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STUDY OF THE SPECTRUM AND RADIAL VELOCITIES OF ζ TAURI IN 1958 AND 1959

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RIASSUNTO. — Si misurano le intensità delle righe spettrali formate nella atmosfera stellare e nell'atmosfera estesa, e si confrontano con precedenti osservazioni eseguite nel periodo 1950-1956. Si trova un massimo di intensità nel 1958; dal 1958 al 1959 le righe dello spettro shell decrescono nuovamente. Si determina la densità elettronica, la diluizione di radiazione e la microturbolenza dell'atmosfera estesa e, per mezzo della relazione di Saha, dall'equilibrio di ionizzazione del Fe I e Fe II si ricava la temperatura di ionizzazione. Si trova: log Ne = 12.39; W = 0.16; T_{ion} = 8500°K; v (Fe I) = 2 km/s; v (Fe II, Cr II) $\simeq$ 4 km/s. Le misure delle velocità radiali delle righe dell'idrogeno e delle righe metalliche formate nell'atmosfera estesa indicano che questa è in espansione con una velocità di circa — 50 km/s nel 1958 e — 80 km/s nel 1959. C'è una sistematica differenza fra le velocità radiali date dalle righe di Balmer e quelle date dalle righe metalliche; quest'ultima è di circa 20 km/s maggiore in valore assoluto.

ABSTRACT. — The total intensities of the shell and stellar lines have been measured, and a comparison with the previous observations for the period 1950-1956 has been made. We find a maximum intensity in 1958; from 1958 to 1959 the intensities of the shell lines begin to decrease again. The electron density, the dilution of radiation and the microturbulence of the shell have been determined and the ionization temperature has been derived from the ionization equilibrium of Fe I and Fe II. We find the following values: log Ne = 12.39; W = 0.16; T_{ion} = 8500°K; v (Fe I) = 2 km/s; v (Fe II, Cr II) $\simeq$ 4 km/s. The radial velocities of the Balmer and metallic lines formed in the extended atmosphere show that it is expanding with a velocity of about — 50 km/s in 1958 and — 80 km/s in 1959. A systematic difference has been found between the radial velocity given by the Balmer lines and by the metallic lines of about 20 km/s the latter being more negative.

INTRODUCTION

The spectrum of the Be star ζ Tauri is characterized by the presence of very shallow absorption lines showing rotational contours, rising from levels of high excitation potential (He I, C II, N II, O II) and by a group of sharp metallic lines and by sharp H I cores, formed in an extended atmosphere or a shell surrounding the stellar atmosphere.

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The V/R variation of the emission wings of the Balmer lines and the variation of intensity of the absorption shell and stellar lines are irregular; for this reason continuous observations of the spectrum of this star are important. The purpose of this paper is to study some spectra of ζ Tauri taken in December 1957, January and February 1958, and in January 1959, and to study the spectral variations from 1950 to 1959. All the spectrograms of 1957-1959 show a strong shell spectrum; the Balmer lines Hβ, Hγ, Hδ show red emission wings, and some of them are asymmetrical, being sharper on the red side.

The spectrograms were taken with the Zeiss spectrograph at the 1m reflector of the Merate observatory by M. Hack and T. Tamburini. The dispersion is 20 A/mm at Hγ. Table I gives the list of spectrograms.

TABLE I

Plate N.	Spectrum N.	Date	Phase	Notes
T 197	601	Dec. 5 1957	0.66 P	(1)
T 200	609	Jan. 8 1958	0.92	(1)
HT 205	626	Feb. 2 1958	0.11	(2)
T 209	637	Feb. 28 1958	0.30	(1)
H 210	641	Mar. 1 1958	0.31	(1)
T 240	730	Jan. 28 1959	0.82	(3)
T 241	734	Jan. 30 1959	0.84	(3)

(1) Red emission wings are visible at Hβ, Hγ, Hδ, and at λλ 4924, 4629, 4584, 4549, 4523, 4233, 4179 Fe II. All the Balmer cores up to the limit of the series are asymmetrical, being sharper on the red side.

(2) Spectrogram of poor quality; the comparison spectrum shows broad or double lines.

(3) Red emission wings are visible at Hβ, Hγ, Hδ and at λλ 4584, 4549, 4523 Fe II. The Balmer cores are symmetrical, with the exception of Hβ, Hγ, Hδ, and of H7 blend with 3968 Ca II and H8 blend with 3889 He I. We note a general weakening of the metallic shell lines in comparison with the spectrograms of 1958.

