RESULTS OBTAINED FROM THE 1961-1962 ECLIPSE OF 31 CYGNI

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Riassunto. — Le osservazioni spettrografiche dell'eclisse di 31 Cygni danno i seguenti risultati: Epoca del primo contatto circa il 19 dicembre 1961; periodo trascorso fra il 2° contatto dell'eclisse del 1951 e il 2° contatto dell'eclisse del 1961 pari a 3784^d.

Si danno le variazioni della larghezza equivalente della riga K del Ca II e delle profondità centrali di parecchie altre righe cromosferiche, e le velocità radiali delle righe prevalentemente cromosferiche. Si sono osservate componenti secondarie della riga K del Ca II aventi velocità radiali di circa + 100 e — 100 Km/s. Un aumento di intensità delle righe cromosferiche, accompagnato da un valore della velocità radiale più negativo che nei giorni immediatamente precedenti e seguenti, è stato osservato 58^d dopo il 3° contatto, e cioè quando la stella B si trova circa due raggi stellari (della stella K) sopra la fotosfera della stella principale.

Si determina il rapporto $\alpha = I_{cB}/I_{cK}$ fra gli spettri continui delle due stelle fra 4300 e 3500 A, mettendo in evidenza la presenza di una forte discontinuità di Balmer nello spettro della stella B.

Si ricostruisce quindi lo spettro della stella B sottraendo dallo spettro composto B + K lo spettro K ridotto del fattore $k = 1/(1 + \alpha)$. Dalle larghezze equivalenti delle righe di Balmer, dell'elio neutro e del silicio ionizzato, dal numero di righe visibili della serie di Balmer (fino ad H 14 o H 15) e dalla discontinuità di Balmer ($D \geqslant 0.30$) si ritiene che il tipo spettrale della compagna sia B5 V.

Abstract. — The spectrographic observations of the eclipse of 31 Cygni give the following results. Epoch of first contact: about December 19. Time elapsed between 2nd contact in 1951, and 2nd contact in 1961: 3784^d.

The variations of the total intensity of the K-line, of the central depths of several chromospheric lines and the radial velocities of lines which are mainly of chromospheric origin are given. Satellites of the K-line are observed, having radial velocities of about + 100 and — 100 km/s. An increase of intensity of the chromospheric lines together with a radial velocity more negative than that observed few days before and few days after has been observed 58^d after 3rd contact, when the B-type star is about two stellar radii (of the K-type star) above the photosphere of the main component.

The ratio $\alpha = I_{cB}/I_{cK}$ in the spectral range $\lambda\lambda$ 4300-3500 is determined: evidence of a strong Balmer discontinuity ($D \geqslant 0.30$) in the spectrum of the B-type star is found.

The spectrum of the B-type star is constructed by subtraction of the K-type spectrum reduced by the factor $k = 1/(1 + \alpha)$ from the composite spectrum B + K.

The intensity of the Balmer lines, of the He I and Si II lines, the quantum number of the last visible Balmer line (H 14 or H 15) and the Balmer discontinuity suggest that the spectral type of the secondary star is B5 V.

(*) Ricevuta il 24 giugno 1963.

THE OBSERVATIONS

The binary star 31 Cygni was observed from October 1961 to October 1962 with the grating spectrograph at the Zeiss reflector, using a dispersion of 22 A/mm in the spectral range λλ 3500-4350 (third order). A list of the spectrograms is found in Table I.

TABLE I

Date	J.D.	Spectrogram
Oct. 31, 1961	2437604.2	K 885
Nov. 1, 1961	605.2	H 888
Nov. 15, 1961	619.2	K 891
Nov. 16, 1961	620.2	G 895
Nov. 16, 1961	620.3	K 896
Dec. 16, 1961	650.2	G 905
Dec. 17, 1961	651.2	G 906
Dec. 19, 1961	653.2	H 915
Jan. 15, 1962	680.2	H 917
Jan 21, 1962	691.2	H 929
Jan. 27, 1962	697.2	G 948
Feb. 13, 1962	708.7	H 962
Feb. 18, 1962	713.7	H 975
Feb. 19, 1962	714.7	H 976
Feb. 20, 1962	715.7	H 982
Feb. 21, 1962	716.7	H 983
Mar. 15, 1962	738.6	H 996
Mar. 18, 1962	741.6	H 1010
Apr. 12, 1962	766.5	K 1052
Apr. 21, 1962	775.5	H 1059
Apr. 26, 1962	780.6	K 1078
Apr. 27, 1962	781.6	H 1083
May 15, 1962	799.6	G 1089
May 21, 1962	805.6	H 1105
June 10, 1962	825.5	H 1131
June 11, 1962	826.5	G 1135
Aug. 10, 1962	887.4	L 1235
Aug. 13, 1962	890.4	Fa 1267
Aug. 14, 1962	891.4	Fa 1283
Oct. 20, 1962	958.2	Fa 1498

EPOCH OF THE ECLIPSE

Because of bad weather conditions we have relatively few plates before totality and none just after totality. However we have been fortunate in obtaining plates of the interval between first and second contact: on December 17 the K-line shows the characteristic cromospheric component much stronger than before, and on December 19 the K-line shows the characteristic rectangular contour. We estimate that the first contact occurred between December 17 and December 19. According to the photoelectric observations of Herczeg and Schmidt ([1]) the first contact occurred on the 19th, the second on the 21st and the third on February 21. The last plate we have during the totality is on February 21: the K-line still has the shape and the total intensity characteristic of the K-type star. After this date we have no further plates until March 3, when the chromospheric K-line is visible again.

The time of second contact adopted by McLaughlin ([2]) and by McKellar and Petrie ([3]) for the eclipse of 1951 was August 12.3 (J.D. 2 433 870.8). Adopting for the time of second contact in 1961 the 21st of December (J.D. 2 437 655) the time elapsed between the two epochs is 3784^d, which is in agreement with the value given by McKellar and Petrie ([3]) of 3781 $\pm$ 8 days.

