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A Spectroscopic Study of VV Cephei during the 1976–78 Eclipse. I. Observations of the Hα Line

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Abstract

A total of 64 spectrograms of Hα in VV Cephei are analyzed. The equivalent widths of the Hα emission lines are about 9 Å for the violet component and about 6 Å for the red component outside the eclipse. They decrease markedly to about 1 Å during the eclipse of the B-type star, but weak emissions are still seen around mid-eclipse. The separation of the emission peaks is about 170 km s^{-1} outside the eclipse and becomes 120 km s^{-1} around mid-eclipse. From the variations of the emission intensities with the eclipse of the B star, the emissions are deduced to be radiated from an envelope surrounding the B star with an effective radius of $\sim 500 R_{\odot}$ and rotating in the same direction as that of the orbital motion of the B star with a representative velocity of 85 km s^{-1}. The emission intensities vary abruptly on time scales of hours to a few days. This is due to atmospheric time variations of the M star.

Key words: Be envelopes; Hα emission; VV Cephei.

1. Introduction

VV Cephei is a long period (≅20.4 yr) eclipsing binary system consisting of an M-type supergiant primary with a B-type companion. It presents an opportunity to study the extended atmosphere of the primary component and the envelope of the secondary. During the 1976–78 eclipse we took about one hundred spectrograms at the Okayama Astrophysical Observatory and the Dodaira Station of Tokyo Astronomical Observatory. In this series of papers we analyze the spectrograms as well as ones taken outside the eclipse. In paper I (present paper), we give the observed values of the equivalent width and radial velocity of the Hα line and find some characteristics of the Hα line. In paper II (Saijo 1981), a model for the structure of the Hα-emitting envelope is proposed so as to satisfy the profiles of the Hα emissions observed outside and during the eclipse. In paper III the atmospheric structure of the M-type supergiant component is examined from the blue and ultraviolet spectrograms on which we can find the atmospheric lines of the M star against the B star's light. In paper IV the characteristics of mass transfer between the components and of the circumstellar matter are studied from an analysis of mainly the forbidden lines of Fe and the red component of the Hα emission.

The observations at Okayama were performed by using the coudé spectrograph of the 188-cm reflector with a grating of 1200 grooves mm^{-1}. The dispersions of the spectrograms are 20.7 and 8.3 Å mm^{-1} for the Hα region and 10.1–10.4 Å mm^{-1} for the blue and ultraviolet regions, respectively. The observations at Dodaira were done only for the Hα region by using the Cassegrain spectrograph of the 91-cm reflector with a grating of 1800 grooves mm^{-1}. The dispersion is 14.5 Å mm^{-1}. Widenings of spectra and spectral regions of the plates related to this paper are shown in footnotes of table 1. The emulsions used are Eastman Kodak 103aE, 103aF, 103aO, IIaF, and IIaO. Radial velocities of the absorption lines were measured by the Mann-type 422 comparator of Tokyo Astronomical Observatory, and those of the emission lines were measured relative to the metallic absorption lines on the charts of density tracing of the spectrograms.