THE RADIAL VELOCITIES

Measurements of radial velocities of the sharp shell lines have been made. The results are given in Table II. From these meausurements it appears that:

1) the radial velocities of the absorption shell lines are all negative;

2) the radial velocities in winter 1959 are more negative than in winter 1957-58;

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3) there is a constant difference between the radial velocities displayed by the hydrogen shell cores and by those of the metallic lines;

4) fig. 1 shows the shell radial velocities compared with the orbital velocity curve (1), and with the stellar radial velocities derived by measuring directly from the tracings the shift of the stellar lines with

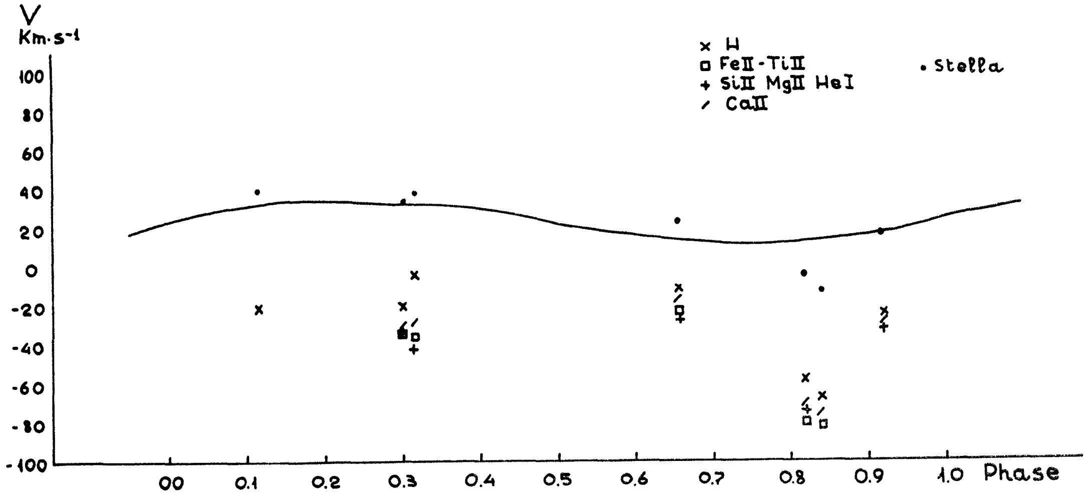


Fig. 1. — Shell radial velocities compared with the orbital velocity curve.

respect to the shell lines. Since these measurements are very uncertain because of the difficulty of estimating the middle of the broad rotational contours of the stellar lines, the agreement of our estimates with the orbital velocity curve can be considered satisfactory, specially for the values corresponding to winter 1957-58.

These results show that the difference between the radial velocity of the shell lines and the orbital radial velocity is about — 50 km/s in 1957-58, and — 80 km/s in 1959, proving that the shell in these epochs is going through an expansional phase. The difference in radial velocity between hydrogen cores and metallic lines suggests the existence of stratification in the shell. Table III gives the results of the measurements of the radial velocities of the stellar lines.

INTENSITY VARIATION OF THE SPECTRAL LINES

The lines in the spectrum of ζ Tauri have been measured at the spectrocomparator for identification, and the shallow lines which were very difficult to see were measured directly on the tracings. By comparing different spectrograms we were able to recognize the weak lines,

TABLE II

Plate N.	Radial velocity (km/s)				phase
	H	Fe II, Ti II	Si II, Mg II, He I	Ca II	
197	— 12.5	— 23.0	— 28.0	— 16.0	0.66 P
200	— 26.5	—	— 32.5	— 28.0	0.92
205	— 21.5	—	—	— 30.5	0.11
209	— 20.5	— 35.0	— 35.5	— 30.0	0.30
210	— 4.0	— 36.0	— 41.0	— 28.0	0.31
240	— 59.0	— 80.5	— 75.0	— 71.0	0.82
241	— 69.0	— 82.5	—	— 75.0	0.84

TABLE III

Plate N.	Stellar radial velocity	Phase
197	+ 22.5	0.66 P
200	+ 17.0	0.92
205	+ 39.5	0.11
209	+ 33.5	0.30
210	+ 37.0	0.31
240	— 5.0	0.82
241	— 12.0	0.84