INTENSITY VARIATIONS OF THE CHROMOSPHERIC LINES

The variation of the equivalent width of the chromospheric K line is shown in Fig. 1. The equivalent widths have been measured relative to a continuum which is the sum of the continuum of the B star and the

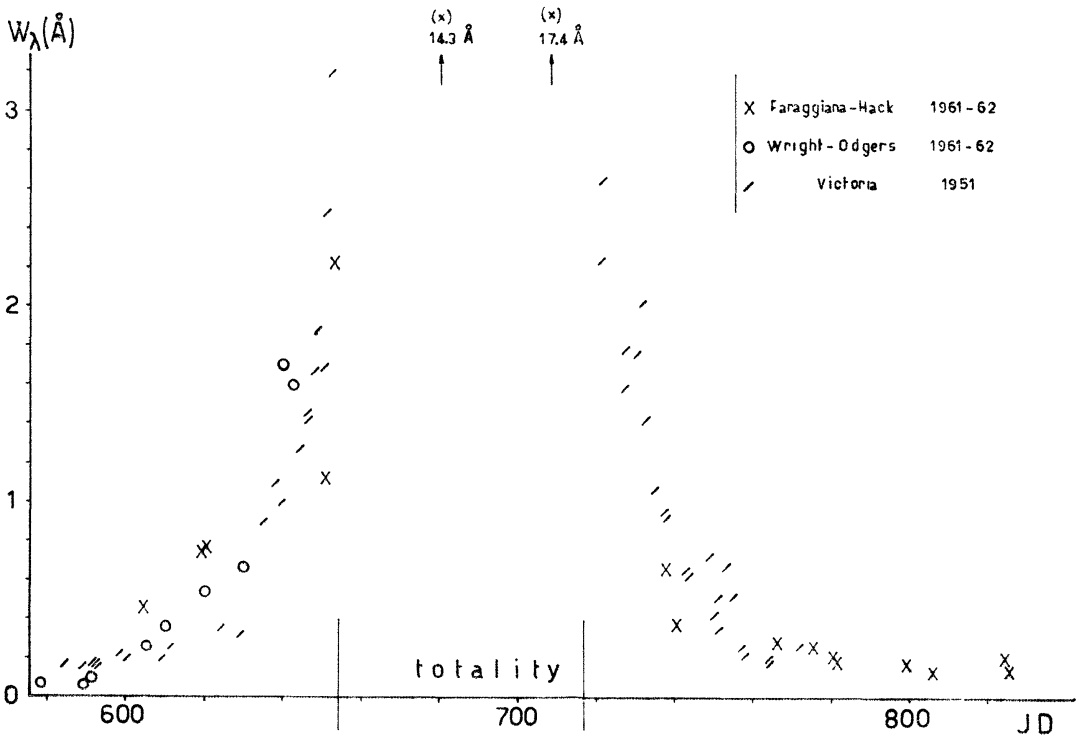

Fig. 1. — Equivalent widths of the K line.

absorption contour of the broad K line due to the K-type star. Our results are compared with those of Wright and Odgers ([4]), and with the results of the 1951 eclipse ([5]); the agreements is very satisfactory.

Fig. 2 gives the variations of the central depths for several other

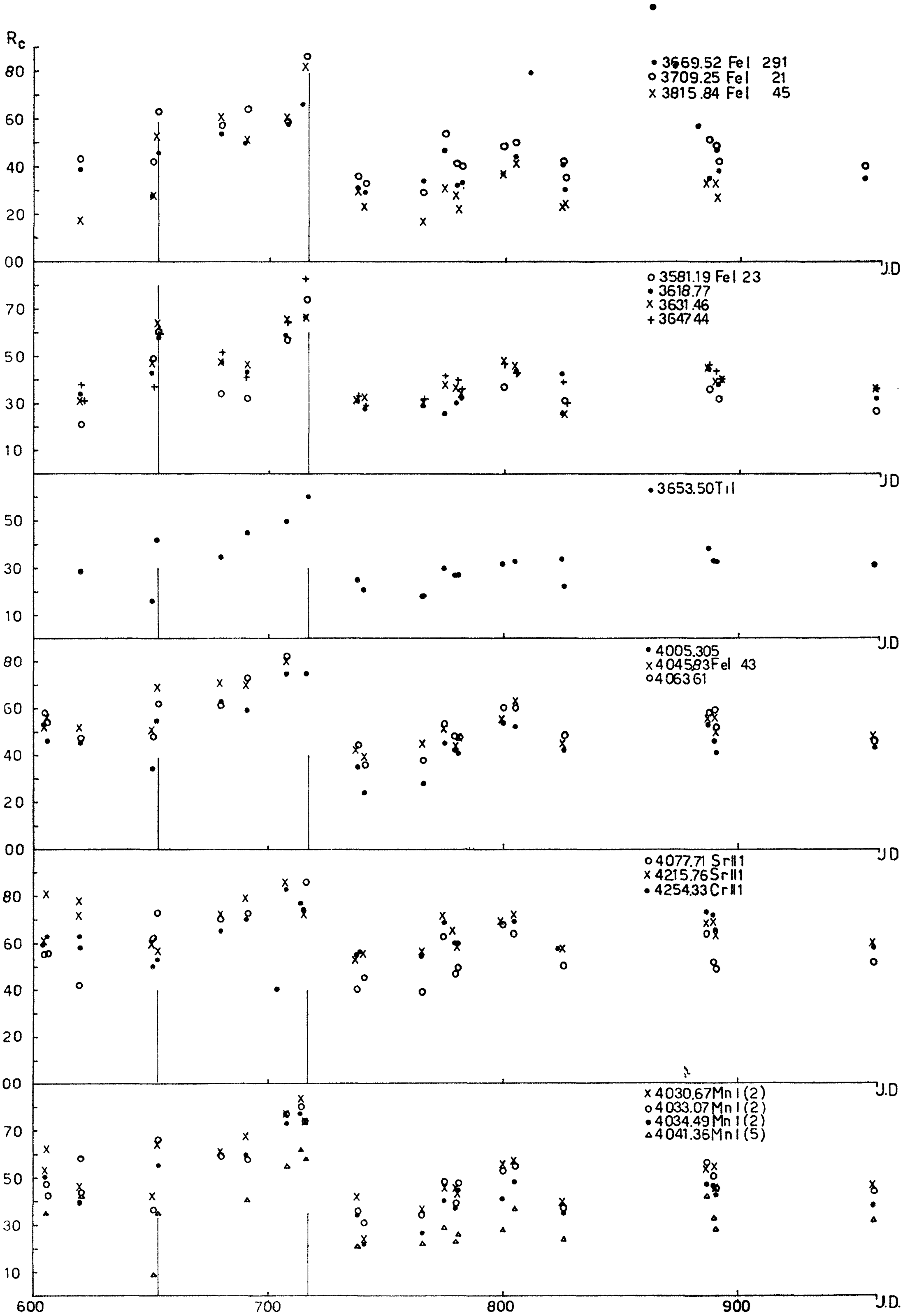

Fig. 2. — Central depths of chromospheric lines.

chromospheric lines. The central depths are measured relative to the continuum of the composite spectrum B + K. The sharp increase of intensity at the epoch of first contact is easily visible. We observe that the effect becomes less and less visible with increasing wave length, since the K spectrum becomes predominant. At the epoch of third contact the lines appear even stronger than during totality.