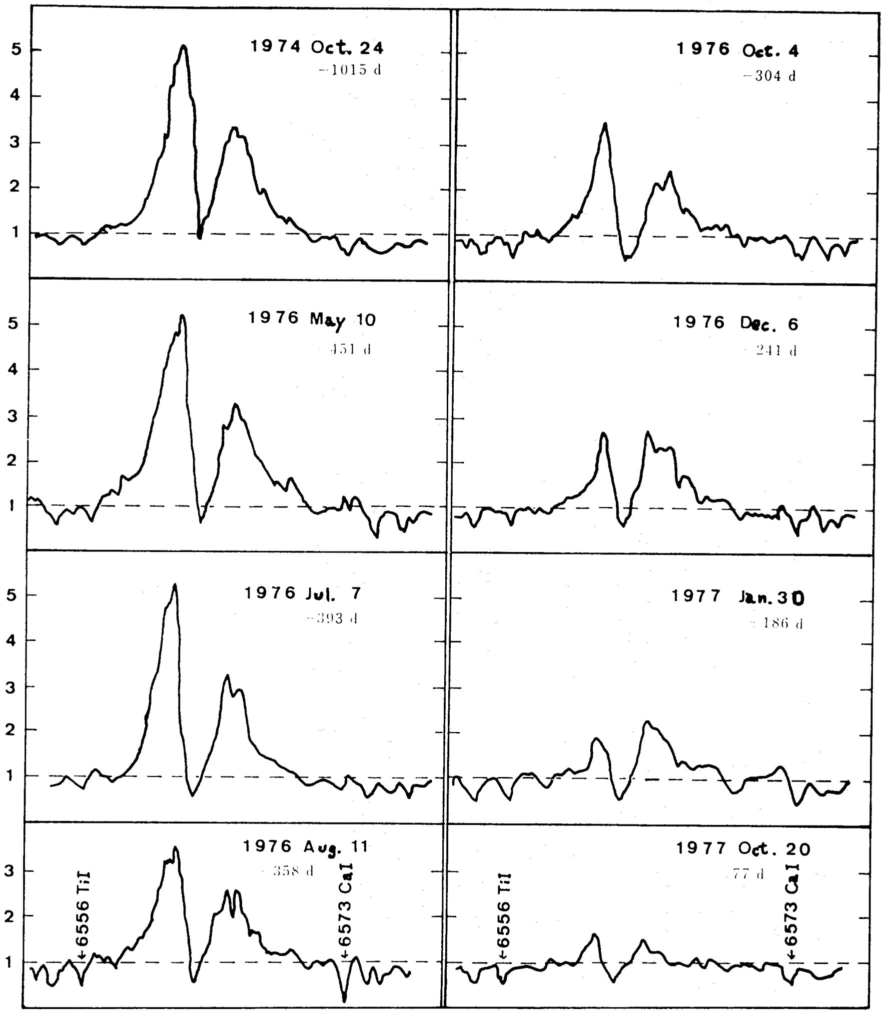
2. Hα Emission Line

Hutchings and Wright (1971) considered that the Hα emission line of VV Cep provides the most reliable data on the orbital motion of the Be component, because the line is stronger and less severely blended with the M star features than the higher Balmer lines. From the observations of this line they proposed an orbit of the B star and a model of the Hα-emitting region around the B star. Wright (1977) analyzed the Hα spectra obtained during 1956–1976 and determined the elements of the system.

We have taken sixty-four spectrograms of the Hα region near and during the 1976–78 eclipse. In the 1956–58 eclipse (Hutchings and Wright 1971) only fourteen Hα plates were obtained, although the eclipse continued for 450 d or more. In figure 1 we show some representative profiles of the Hα lines obtained outside the eclipse, on ingress, on totality, and on egress. The phases are calculated from JD 2443360 the date of the mid-eclipse, determined by Saitō et al. (1980). All the emission lines are separated into the violet and red components by the central absorption lines. It is obviously seen that the intensities of the emissions decrease with the eclipse, that even near the mid-eclipse weak emissions still remain, and that during ingress (egress) the violet component weakens (strengthens) more rapidly than the red one.

(a) *Intensities of the Violet and Red Components*

The equivalent widths and peak heights of the Hα emission components are listed in the fifth to ninth columns of table 1. These values are measured in units of the continuum. From the photometry of this eclipse the continuum levels at 5080 Å (Saitō et al. 1980) and at the Hα region (McCook and Guinan 1978) are scarcely affected by eclipse and vary semi-regularly by about 20%. Such variation of the continuum level is considered to be caused by the intrinsic nature of the M star. We neglect the influence of the variation in continuum radiation on the equivalent width and peak height and consider that the equivalent width is ap-



(a)

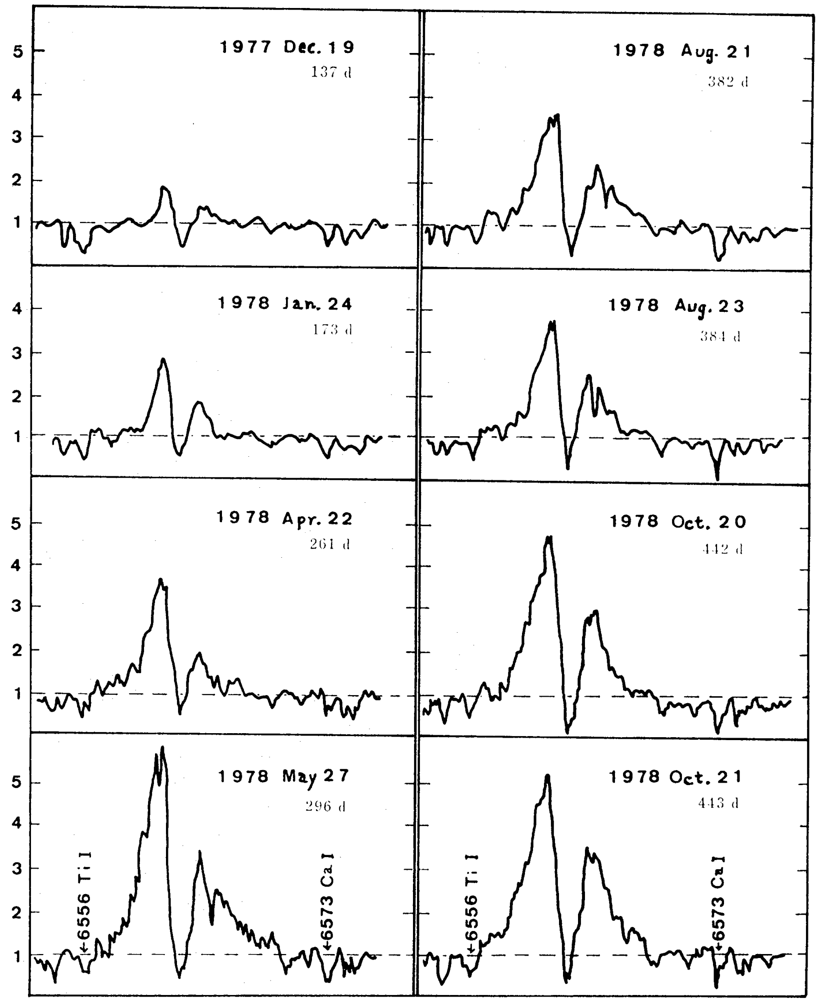
Fig. 1. See the legend on the next page.