TABLE IV

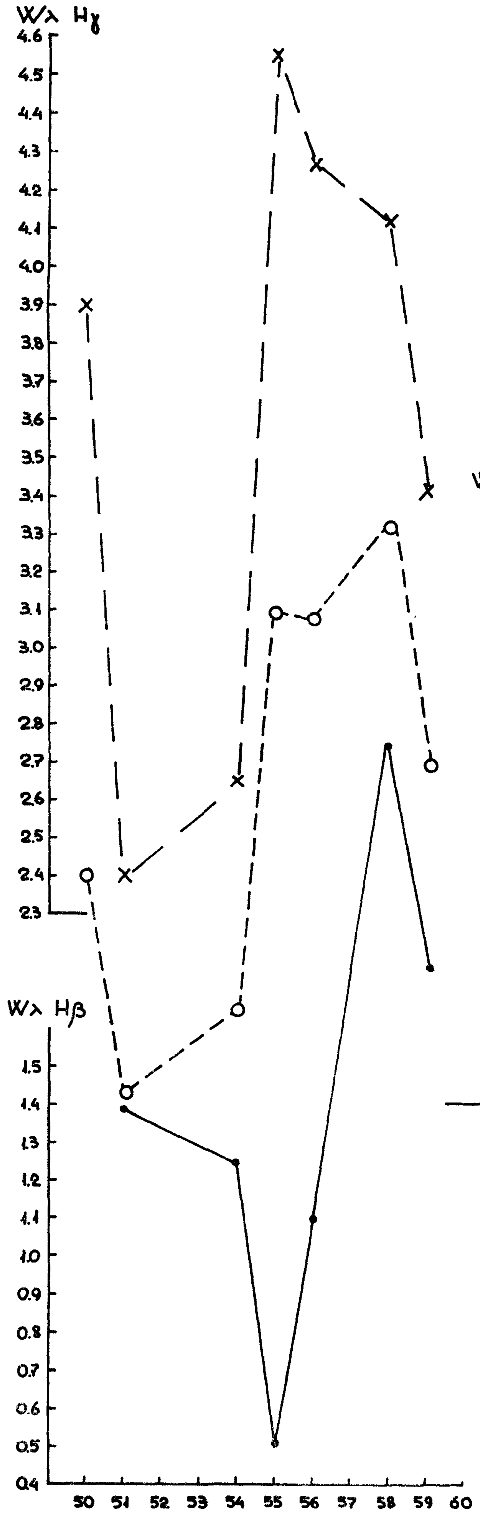
Date \ W_λ	H β abs.	R em.	V em.	Hγ	Hδ	R_c	n
Jan. 1950				3.9	3.1	0.65	30
Febr. 50				3.9	3.1		
Nov. 51	1.39			2.39	2.43	0.65	26
March. 54	1.25	0.06	0.14	2.65	2.65	0.87	33
Febr. 55	0.51		0.21	4.57	3.70	0.77	25
Febr. 56	1.11	0.22		4.26	3.68	0.84	34
Dec. 57-Jan. 58	2.34	0.40		3.59	3.10	0.90	29
Jan. 59	1.75	0.60		3.40	3.30	0.70	26

TABLE V

	— log (W_λ /λ)	log X_f	lower E.P.
Cr II			
4284.21	4.21	— 1.02	3.84
4558.66	4.22	— 0.98	4.06
4592.09	4.08	— 1.64	4.06
4616.64	4.36	— 1.71	4.06
4824.13	4.15	— 0.95	3.85
4848.24	4.07	— 1.62	3.85
4856.19	4.25	— 2.24	3.84
4884.57	4.17	— 2.20	3.84
Fe I			
3763.79	4.62	+ 1.88	0.99
3812.96	4.40	+ 1.33	0.95
3920.26	4.40	+ 1.36	0.12
4005.25	4.49	+ 1.48	1.55
4045.82	4.42	+ 2.18	1.48
4191.44	4.56	+ 0.84	2.46
4202.03	4.53	+ 1.32	1.48
4217.55	4.62	— 0.30	3.42
4219.38	4.60	— 0.27	3.56
4282.41	4.56	+ 0.48	2.17
4404.75	4.50	+ 1.81	1.55
Fe II			
4178.86	3.83	— 0.63	2.57
4296.57	4.31	— 0.79	2.69
4508.28	3.96	— 0.81	2.84
4515.34	4.03	— 0.87	2.83
4520.22	4.25	— 0.90	2.80
4522.63	4.06	— 0.26	2.83
4541.52	4.09	— 1.58	2.84
4576.33	4.18	— 1.46	2.83

which are present on all the tracings, from the plate grain. The identification was made with the help of the Multiplet Table ([2]).