Fig. 3 shows a reproduction of intensity tracings between λ 3815 and λ 3950 of spectrograms taken during the phases preceeding and following the totality together with tracings of spectrograms taken during totality (K-type) and completely out of totality (B + K-type).

We remark that the spectrogram H 1059 taken 58 days after the end of totality shows many sharp lines characteristic of the high chromospheric layers of the K-type star. The radial velocity derived by means of these lines is 15 to 30 km/s more negative than the radial velocity given by the spectrogram H 1052 taken 9 days before and by the spectrogram K 1078 taken 5 days later. Moreover the intensity of the chromospheric lines are stronger suggesting that we are observing a condensation of the chromosphere of the K-type star. Since the relative motion of the B star is about 2.5 solar diameters per day this condensation should be about 150 solar diameters high above the K photosphere, namely about 2 radii of the K-type star.

RADIAL VELOCITIES OF THE CHROMOSPHERIC LINES

Radial velocities were measured using lines in the spectral region λ 4070 - λ 3500, where the contribution of the K-type spectrum is less, and the lines are mainly due to the chromosphere of the K star.

The errors are large (from ± 1 to ± 4 km/s) since almost all the spectrograms were taken with large hour angle and flexure effects were not negligible. However a good agreement is found between our measurements of the K line and those made with higher dispersion by Wright and Odgers ([4]) during the ingress phase. We find negative velocities as low as — 50 km/s, 34 days before and 2 days before 1st contact, and 58 days after 3rd contact (Fig. 4). In two spectrograms taken 58 days (H 1059) and 63 days (K 1078) after 3rd contact the K line shows two peaks, the separation of which corresponds to about 30 km/s. This feature can be interpreted as a central emission. At several phases red-shifted and violet-shifted components of the chromospheric K line are present; separations of the order of + 100 km/s and — 100 km/s respectively are observed. Velocities 10 to 15 km/s more negative than the orbital velocity are observed also in October 1962, six months after totality. This effect is probably due to large scale motions in the extended atmosphere of the K star.

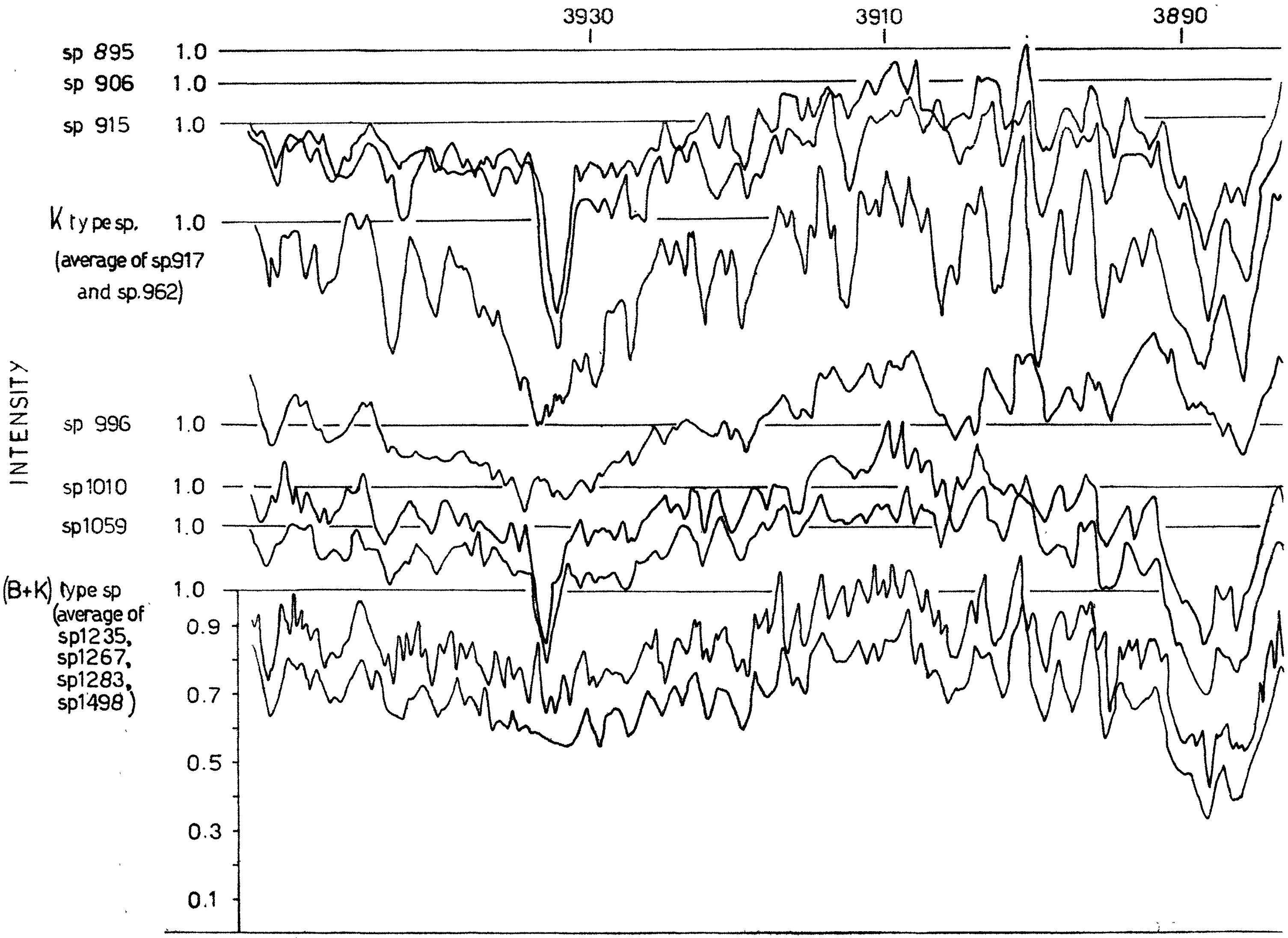

Fig. 3a. — Intensity tracings of spectrograms taken before the ingress (G 895, G 906 and H 915), during totality (average of spectrograms H 917 and H 962), after the egress (H 996, H 1010 and H 1059), and well out of eclipse (average of spectrograms L 1235, Fa 1267, Fa 1283 and Fa 1498).