proximately proportional to the emission intensity. The equivalent widths listed have been corrected for the absorption of the M star, which has been assumed to be the same with the mean value of α Ori (M2Iab) for a plate (plate number C 10-3402) taken at Okayama on November 29, 1977, and α Sco, (M2Iab) for a plate (plate number C 10-3456) taken at Okayama on January 25, 1978. Our plates show that these two stars have similar profiles of Hα absorption.

Figure 2 shows the equivalent widths of the emission as functions of Julian Date. The values decrease drastically in the eclipse; they are 6–10 Å outside the eclipse and 0.5–1 Å at the minimum. In the ingress the violet component first begins to decrease its intensity and then the red component does. The values of V/R is minimum, $\sim$0.5 around a phase of -186 d. After the mid-eclipse the violet component strengthens earlier than the red component, and thus V/R begins to increase. The value of V/R reaches a maximum, 2.3, around at the phase of 293 d and then decreases until the eclipse ends.

(*b*) *Radial Velocities*

The radial velocities of the violet and red components of the Hα emission, the Hα central absorption, and the metallic lines are, respectively, listed in the tenth



(b)

Fig. 1. Representative linear intensity tracings of the Hα line for the phases outside eclipse (phase$=-1015$ d), in ingress (phases$=-451$ d to -186 d), on totality (phases$=77$ d and 137 d), and in egress (phases$=173$ d to 443 d). The dates and phases are shown in each figure.

to fourteenth columns of table 1. These velocities are also plotted in figure 3 as functions of the Julian Date. The radial velocities of metallic lines agree wtih the orbital motion of the M star calculated by using Wright's (1977) elements. The Hα absorption line has velocities about 10–20 km s^{-1} less than that of the metallic lines. Such a difference was also seen for the corresponding phases, namely JD 2435500–JD 2436500 of the last eclipse observed by Wright and Larson (1969), whose result showed that the difference continued till about 3 yr before the secondary eclipse, and that after that time the velocities of Hα absorption and those of the M-type metallic lines agreed. The radial velocities of Hα absorption seem to be related to those of the M star's metallic lines, rather than those of the emission component. The displacement of the radial velocities of the Hα central absorptions to lower velocities may be due to the H I gas expanding with velocities of 10–20 km s^{-1} from the M star toward the sun. This problem will be discussed in paper IV.

Table 1. Intensities of the violet and red components of Hα emission and radial velocities of the Hα emission, the central absorption of Hα line, and the metallic lines.