We know that the intensities of the lines of ζ Tauri show irregular variations. An attempt to find some correlation with the phase has been made using the measurements of equivalent widths found in the literature for the period between 1950 and 1959; it has been negative, confirming the secular character of the spectral variations of ζ Tauri. Collecting the observations from the literature ([3]) for the same period we have constructed the curves of fig. 2 showing the secular variations of the lines. We see that stellar and shell lines show roughly the same general behavior, decreasing from 1950, reaching a minimum between 1952 and 1955 and attaining a maximum in 1958. From 1958 to 1959 there is a general decrease in intensity of the shell lines, which is shown also by fig. 3. The stellar lines of He I on the contrary increase. The Balmer lines (we consider the equivalent widths of the line including



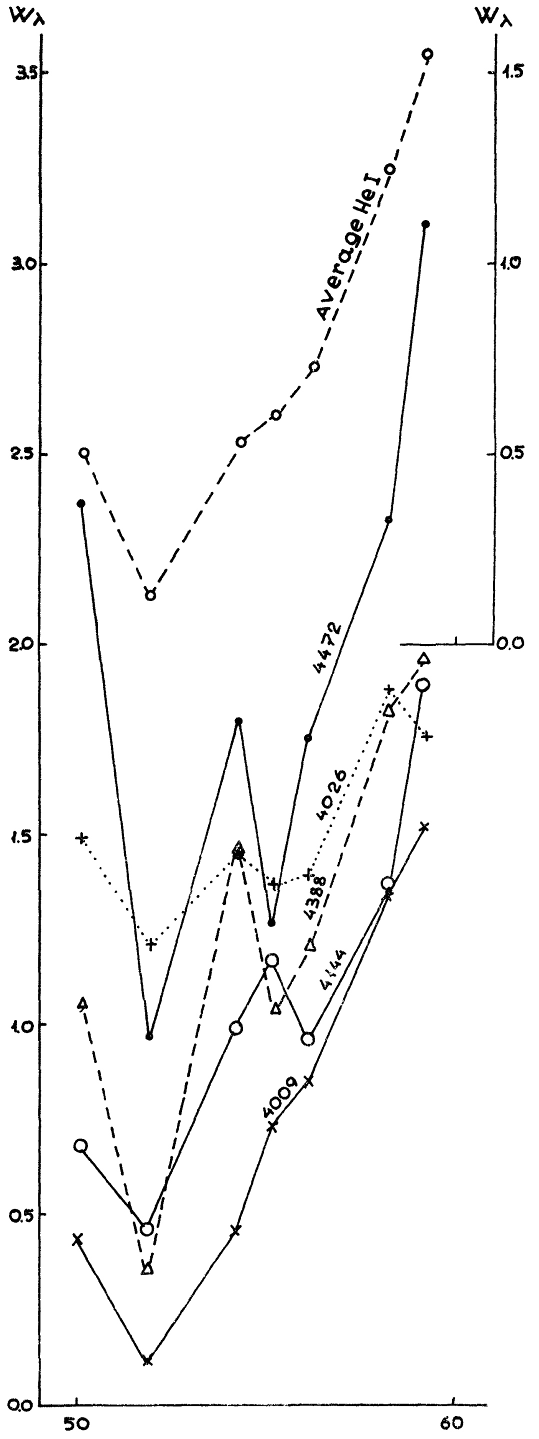


Fig. 2 a. — Intensity variations of the Balmer lines.

Fig. 2 b. — Intensity variations of the single He I lines (scale on the left) and of the average of the He I lines (scale on the right).