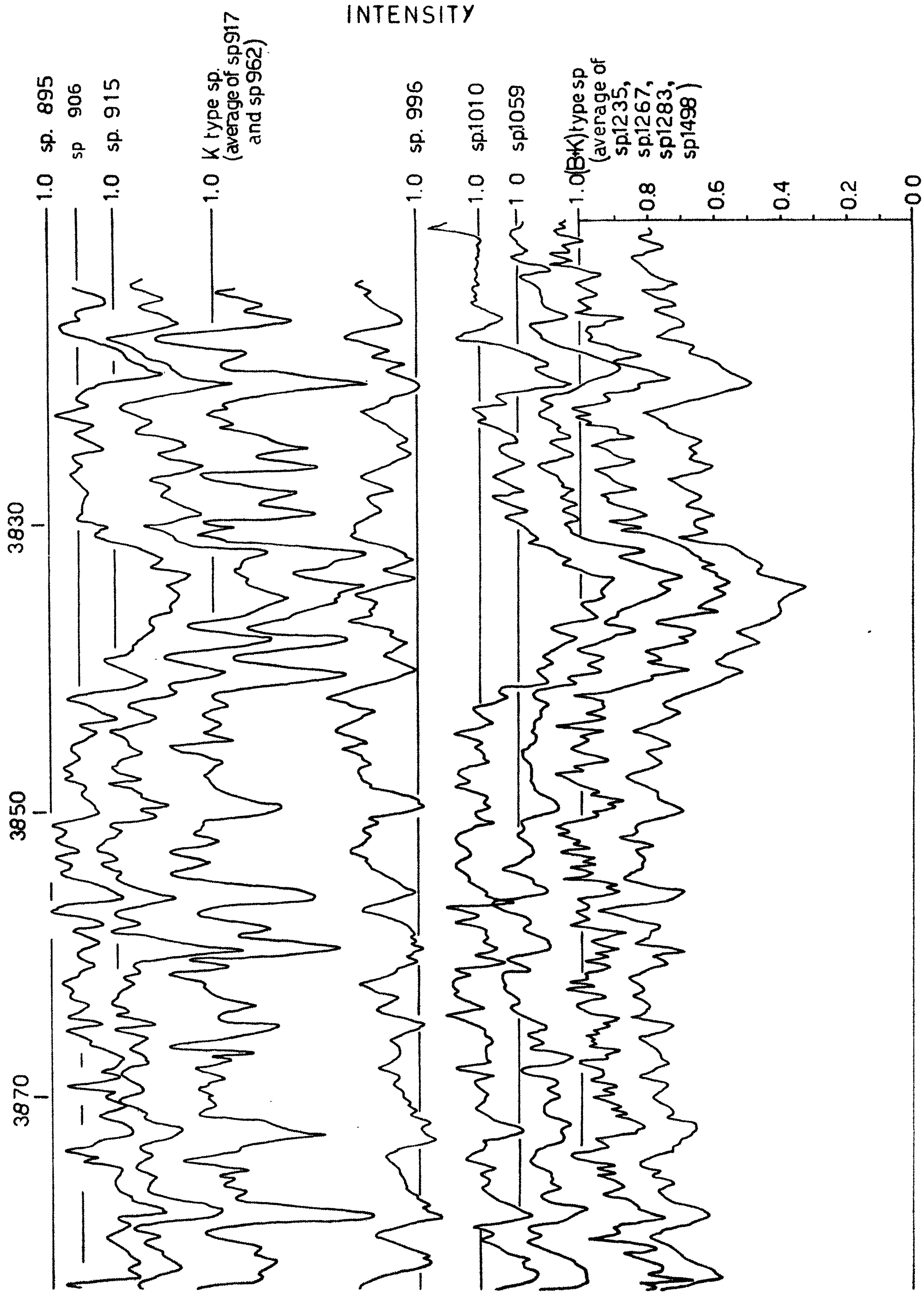
INTENSITY
1.0 sp. 895
sp 906
1.0 sp. 915
1.0 K type sp. (average of sp917 and sp962)
1.0 sp. 996
1.0 sp1010
1 0 sp1059
1.0 (B+K) type sp (average of sp1235, sp1267, sp1283, sp1498)
0.8
0.6
0.4
0.2
0.0
3830
3850
3870

Fig. 3 b

TABLE II

Spectrogram	J.D.	Radial velocity (Km/s) Mg I 3 E.P. = 2.7	Ca II (K line, main compon.)	Mn I 2 E.P. = 0.0	Fe I 4 and 5 E.P. 0.0	Fe I 20 and 21 E.P. 1.0	Fe I 43 and 45 E.P. 1.5	Ni I 30 and 32 E.P. = 0.42
K 885	2437604.2		— 7	— 12.2	— 7.5		— 1.9	
H 888	605.2		— 28.2	— 10.8			— 16.7	
K 891	619.2		— 49					
G 895	620.2		— 36	— 35	— 24.5	— 18	— 12.5	— 0.5
G 896	620.3		— 29	— 32	— 25.8		(— 22.5)	
G 905	650.2		— 43	— 27				
G 906	651.2	— 20	— 15	— 29	— 20.5	— 22.5	— 9.2	
H 915	653.2	+ 2.7	— 1	— 2.7	+ 2.3	+ 1.1	+ 1.4	+ 5.2
H 917	680.2			— 2.1	— 17.5	— 11	— 5	+ 10
H 962	708.7			— 14.8	— 6.2	— 3.8	— 5.6	— 4.5
H 982	715.7					— 14.5	— 6.5	
H 983	716.7	+ 11.9		— 1.8	— 0.5	+ 5.3	+ 33.4	+ 2.9
H 996	738.6		— 6.1		— 5.1	— 4.5		— 3.8
H 1010	741.6	— 21.5	— 2.3	— 10.5	— 3.1	— 13.8	+ 0.5	— 4.5
K 1052	766.5		— 24.3	— 18.6	— 12.6	— 14.5	— 7.8	
H 1059	775.5	— 34	— 35.5	— 49	— 28.5	— 34	— 27.2	— 18
K 1078	780.6		— 28	— 27	— 15.8	— 27	— 17.3	— 10
H 1083	781.6		— 14.5	— 9.4	— 2.2	— 6.2	— 1.5	+ 4.5
G 1089	799.6	— 16	— 29	— 32	— 24	— 18	— 14.5	— 18
H 1105	805.6	— 17	— 37	— 31	— 19.4	— 5.4	— 14.4	— 5.5
H 1131	825.5	+ 4.5		— 13.2	— 14.4	— 15	— 11.0	— 20
G 1135	826.5	— 16		— 19	— 7.3	— 11	— 12.7	— 10
L 1235	887.4	— 18		— 22.5	— 19.4	— 10.6	— 12.4	— 7.5
Fa 1267	890.4			— 23	— 18.4	— 16.6	— 23.3	— 23
Fa 1283	891.4	— 16		— 20	— 19	— 8.6	— 14.4	— 15
Fa 1498	958.2	— 3.1		— 20	— 7.2	— 7.9	— 6.2	— 1.1