Plate No*	Date (UT)	JD Hel. 2440000+	Phase** (d)	Equivalent width			Peak height+		Radial velocity++ (km s^{-1})					Remarks
				Violet (Å)	Red (Å)	V/R	Violet	Red	Violet	Red	R−V	Central absorption	Metallic lines+++	
L-3195	1974 Oct. 24	2344.96	−1015	8.4	6.2	1.4	3.9	2.3	−73.3	61.2	134	−24.8	−27.5 (10)	
L-3383	1976 May 10	2909.29	−451	7.1	6.9	1.0	3.3	1.7	−76.8	76.3	153	−35.2	−21.1 (9)	
L-3389	May 13	2912.29	−448	4.1	3.0	1.4	1.9	1.0	−95.7	68.6	164	−27.2	−22.3 (7)	
L-3407	July 7	2967.22	−393	8.0	5.7	1.4	4.8	2.6	−82.3	65.8	158	−30.6	−22.7 (11)	
C10-3199	Aug. 7	2998.03	−362	5.0	4.4	1.1	2.8	1.6	−88.2	84.0	172	−35.1	−20.9 (37)	
C10-3200	Aug. 7	2998.08	−362	5.8	4.8	1.2	3.0	1.8	−79.3	85.8	175	−34.0	−19.7 (36)	
C4-4725......	Aug. 8	2999.32	−361	6.4	4.4	1.5	1.9	1.3	−94.0	70.4	164	−26.8	−19.5 (27)	
C10-3206	Aug. 11	3002.12	−358	4.7	4.4	1.1	2.6	1.5	−84.2	56.8	141	−35.7	−19.2 (33)	
C4-4739......	Aug. 14	3005.11	−355	4.8	3.6	1.4	2.0	1.2	−104.2	69.2	173	−25.7	−19.4 (29)	
C4-4740......	Aug. 14	3005.17	−355	4.7	3.5	1.3	1.9	1.1	−96.4	74.8	171	−20.3	−16.7 (6)	U.E.§
C4-4762......	Oct. 3	3055.25	−305	3.3	3.5	0.94	1.4	1.1	−97.4	88.2	185	−27.4	−19.1 (11)	
C10-3214	Oct. 4	3056.10	−304	3.5	3.5	1.0	2.0	1.4	−87.7	81.8	168	−27.2	−20.0 (33)	
C10-3235	Dec. 3	3116.90	−243	3.0	5.1	0.59	2.0	1.8	−83.6	47.7	131	−36.6	−19.5 (37)	
C10-3239	Dec. 4	3117.06	−243	2.6	4.6	0.56	1.5	1.5	−86.6	48.1	135	−36.9	−19.1 (34)	
C10-3247	1976 Dec. 6	3119.08	−241	2.4	4.4	0.54	1.6	1.7	−87.6	47.4	135	−36.0	−21.7 (35)	
C4-4957......	1977 Jan. 28	3171.97	−188	1.8	3.7	0.47	0.9	1.2	−79.5	62.5	142	−31.3	−19.7 (36)	
C4-4962......	Jan. 30	3173.92	−186	1.9	3.8	0.49	1.2	1.6	−84.1	57.8	142	−36.8	−19.3 (38)	
C4-4963......	1977 Jan. 30	3173.99	−186	1.4	3.1	0.46	0.9	1.1	−88.6	53.4	142	−36.1	−19.4 (34)	

Table 1. (Continued)

Plate No.*	Date (UT)	JD Hel. 2440000+	Phase** (d)	Equivalent width Violet (Å)	Equivalent width Red (Å)	Equivalent width V/R	Peak height⁺ Violet	Peak height⁺ Red	Radial velocity⁺⁺ (km s⁻¹) Violet	Radial velocity⁺⁺ Red	Radial velocity⁺⁺ R−V	Radial velocity⁺⁺ Central absorption	Radial velocity⁺⁺ Metallic lines⁺⁺⁺	Remarks
C4-5058......	1977 Aug. 19	3375.04	−15	0.81	1.1	0.74	0.44	0.49	−86.9	27.2	114	−35.4	−13.8 (30)	
C10-3363	Aug. 19	3375.17	−15	0.76	1.1	0.69	0.55	0.57	−94.9	28.2	123	−24.7	−16.6 (8)	U.E.
C4-5059......	Aug. 19	3375.31	−15	0.49	—	—	0.55	—	−86.9	—	—	−36.8	−12.9 (35)	A plate flaw on the red emission
C4-5103··	Oct. 20	3436.98	77	1.1	1.2	0.88	0.65	0.50	−61.0	54.1	115	−29.1	−10.9 (27)	
L-3485	Oct. 21	3437.95	78	0.92	1.1	0.84	0.58	0.42	−86.4	48.4	135	−36.8	−16.2 (21)	
L-3486	Oct. 21	3438.04	78	1.0	1.1	0.93	0.56	0.36	−87.7	48.0	136	−36.6	−16.7 (20)	
C4-5161......	Dec. 19	3496.88	137	0.77	0.93	0.82	0.16	0.10	−80.6	57.7	138	−33.6	−17.8 (25)	
C4-5162......	Dec. 19	3496.90	137	1.6	1.1	1.4	1.0	0.39	−90.1	38.2	128	−31.1	−16.8 (15)	
C10-3405·· ..	1977 Dec. 19	3496.96	137	1.3	1.1	1.2	0.83	0.40	−95.0	47.3	142	−35.3	−15.0 (34)	
C10-3451·· ..	1978 Jan. 24	3532.96	173	1.5	1.1	1.3	1.0	0.43	−90.6	50.7	141	−39.5	−18.5 (9)	U.E.
C4-5204··	Jan. 24	3532.97	173	2.9	1.8	1.6	1.8	0.82	−79.6	47.5	127	−33.9	−17.7 (32)	
C10-3452·· ..	Jan. 25	3533.92	174	—	—	—	—	—	−91.3	34.1	125	−35.9	−21.1 (18)	U.E.
C10-3458·· ..	Jan. 27	3535.94	176	1.3	1.0	1.3	0.95	0.52	−90.8	44.9	135	−32.0	−21.9 (6)	U.E.
L-3505	Apr. 22	3621.27	261	5.8	2.7	2.2	2.4	0.96	—	—	—	—	—	Lack of comparison lines
C4-5258......	May 24	3653.18	293	8.8	3.8	2.3	4.1	1.5	−117.8	54.1	172	−38.5	−23.7 (28)	
C10-3544	May 25	3654.21	294	—	—	—	—	—	−92.3	46.6	139	−37.4	−21.3 (4)	U.E.
C4-5261......	May 25	3654.29	294	8.5	4.3	2.0	3.6	1.7	−97.5	63.2	161	−23.8	−14.0 (23)	
L-3507	May 26	3655.25	295	11.5	5.2	2.2	6.0	2.4	−86.5	70.5	157	−26.0	−14.9 (27)	
C10-3546	May 26	3655.31	295	5.4	2.9	1.9	2.5	1.1	−108.2	55.3	164	−44.0	−17.7 (21)	
C4-5265......	1978 May 27	3656.17	296	7.1	3.9	1.8	3.3	1.6	−98.1	58.9	157	−31.3	−16.5 (23)	