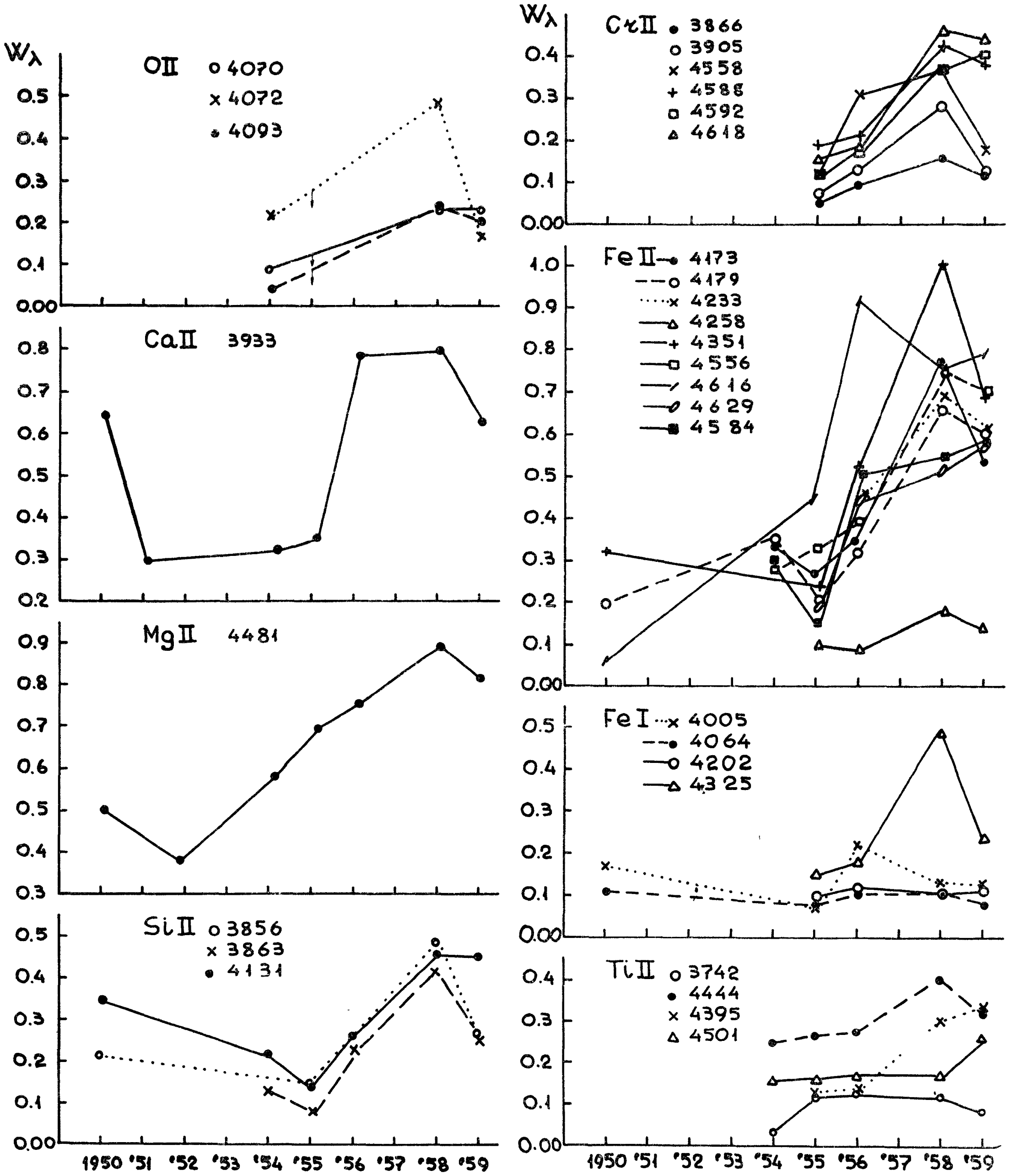


Fig. 2 c. — Intensity variations of the other lines.

the shell core and the stellar broad wings) decrease strongly from 1958 to 1959. The contours of H_β, H_γ, H_δ are shown in fig. 4. Generally there is no strong variation from one contour to the other; only a sharp decrease of the emission of H_β is visible from plate 240 to plate 241 (representing an interval of only two days). The red emission wings are increased in intensity from 1956 to 1958 and from 1958 to 1959