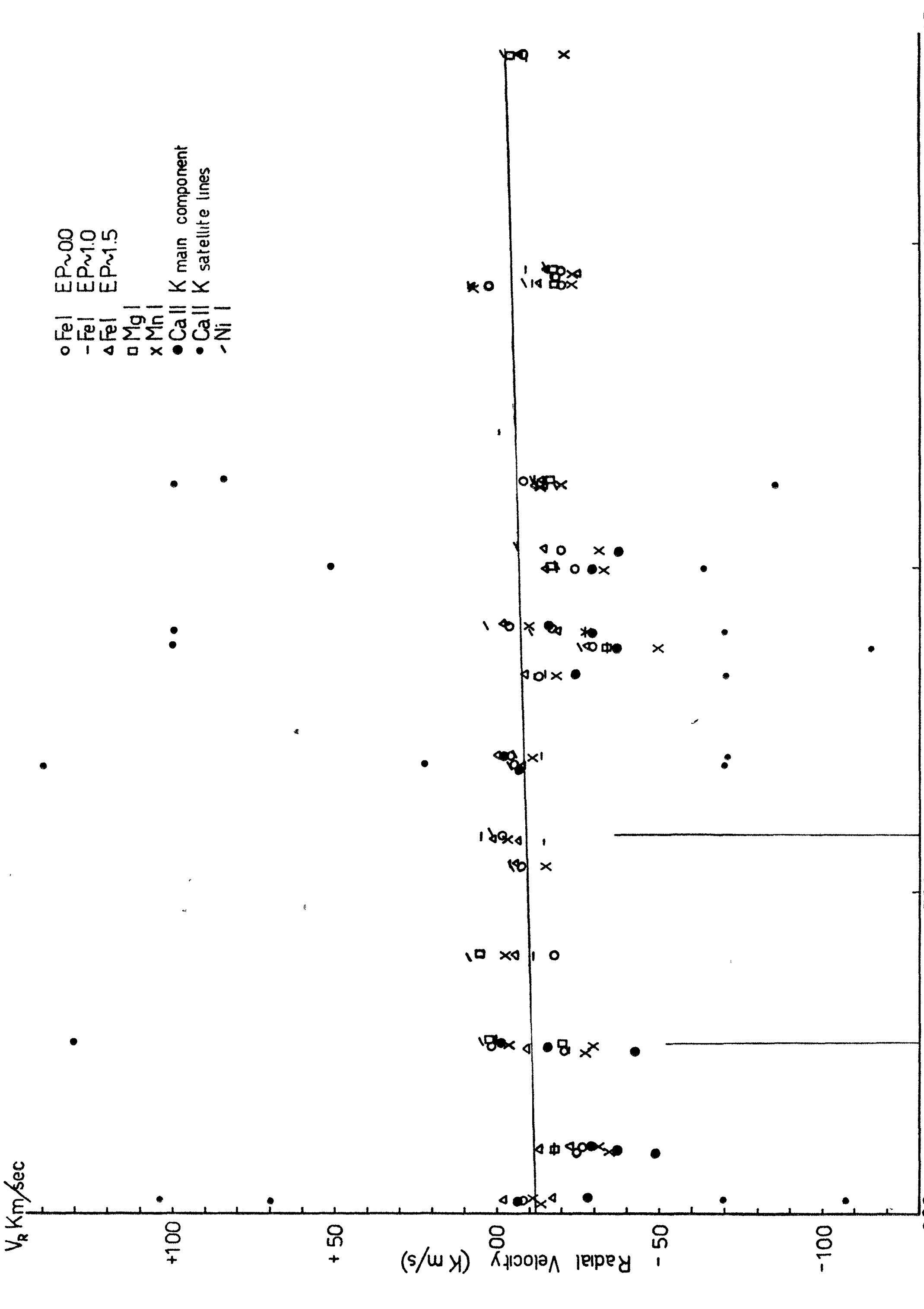

Fig. 4. — Radial velocities of chromospheric lines.

DETERMINATION OF THE RATIO BETWEEN THE CONTINUOUS SPECTRA OF THE B AND K STAR.

It is well known ([6]) that if $\alpha = I_{cB}/I_{cK}$ is the ratio of the continuous spectra of the B and K-type star, α is given by the relation

$$\alpha = (W_K/W_{BK}) - 1$$

where W_K is the total intensity of a line of the K spectrum (and therefore is measured during totality) and W_{BK} is the total intensity of the same line on the composite spectrum B + K (and therefore is measured well out of eclipse). We assume that regions where absorption lines of the Be spectrum are present are avoided.

For the computation of α we use the two best spectrograms obtained during totality (H 917 and H 962) and four spectrograms obtained in August and October 1962 (L 1235, Fa 1267, Fa 1283 and Fa 1498). The continuum which has been adopted for the K-type star is a line joining the points of greatest intensity at λλ 3501.5; 3626.5; 3691.8; 3780.0; 4018.4; 4051.6; 4081.5; 4216.5; 4244.1; 4279.1; 4316.3; 4349.5. Comparison with the Utrecht Solar Atlas ([7]) shows that the lowest points on the tracings for 31 Cygni always correspond to positions on the solar continuum.