Table 1. (Continued)

Plate No.*	Date (UT)	JD Hel. 2440000+	Phase** (d)	Equivalent width			Peak height+		Radial velocity++ (km s^{-1})					Remarks
				Violet (Å)	Red (Å)	V/R	Violet	Red	Violet	Red	R−V	Central absorption	Metallic lines+++	
L-3508	1978 Jun. 21	3681.15	321	5.8	3.3	1.8	2.5	0.98	—	—	—	—	—	Lack of comparison lines
L-3510	Aug. 2	3723.17	363	5.6	3.1	1.8	2.6	1.0	−102.9	51.3	154	−31.8	−18.1 (20)	
C10-3589	Aug. 21	3741.96	382	6.0	4.4	1.4	2.5	1.5	−104.3	55.2	160	−37.2	−17.7 (26)	
L-3510 B	Aug. 21	3742.04	382	4.8	3.1	1.6	2.1	1.0	−103.6	85.8	189	−29.6	−18.7 (22)	
C10-3590	Aug. 21	3742.29	382	5.5	4.4	1.3	2.5	1.3	−78.8	63.2	142	−32.7	−16.8 (20)	
C10-3591	Aug. 22	3743.13	383	5.3	3.5	1.5	2.2	1.1	−87.0	52.8	140	−35.8	−17.2 (30)	
L-3514(2)	Aug. 22	3743.16	383	—	—	—	—	—	−94.5	64.9	159	−31.8	−17.0 (16)	
C10-3594	Aug. 23	3744.00	384	5.6	3.9	1.5	2.5	1.4	−87.9	46.6	134	−30.7	−15.0 (26)	
C10-3595	Aug. 23	3744.13	384	5.8	3.6	1.6	2.8	1.4	−93.1	52.7	146	−33.1	−14.5 (24)	
C10-3598	Aug. 24	3745.08	385	5.8	3.2	1.8	2.7	1.1	−75.7	66.4	142	−27.3	−13.9 (19)	
C10-3608	Oct. 17	3799.02	439	—	—	—	—	—	−84.6	72.7	157	−32.5	−14.0 (7)	U.E.
C10-3609	Oct. 17	3799.06	439	8.5	4.9	1.7	3.7	2.1	−87.2	51.1	138	−23.6	−13.3 (11)	
C10-3610	Oct. 18	3800.04	440	—	—	—	—	—	−90.0	60.0	150	−30.5	−13.1 (17)	
C10-3611	Oct. 18	3800.08	440	7.8	6.3	1.2	2.8	2.1	−93.8	44.5	138	−29.0	−14.3 (20)	
C10-3612	Oct. 19	3800.96	441	8.8	5.8	1.5	4.1	2.4	−80.8	50.0	131	−33.6	−16.2 (22)	
C10-3613	Oct. 20	3801.98	442	8.3	5.3	1.6	3.9	2.1	−103.4	68.5	172	−31.0	−16.5 (9)	
C10-3615	1978 Oct. 21	3803.08	443	8.9	6.2	1.5	3.9	2.3	−85.4	56.6	142	−34.1	−15.3 (20)	

Table 1. (Continued)