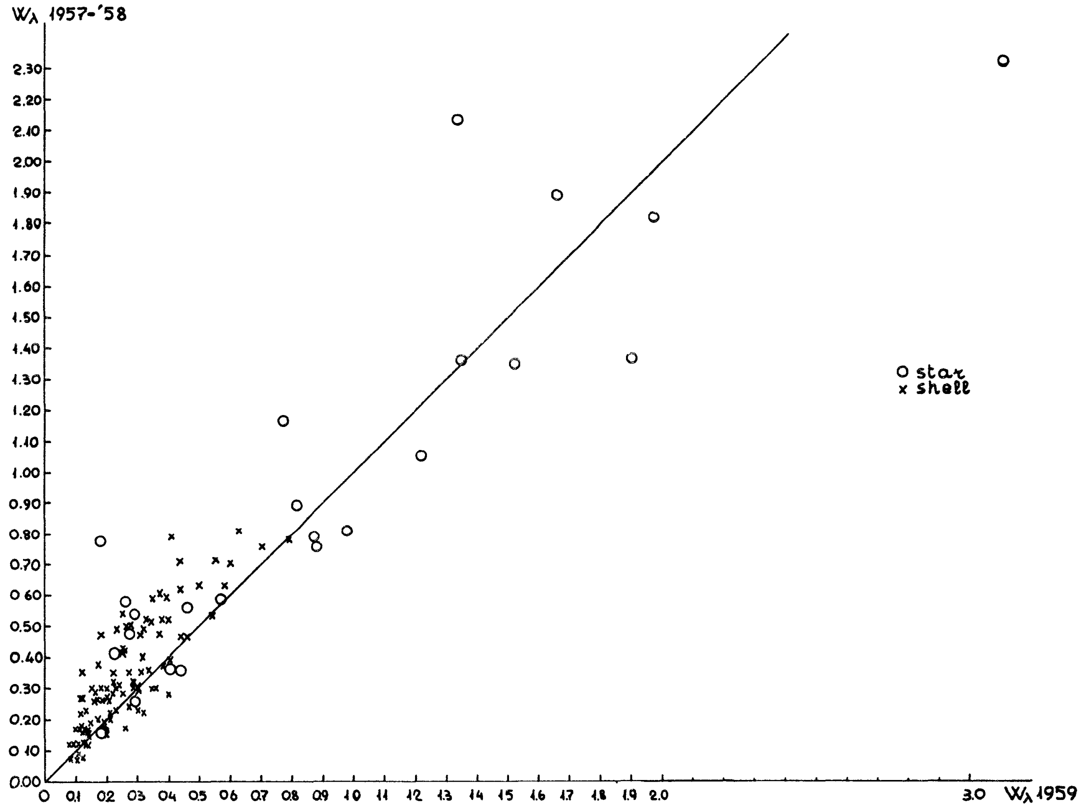


Fig. 3. — Comparison of the equivalent widths in 1957-58 and in 1959.

(Table IV). The central depths in 1959 are all lower than in 1957-58 probably due to presence of central emission filling the core; the central depths change from about 0.90 in 1957-58 to 0.70 in 1959. The quantic number of the last Balmer line seems to be a little lower in 1959; from 29 in 1958 to 26 or 27 in 1959 (fig. 5). However such small variations can also be imputed to slight difference in the quality of the plates and to the exposure.

TEMPERATURE, MICROTURBOLENCE, ELECTRON PRESSURE AND DILUTION OF RADIATION IN THE SHELL.

Using the lines of Fe I, Fe II, and Cr II appreciably free from blends, (Table V), we have constructed three branches of the curve of growth for the shell of ζ Tauri. By comparing these branches with the solar curve of growth (4) we find the following values for the microturbulence: v (Fe I) = 2 km/s; v (Fe II) = 4,5 km/s; v (Cr II) = 4 km/s; and for the ratio between the number of atoms contained in a