TABLE III

λ	identification	W_K	W_{BK}	α	λ	identification	W_K	W_{BK}	α
3510.54	Cr I (109)	.45	.20	1.25	4018.10	Mn I (5)	.53	.20	1.65
3521.26	Fe I (24)	.47	.18	1.60	4030.67	Mn I (2)	1.22	.57	1.14
3526.04	{ Fe I (6)	{ .48	.20	1.40	4033.07	Mn I (2)	1.37	.54	1.54
3526.17	{ Fe I (24)				4034.49	Mn I (2)	.98	.45	1.18
3533.36	Co I (5)	.45	.16	1.80	4041.36	Mn I (5)	.54	.27	1.00
3535.16	{ Zr I (59)	{ .35	.15	1.34	4045.83	Fe I (43)	1.46	.68	1.15
3535.44	{ Ti II (98)				4058.93	Mn I (5)	1.00	.43	1.32
3558.52	Fe I (24)	.54	.30	0.80	4063.61	Fe I (43)	1.46	.68	1.15
3581.19	Fe I (23)	63	.28	1.25	4152.77	Cr I (261)	1.08	.59	.85
3593.49	Cr I (4)	.51	.30	0.70	4161.05	Cr II (162)	.85	.46	.85
3605.33	Cr I (4)	.36	.28	0.40	4177.60	Fe I (18)	1.27	.63	1.02
3610.46	Ni I (18)	.53	.26	1.03	4191.59	Fe (152)	1.10	.64	.72
3618.77	Fe I (23)	.76	.34	1.24	4202.09	Fe I (42)	1.32	.80	.65
3631.46	Fe I (23)	.88	.37	1.38	4210.35	Fe I (152)	.88	.50	.76
3647.44	Fe I (23)	.88	.41	1.15	4215.76	Sr I (1)	1.57	.97	.62
3649.51	Fe I (292)	.82	.29	1.82	4235.91	Fe I (152)	1.00	.70	.43
3669.52	Fe I (523)	.74	.35	1.12	4239.72	Mn I (23)	.95	.56	.70
3679.82	{ Cr I (48)	{ .93	.44	1.12	4246.82	Sc II (7)	.75	.55	.27
3679.91	{ Fe I (5)				4250.46	Fe I (42)	1.22	.90	.35
3759.29	Ti II (13)	.91	.28	2.25	4254.33	Cr I (1)	1.38	1.02	.35
3815.84	Fe I (45)	.76	.24	2.16	4258.32	Fe I (?)	.97	.79	.23
3859.89	Fe I (4)	.91	.22	3.14	4260.43	Fe I (152)	1.30	.90	.45
3865.53	Fe I (20)	.91	.22	3.14	4271.55	Fe I (42)	1.59	1.07	.49
3899.71	Fe I (4)	.92	.35	1.64	4274.80	Cr I (1)	1.35	.97	.40
4005.30	Fe I (43)	1.24	.49	1.53	4315.09	Fe I (71)	.96	.90	.07

Table III gives the list of lines selected for the determination of α, and the average total intensities for the K-type spectrum and for the composite B + K spectrum. The total intensities were computed using the measured central depths and the relation between central depths and half-widths, which was derived by using the best lines on each spectrogram (Fig. 5).

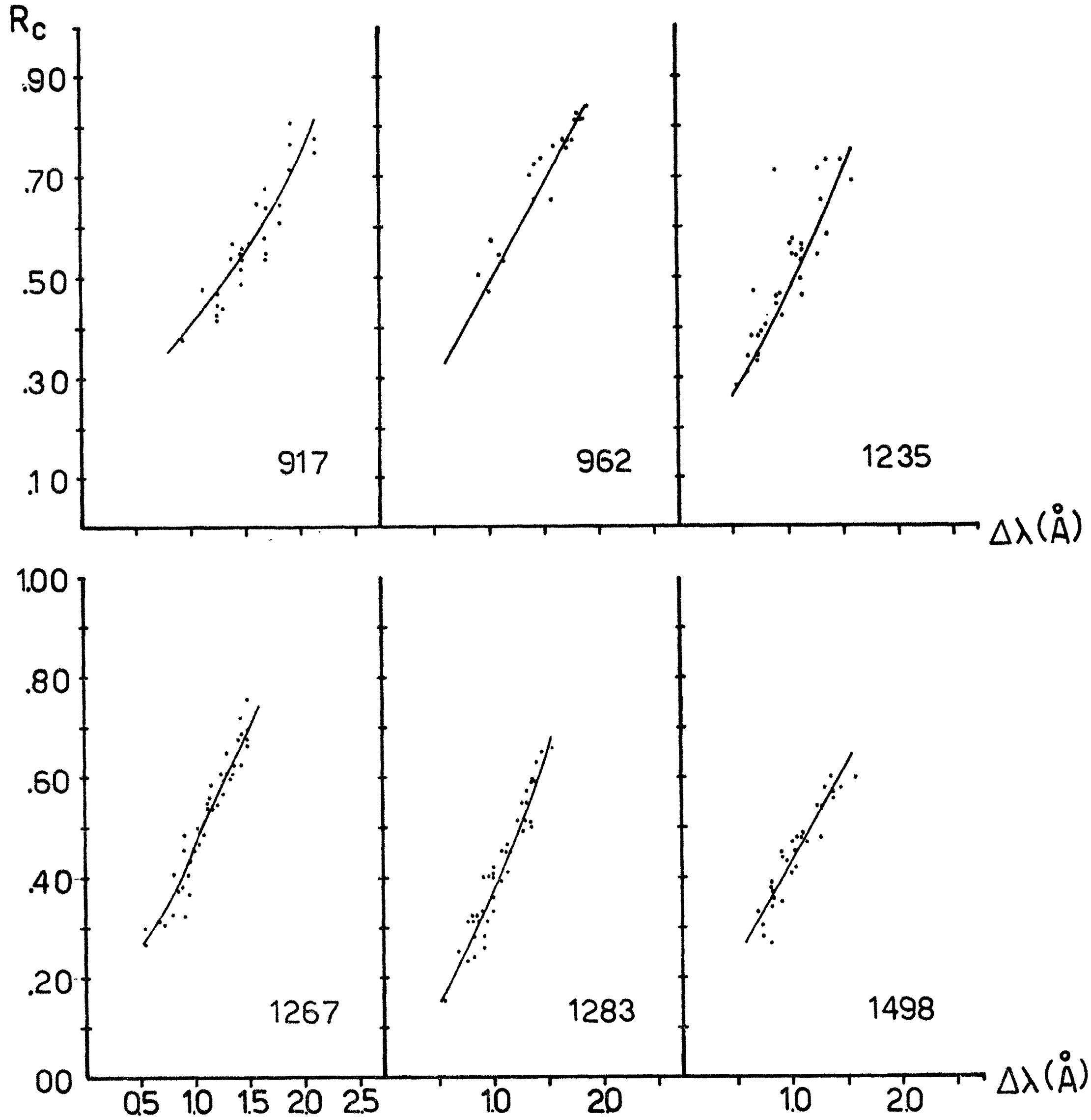

Fig. 5. — Relation between central depths and half-widths.

