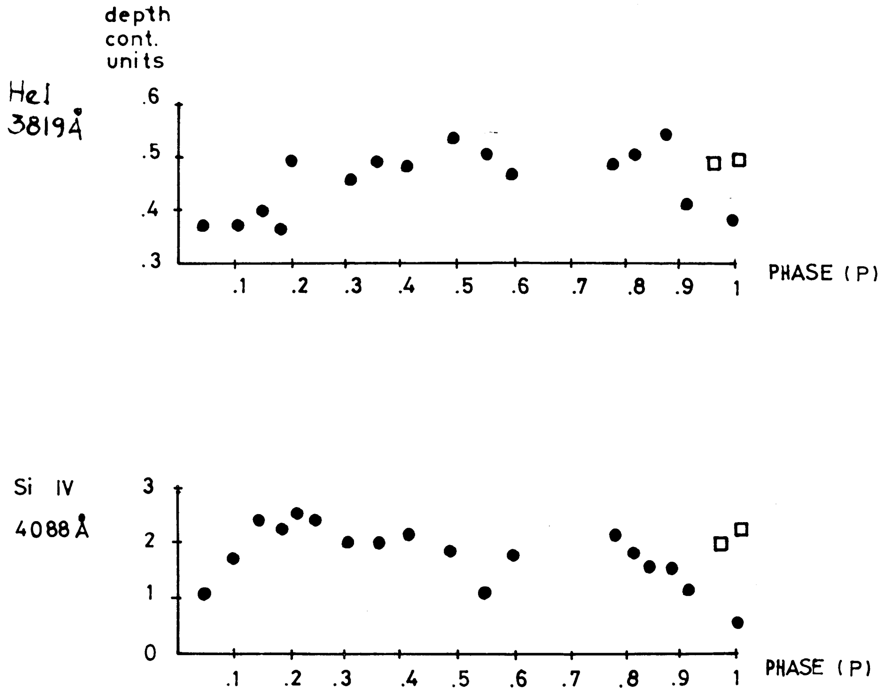

Fig. 9. a) and b) Variation of line depth with phase.

that the relation would be the same; and there is a phase (different for both lines) where the intensity of the line decreases by an important amount; the line profiles at these phases are shown in Figs. 10a and 10b where we have also drawn the profiles at the phases immediately preceding and immediately following the phase presenting the peculiarity. This effect, the flattening of the line profile, is detected, as we have said, at different phases in different lines. We think that this feature is related to the anomalies pointed out by Lesh and Karp (1973) who found that not all profiles of Si III λ 1294 A, on the ascending branch of the radial velocity curve, are narrow. This phase shift of the anomaly is probably correlated to the phase shift of the minima at different atmospheric layers.

A last comment refers to the doubling of the core in the lines of He I and Si IV around phase 0.55P. The effect is observed (as it was the case for the flattening of the profile) at different phases in different lines.

Our results cannot be directly compared with those of Burger *et al.* (1981) on account of the fact that, a) their measurements have been performed in the deep nucleus, b) their time resolution is different and, c) their results refer to a different cycle, and we have seen that lines formed in the outer layers yield, for the radial velocity curve, different amplitudes from one cycle to the other. However, if we consider the lines they analyzed, Si III λ 1294 A (which according to Kamp (1973) is formed in the very outer layers of the atmosphere) and the resonance lines of C IV and Si IV, we see that the velocity curves -reproduced in Figs. 11, 12 and 13, after been corrected for Earth's and binary orbital motion- have amplitudes and phases