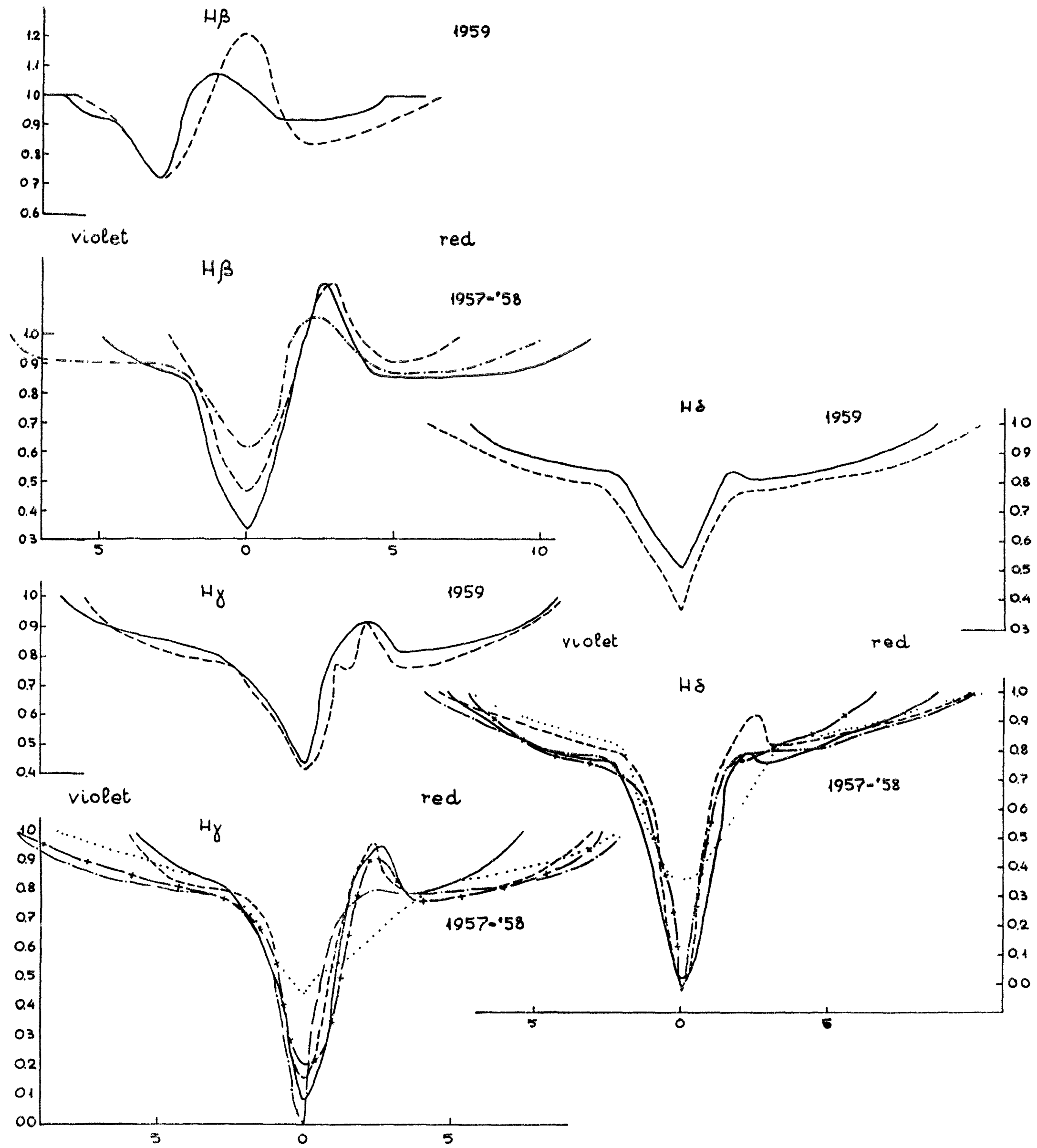


Fig. 4. — The contours of Hβ, Hγ, Hδ.

column of the extended atmosphere of ζ Tauri and in a column of the solar atmosphere:

$$\log \frac{Nh_*}{Nh_\odot} (Fe\ I) = -1.80\ ;\ \log \frac{Nh_*}{Nh_\odot} (Fe\ II) = +0.76\ ;\ \log \frac{Nh_*}{Nh_\odot} (Cr\ II) = +0.57$$

These values are computed assuming $5040/T_* = 0.5$ and $5040/T_\odot = 1.0$ for the reciprocal of the excitation temperatures. Since the extended

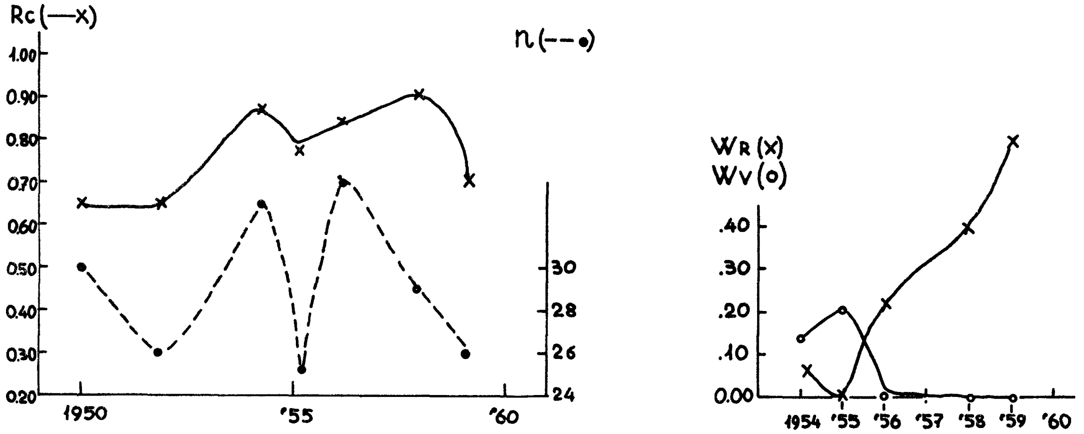


Fig. 5. — The variations of R_c, n and the intensities of the red and violet emission wings of Hβ.

atmosphere is illuminated by the diluted radiation of the star, calling *W* the factor of dilution we write the Saha equation for Fe I and Fe II as follows:

$$\log (P_{e*}/ W) - \log P_{e\odot} = - \log \frac{Nh_*}{Nh_\odot} (Fe\ II) + \log \frac{Nh_*}{Nh_\odot} (Fe\ I) +$$

$$+ 2.5 \log \frac{T_*}{T_\odot} - \chi_0 (\theta_* - \theta_\odot)$$

Assuming $5040/T_* = 0.5$ and $5040/T_\odot = 0.88$ for the reciprocals of the ionization temperatures, we find

$$\log (P_{e*}/W) - \log P_{e\odot} = + 1.0$$

and, for $\log P_{e\odot} = 1.20$, it follows $\log (P_{e*}/W) = + 2.20$.