The scatter of the values of α is large but it is clearly visible a sharp break between the two curves corresponding to $\lambda > 3700$ and to $\lambda < 3700$ A, showing the presence of a strong Balmer discontinuity (Fig. 6). We find $D \simeq 0.36$. However the uncertainty in the determination of the continuum of the K star, especially at $\lambda < 4000$ A is responsible for errors in the determination of α. Taking this source of error into account we estimate that $0.30 \leqslant D \leqslant 0.36$. This value of D suggests that the B-type spectrum is at least B5 or more advanced. The high value of the Balmer discontinuity is shown also by a first visual inspection of spectrograms well out of eclipse. The ultraviolet for $\lambda > 3700$ is dominated by the B-type spectrum and the Balmer lines until H 14 are clearly visible. H 15 and H 16 might be present, however they are strongly blended with Fe I lines of the K star. At $\lambda < 3700$ several metallic lines of the K-type star are clearly visible suggesting that the effect of the B-type continuum is relatively less important than at $\lambda > 3700$.

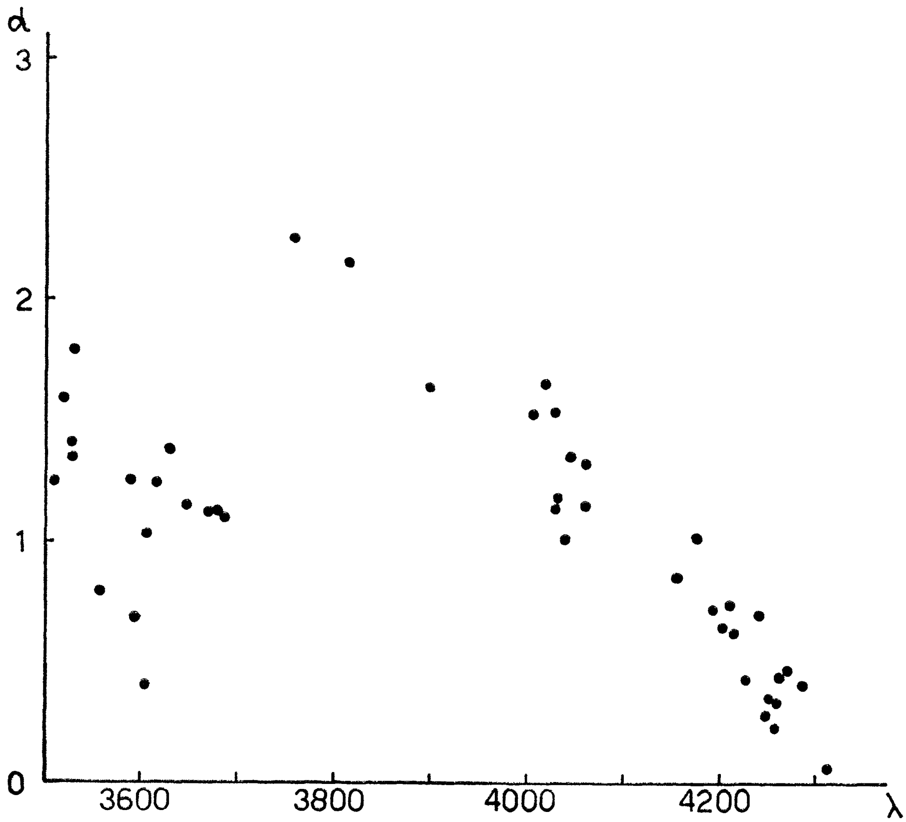

Fig. 6. — α versus λ.

Comparison of our values of α with those derived by other investigators during the eclipse of 1951 is interesting. Underhill ([8]) and Wright and Lee ([6]) derived a series of values for α using the same series of spectrograms. However they arrived to different results because of different criteria adopted in tracing the continuum of the K star. Underhill found α ($\lambda\lambda$ 3920-3944) = 2.3 and α = 1.9 by using respectively a new method and the classical method used by us and by Wright and Lee. Wright and Lee found $\alpha = 0.85$ in the same spectral region, because the different adopted continuum: namely Underhill drew the continuum at 77% of the continuum adopted by Wright and Lee. Larsson-Leander [9] derived $\alpha = 2.3$ by spectrograms having a dispersion of 12 A/mm. Our value of α in the same spectral region is 1.40.

The differences among various researchers are mainly imputable to different criteria adopted for the position of the continuum and probably, at least partly to the different dispersions.

THE B-TYPE SPECTRUM

By using the values of $\alpha(\lambda)$ we reconstruct the spectrum of the B-type star by the usual procedure [6]. We consider the region $\lambda\lambda$ 4050-3815 because the contribution of the B-type spectrum to the composite spectrum is more important, and because several lines characteristic of the B star are found there, such as H7, H8, H9, 3819.7 He I, $\lambda\lambda$ 3856, 3863 and 3854 Si II. The K-type spectrum is reduced by a factor $k = 1/(1 + \alpha)$ and is substracted from the B + K spectrum, the continuum of which is made equal to one. The difference gives the B-type, spectrum, the continuum of which being equal to $1 - (1/1 + \alpha)$. Fig. 7 gives the intensity tracings of the B + K spectrum, of the K-type spectrum reduced by the factor k, and of the B-type spectrum resulting from the difference. The equivalent widths of H8, H9, 3819.7 He I and 3856 Si II have been measured (Table IV). The results agree well with those derived by Wright and Lee [6] for the 1951 eclipse.