Plate No.*	Date (UT)	JD Hel. 2440000+	Phase** (d.)	Equivalent width: Violet (Å)	Equivalent width: Red (Å)	Equivalent width: V/R	Peak height⁺: Violet	Peak height⁺: Red	Radial velocity⁺⁺ ($km\ s^{-1}$): Violet	Radial velocity: Red	Radial velocity: R−V	Radial velocity: Central absorption	Radial velocity: Metallic lines⁺⁺⁺	Remarks
L-3521	1978 Nov. 9	3822.06	462	5.1	4.1	1.3	2.4	1.7	−100.8	54.9	156	−50.4	−20.5 (6)	U.E.
C10-3626	Nov. 20	3832.91	473	6.8	4.6	1.5	3.2	2.4	−103.7	57.4	161	−30.6	−17.2 (14)	
C10-3635	Nov. 21	3833.89	474	5.5	4.4	1.3	2.8	2.1	−122.4	42.5	165	−29.2	−18.4 (8)	
L-3522·	Dec. 27	3869.88	510	8.7	6.3	1.4	3.2	2.8	−111.5	54.2	166	−33.9	−16.8 (22)	
L-3523·	Dec. 27	3869.94	510	6.8	5.7	1.2	2.5	2.3	−112.8	57.6	170	−35.7	−15.2 (15)	
L-3524	1978 Dec. 27	3869.96	510	—	—	—	—	—	—	—	—	−34.1	−16.2 (23)	O.E.§§
L-3525·	1979 Jan. 25	3898.89	539	5.1	3.7	1.4	2.1	1.6	−99.6	60.8	160	−31.0	−15.1 (18)	
L-3526·	Jan. 25	3898.92	539	5.7	3.9	1.5	2.4	1.5	−96.7	87.7	184	−28.2	−13.6 (9)	
L-3541	1979 Dec. 25	4232.90	873	10.1	5.5	1.8	4.9	3.0	−90.4	58.6	149	−27.3	−12.0 (23)	

* C4– and C10–plates were taken at Okayama and L-plates at Dodaira, and the dispersions are, respectively, 20.7, 8.3, and 14.5Å mm^{-1}. Widenings of spectra are 0.20 mm for C4–, 0.45 mm for C10–, and 0.40 mm for L-plates, respectively, and spectral regions are 5530-7200 Å for C4–, 5930-6800 Å for C10–, and 5900-7000Å for L-plates, respectively. The plates superscripted with single dot after the numbers are 103aE emulsions, the plates doubly dotted are IIaE emulsions, and others are 103aF emulsions.

** Days counted from the mid-eclidse, JD 2443360.

⁺ Measured from the continuum level in units of the continuum level around the Hα line. Lack of values is due to a large uncertainty of the continuum level and zero level.

⁺⁺ "Violet" and "red" components of the Hα emissions are measured relative to the values of "metallic lines" in the last column. "Central absorption" of Hα and the "metallic lines" are measured relative to the sun. Errors of the measurements are less than 2 $km\ s^{-1}$.

⁺⁺⁺ Numbers in parentheses are the numbers of the metallic lines measured.

§ Under exposure.

§§ Over exposure.