Another way of deriving $\log P_e$, which does not require the knowledge of *W*, is given by the Inglis-Teller formula

$$\log N_e = 23.26 - 7.5 \log n$$

where *n* is the quantic number of the last visible line of the Balmer series. Taking $n = 28$ we have $\log N_e = 12.39$ and then

$$\log P_e = \log N_e + \log k + \log T$$

which is only slightly affected by the uncertainty of the temperature. For $T_* = 10\ 000$ °K we have $\log P_e = 0.53$. If we assume that iron and hydrogen lines are formed in about the same layers of the shell, this value of the electron pressure can be used to derive the factor of dilution:

$$\log W = 0.53 - 2.20 = - 1.67$$
$$W = 0.02$$

We can also derive W by another method. The geometrical dilution factor is given by $W = \omega/4\pi$, where ω is the solid angle under which a point A in the shell subtends the diameter of the star. We have

$$W = \omega / 4 \pi = \frac{1}{4\pi} \int_0^{2\pi} d \varphi \int^{\theta} \sin \theta \, d \theta = \frac{1}{2} \left[1 - \sqrt{1 - (\frac{R}{r})^2} \right]$$

where R represents the radius of the star and r the radius of the shell corresponding to a given line. Now if we call v_s and v the rotational velocities of the shell and the star, the broadening of the stellar lines give us v, and the observed broadening of the shell lines give us $v'_s = v_s \sin \theta = v_s(R/r)$ (since the absorption shell lines are given only by the part of the shell which is in front of the disk of the star, and not from the whole shell). If we assume that there is conservation of angular momentum we have: $rv_s = Rv$, and finally $(r/R)^2 = v/v'_s \cdot v$ and v'_s have been derived by measuring the half-width of lines which are not affected by Stark broadening. For the star we use the lines of N II, S II, C II, Mg II, Al III, O II (Table VI).

It follows $v = 230$ km/s. For the shell we use the lines of Fe II and the Balmer lines which are very sharp; given the low electron density of the shell, the Stark effect is probably negligible; the close agreement between the rotational velocities given by Fe II and Balmer lines, confirms this assumption. It is possible that the lower value given by the Balmer lines corresponds to a real stratification in the shell. We find $v'_s = 127$ km/s. Therefore it follows that $W = 0.16$ and $r/R = 1.5$. This value is one order of magnitude greater than the value given by the ionization equilibrium of iron.

This great difference cannot be imputed to the assumption that H and Fe lines are formed in approximately the same layers. However we have assumed a value for the temperature which could not be derived directly. Since θ in the Saha equation is multiplied by the ionization potential of iron, a small error in θ is multiplied by 7.8. So by the reverse procedure we can use the value of P_e given by the Inglis-Teller formula (which is only slightly affected by the choice of the temperature) and the value of W computed by the rotational velocities, thereby deriving the ionization temperature from the Saha equation for Fe I and Fe II. Assuming for the ionization temperature of the sun

TABLE VI

Stellar lines	v	shell lines	v'_s
3995 N II	180	Hγ	128
4153 S II	180	Hδ	138
4267 C II	175	H8	130
4481 Mg II	234	H9	117
4529 Al II	258	H 10	112
4610 O II	312	H 11	117
4650 O II	271	H 12	88
	$\bar{v}$ = 230	$\bar{v}'_s$(H) =	119
		3936 Fe II	76
		3961 Fe II	113
		4179 Fe II	215
		4296 Fe II	111
		4508 Fe II	159
		4515 Fe II	152
		4520 Fe II	106
		4522 Fe II	165
		4541 Fe II	171
		4576 Fe II	118
		4625 Fe II	103
		$\bar{v}'_s$(Fe II) =	135
		$\bar{v}'_s$ =	127

$T_\odot = 5700$°K we find $T_* = 8500$°K. This value is appreciably lower than the value which is characteristic of a star such as ζ Tauri with spectral type B3 or B4; on the other hand the temperature which we find is of the same order as the temperature for the atmospheres of the A stars. This result suggests that probably the innermost layers of the shell which are transparent in the visible region of the spectrum are opaque enough to absorb the radiation of the star beyond the Balmer limit at λ 3647, and this radiation is converted in continuous radiation of the shell itself. Therefore the ionization equilibrium of the elements in the shell is governed by the temperature characteristic of the shell itself. From an inspection of some spectrograms of ζ Tauri taken with a grating spectrograph which is transparent in the ultraviolet we confirm the opacity of the shell beyond the Balmer limit: no trace of λ 3634 He I is visible.

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