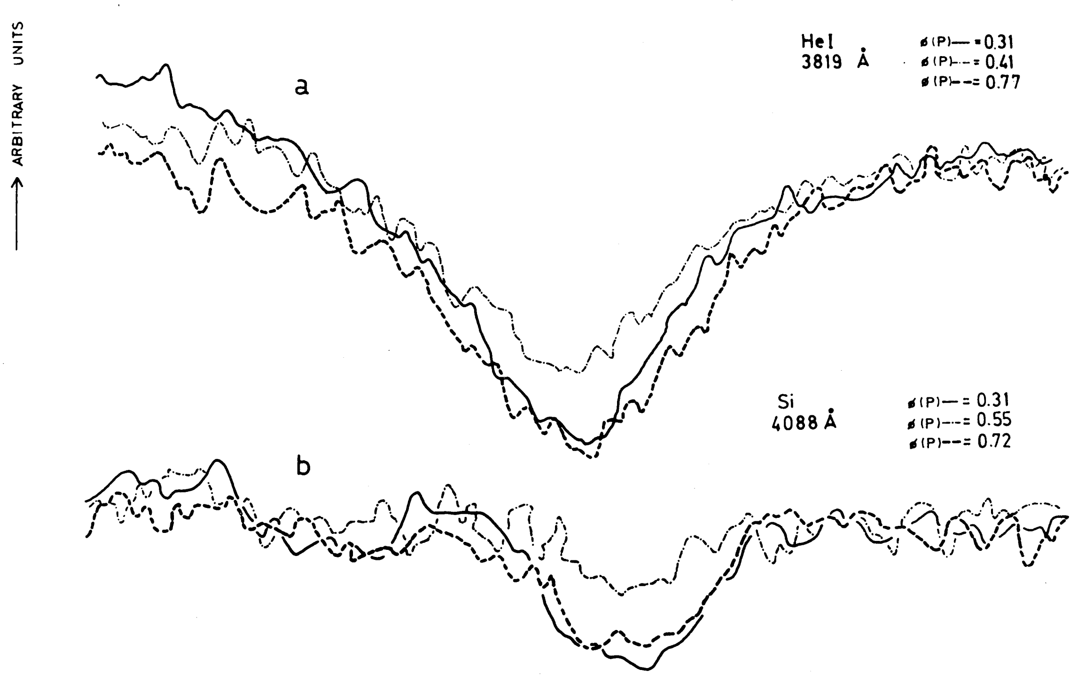

Fig. 10. a) Profiles of He I λ3819 A and b) profiles of Si IV λ4088 A, for three different phases.

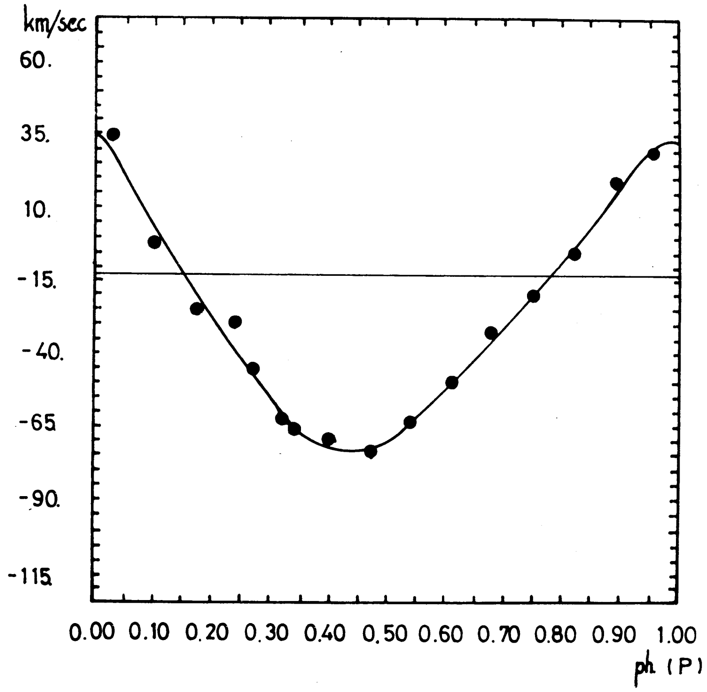

Fig. 11. Radial velocity curve of Si III λ1294 A.

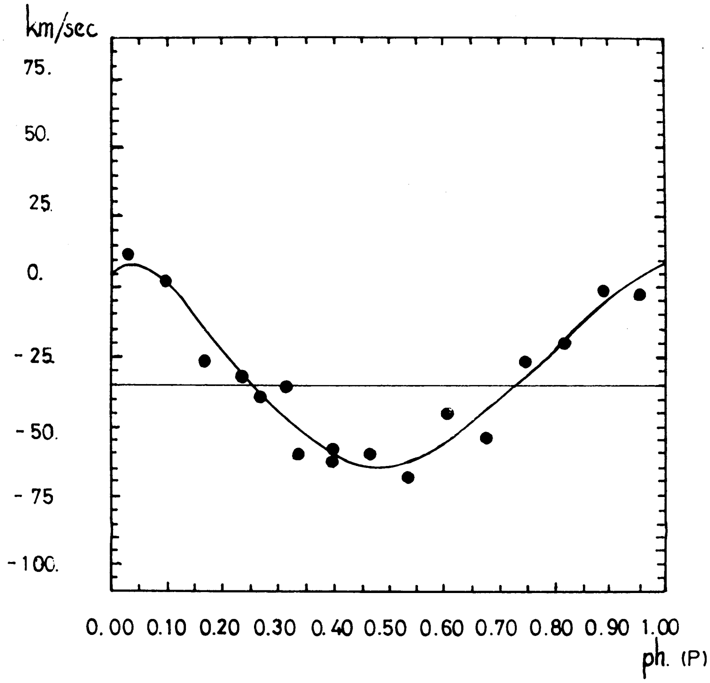

Fig. 12. Radial velocity curve of resonance lines of Si IV.