We estimate the spectral type and luminosity class of the B star by means of the values of the Balmer discontinuity D, the quantum number of the last visible Balmer line n, and of the equivalent widths of the hydrogen, He I and Si II lines (Table IV). From the series of observations of Williams [10] we see that the Balmer lines from Hγ to H8 have about the same equivalent widths, and the same is true for λ 4026 and λ 3819 He I. We can therefore estimate the spectral type and the luminosity class by using the relation: total intensity versus spectral type and luminosity class derived by Casati and Hack [11] for Hβ, Hγ and

TABLE IV

Spectral criterion	Corresponding spectral type and luminosity class
n: 14 or 15	B3 or earlier, V
D: $0.30 \leqslant D \leqslant 0.36$	B5 IV-V or B5 III $\div$ B8 IV-V or B8 III
H7: $W_\lambda = 7.1$ A	B5 IV-V
H8: $W_\lambda = 4\ 3$ A	B3 IV-V or B5 III
H9: $W_\lambda = 5.1$ A	B3 IV-V or B5 III
3819.7 He I: $W_\lambda = 1.5$ A	B4 IV-V or B4 III
3856.0 Si II: $W_\lambda = 0.2$ A	B5-B6 III

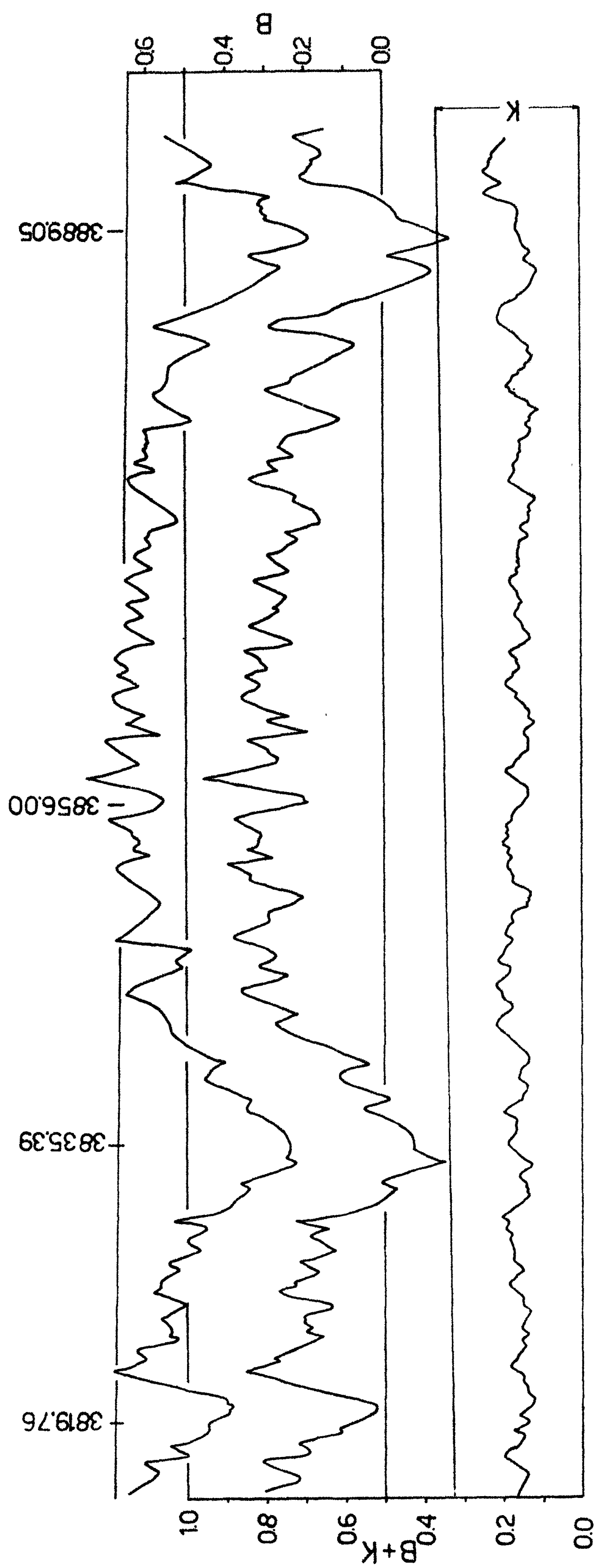

Fig. 7. — Intensity tracings of the composite spectrum B + K, of the K-type spectrum reduced by the factor *k*, and of the B-type spectrum.

Hδ, for 4471 and 4026 He I, and for 4128 and 4131 Si II, using the data by Williams. The luminosity class is derived also by means of the relation between the total intensity of Hγ and the absolute visual magnitude given by Petrie ([12]).

From the value of the Balmer discontinuity a spectral type earlier than B5 is not probable, from the intensity of the helium lines a spectral type later than B5 is also improbable. From the quantum number n and from the equivalent widths of the Balmer lines, the luminosity class is probably IV or V. We therefore conclude that the more probable classification for the B-type star is B5 V or B5 IV, which corresponds to an absolute magnitude $M_v = -1.3$ or $M_v = -2.2$ respectively ([13]).

A complete study of the chromosphere of the K-type star and of the occultation effect due to the low chromosphere is difficult because we have only three spectrograms just before ingress (G 905, G 906 and H 915) and none just after egress. However a study is in progress with the attempt to derive more complete information about the low K chromosphere.

Part of the preliminary work concerning line identification and tracing of the continuum has been done by Amador Muriel and by Antonio Liverani. We are indebted to Mrs. Mildred Shapley Matthews for the heavy task of measuring the tracings point by point. These measurements were reduced to intensity, in unity of the continuum, by means of the electronic computer IBM 1620 of the Astronomical Observatory of Brera, Milano using a program prepared by one of us (Rosanna Faraggiana).

REFERENCES

(1) T. Herczeg und H. Schmidt - Z.f. Ap **55**, 161, 1962.
(2) D. B. McLaughlin - P.A.S.P. **64**, 109, 1952.
(3) A. McKellar and R.M. Petrie - Publ. Dom. Astroph. Obs. Victoria **11**, 1, 1958.
(4) K.O. Wright and G.J. Odgers - Contr. Dom. Astroph. Obs. Victoria No 77, 1962. J.R.A.S. of Canada **56** 149, 1962.
(5) A. McKellar, L.H. Aller, G.J. Odgers, E.H. Richardson - Publ. Dom. Astroph. Obs. **11**, 35, 1959.
(6) K.O. Wright and E.K. Lee - Publ. Dom. Astroph. Obs. **11** 59, 1959.
(7) M. Minnaert, G.F.W. Mulders, J. Houtgast - Photometric Atlas of the Solar spectrum, Utrecht, 1940.
(8) A.B. Underhill - Monthly Notices **114**, 558, 1954.
(9) G. Larsson-Leander - Stockholms Obs. Annaler, **19** No 8, 1957.
(10) E.G. Williams - Ap. J. **83** 279, 1936.
(11) B. Casati e M. Hack - Mem. S.A.I. **27** 307, 1956.
(12) R.M. Petrie - Publ. Dom. Astroph. Obs. **9**, 251, 1952.
(13) P.C. Keenan and W.W. Morgan - Astrophysics, ed. by J.A. Hynek pag. 12, McGraw-Hill Book Company, New York, 1951.