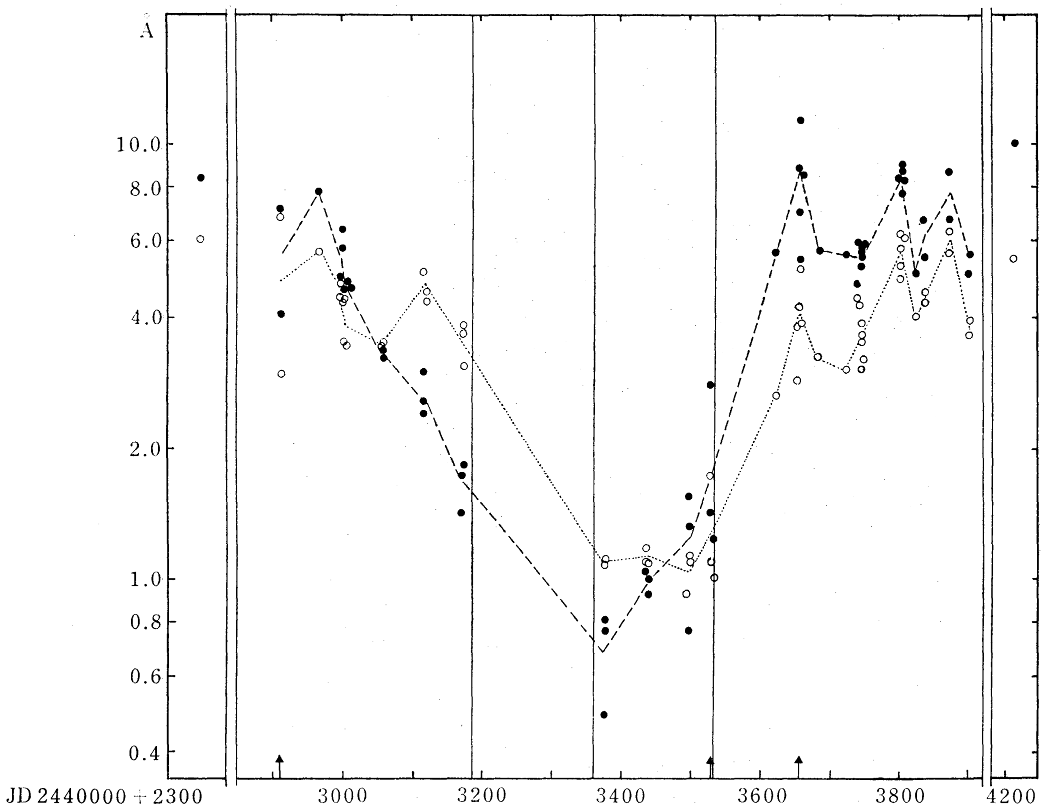


Fig. 2. Equivalent widths of the violet (filled circles) and red (open circles) components of the Hα emission as functions of the Julian Date. The dashed (violet) and dotted (red) lines connect average values, where each average value is that of the values obtained on three successive days. The arrows indicate the phases corresponding to abrupt variations in intensity. The vertica llines show, respectively, the dates of the first contact, the mid-eclipse, and the fourth contact of the B star's eclipse (Saitō et al. 1980). The absolute flux corresponding to 1 Å of the equivalent width is 5.76×10^{-11} erg cm^{-2} s^{-1}, which is estimated by the relation given in Allen (1973), $m_V=5.1$ (Saitō et al. 1980) assumed to be constant around Hα during the eclipse, and $T=3000$ K for VV Cep.

It is notable that the separation of the emission peaks is 120 km s^{-1} around mid-eclipse which are smaller than the values, ~130 to ~170 km s^{-1} in other phases, although the emission intensities decrease drastically in the eclipse.

(*c*) *Peculiar Phases of Intensities and Radial Velocities*

There are some instances when the emission intensity varies abruptly by a factor two or more in one night or during a few days. These are JD 2442909–2442912, JD 2443532–2443535, and JD 2443653–2443655, as indicated by the arrows in figure 2. Figure 4 shows an example of such variations of the Hα profiles. The intensity varies by about a factor two between the two cases shown in figure 4. It should be noted that such phases correspond to the descending branches of the intrinsic light variation of the M star observed at 5080 Å (Saitō et al. 1980). At JD 2443496, where the light curve is at nearly maximum, only the violet component varies by about a factor two. For JD 2443436–2443438 and JD 2443898 the phases also cor-

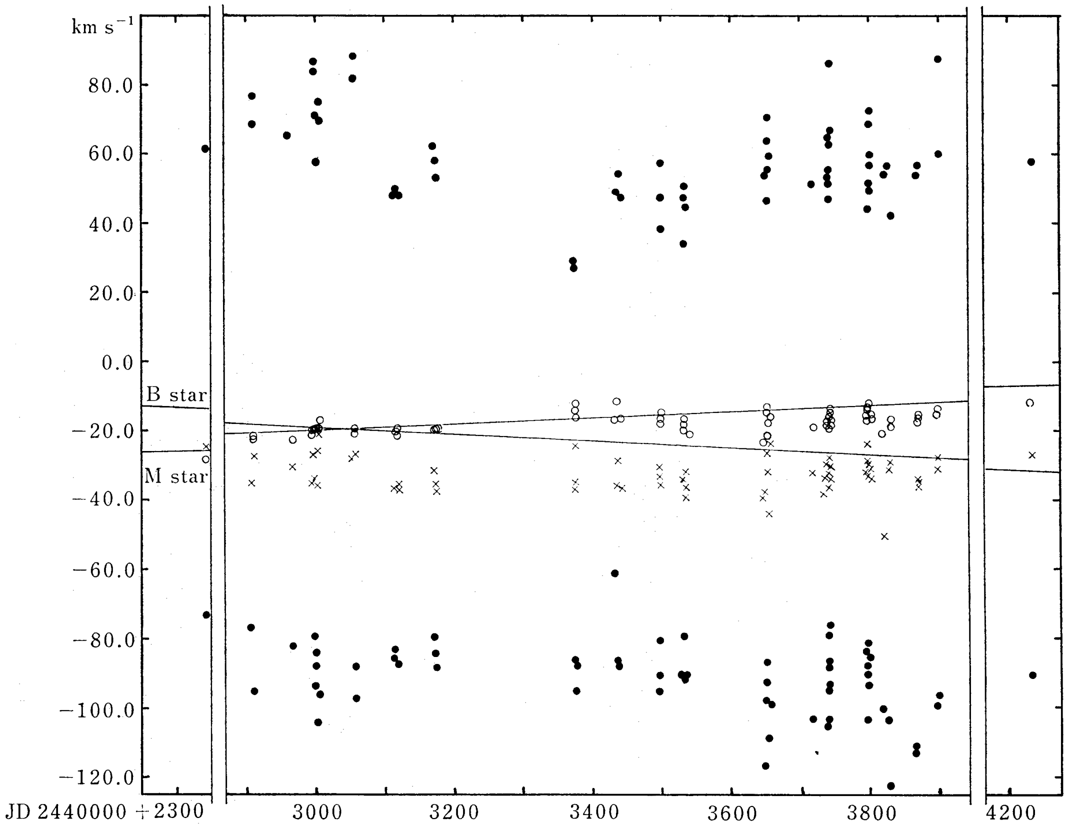


Fig. 3. Radial velocities of the violet and red components of the Hα emissions (dots), the central absorption of Hα (crosses), and the metallic lines (open circles) as functions of the Julian Date. The solid lines represent the orbits of M and B stars.