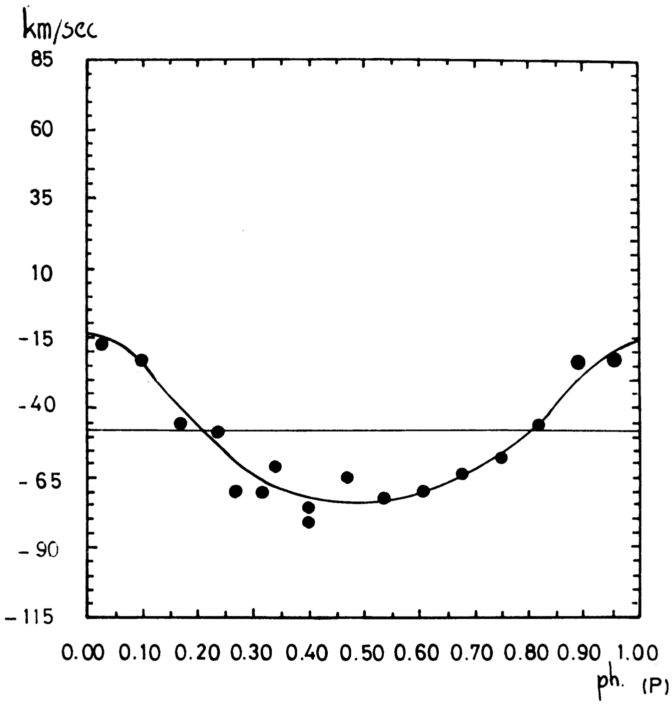

Fig. 13. Radial velocity curve of resonance lines of C IV.

of minimum which are dependent of γ in the same way as our results on Figs. 5 and 6, as can be verified from Table 5.

TABLE 5

PARAMETERS OF CURVES FROM BURGER *et al.* (1981)

LINE		γ	A	PHASE OF MINIMUM
ION	λ(A)	KM/SEC	KM/SEC	(P)
SiIII	1294	-13	55	0.43
SiIV	1393 1402	-35	37.5	0.50
CIV	1443 1550	-47.5	30	0.52

IV. CONCLUSIONS

From the analysis we have made of the 1981 observations of σ Sco we conclude:

1) In atmospheric layers, where $\tau_c < 1$, the amplitude of the pulsations seems to decrease outwards, thus indicating loss of mechanical energy. This amplitude decreases drastically in the chromosphere and transition region.

2) In the same layers $\tau_c < 1$) the value of γ decreases monotically outwards; therefore, a positive acceleration is present.

3) The energy balance from 1) and 2) in our case, is positive.

4) There is a steady outflow of matter which yields mass-loss in the range of values generally accepted for the spectral type.

5) At certain phases, a break-down of the pulsation is observed and this would imply the existence of a non-continuous mass-loss phenomenon which is to be added to the steady outflow of matter.

6) Ca II λ 3933 A has a chromospheric component.

Our conclusions are qualitative statements since we cannot circunscribe, quantitatively, the regions of line formation; in any case, Si IV λ 4088 A, He I λ 3819 A, He I λ 3867 A and Ca II λ 3933 A represent different depths in the atmosphere. The positive energy provided by the decrease in amplitude of the oscillations is not exhausted by the increase in outward acceleration, and the fraction of energy left can contribute significantly to the heating of the transition region. The phase shift of certain features such as minimum of the radial velocity curve, flattening or doubling of the profile, cannot be discussed until a model is worked out. However the phase lag of minima of different radial velocity curves must be related, at least in part, to the energy balance along the atmosphere.

Our results, describing the atmosphere from $\tau_c < 1$ to the border fit the results by Burger *et al.* (1981) and propose the existence of chromospheric Ca II.

Our next step will be to elaborate a model describing the pulsations in the outer layers.

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