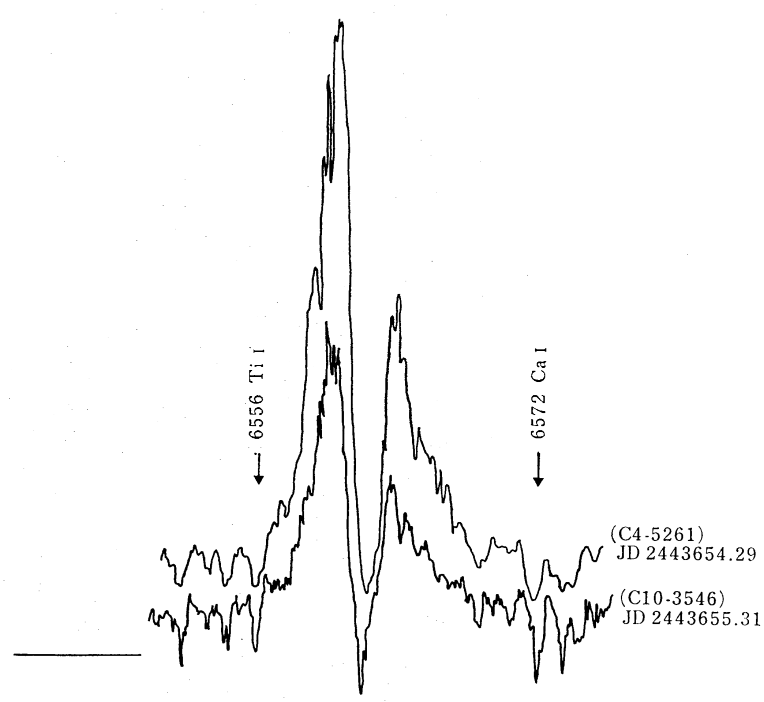


Fig. 4. Abrupt variation of the profile of the Hα line. JD's and plate numbers are shown in the figure. The horizontal lines represent the zero levels.

respond to the descending branches of the intrinsic light variation, but the Hα intensities scatter within a relatively small range for these days, compared with those during the three phases mentioned above.

3. Conclusions

From the observations we find the following characteristics of the Hα-emitting region:

(1) The emission intensities vary with the B star's light undergoing an eclipse by the M star, and as is shown in figure 2, in the ingress the violet component of the Hα emission first weakens and then the red component does. From these results we can confirm Hutchings and Wright's (1971) proposal that the B star accompanies the emitting region which rotates in the same direction as the orbital motion of the B star. (2) We can see from figure 2 that in the ingress the emission intensity begins to decrease steeply at JD 2442967 for the violet component and at JD 2443117 for the red component. The time interval is 150 d. Thus the effective radius of the emitting region is estimated from the orbits of the components (Wright 1977) to be about 3.5×10^{8} km, i.e., $\sim500R_{\odot}$. This value is not inconsistent with Hutchings and Wright's (1971) value, $\sim650R_{\odot}$, obtained from the analysis of the observations of last eclipse and with Möllenhoff and Schaifers' (1978) lower limit, $96R_{\odot}$, of the radius of the Hβ-emitting region obtained from the observations during the ingress of this eclipse. (3) Since the separation of the emission peaks is $\sim170\,\mathrm{km\,s^{-1}}$ outside the eclipse, the rotational velocity in the main part of the envelope is greater than $85\,\mathrm{km\,s^{-1}}$. A simple model for the structure of the Hα-emitting region is proposed by Saijo (1981) in paper II of this series.

As mentioned in section 2, the intensities of the Hα emissions vary abruptly on some occasions. Such phenomena occur on the descending branches of the pulsating intrinsic light curve of the M star, and the time scales of the variations seem to be from one hour to a few days. The phenomena may be caused by an abrupt change of the continuum level of the M star or by an abrupt change of the opacity of the M star's atmosphere due to some variations in its physical state. The former explanation may be discarded because the light curve at 5080 Å observed by Saitō et al. (1980) did not show such large variations. We suppose that the atmospheric structure of the M star varies with time scales of hours and the variations of the physical state of the atmosphere strongly affect on the observed intensity of the Hα emissions.

Note added: After submitting this paper for publication we received a preprint by Möllenhoff and Schaifers (1980) who studied similar data, from the egress phase of the same eclipse of VV Cep. They found the radius of the Be envelope to be $300R_{\odot}$. They also found sudden variations of the emission components of Hα and Hβ.

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