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Spectroscopic Observations of VV Cep

II. The Egress Phase of the 1976/78 Eclipse

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Summary. We made repeated spectroscopic observations at medium dispersion of the egress phase of the VV Cep eclipsing binary system. The double emission profiles of H_β and H_α showed characteristic variations: The blue emission component reappeared first followed by the red one. This agrees with the corresponding results obtained during the ingress phase (Paper I). A rapidly rotating oblate envelope around the hot companion is proposed as a model for the emission region. The contact epochs of the different emission components allow conclusions on the morphology of the envelope.

Key words: VV Cep stars – eclipsing binaries – spectroscopic binaries – envelopes

1. Introduction

VV Cep is one of the most interesting spectroscopic binaries. It is the prototype of a class of supergiant binary systems whose spectra show emission lines of hydrogen and [Fe II] (Cowley, 1969). The primary star of the VV Cep system is an M supergiant of extremely large radius ($\approx 1800 R_\odot$) and of $20 M_\odot$. The B type secondary star has the same mass while its radius is only $13 R_\odot$.

VV Cep is particularly interesting since it is an eclipsing binary with a period of 7430 d (20.4 yr). As the hydrogen emission lines originate from an emission envelope which surrounds the hot companion, they too disappear during the eclipse. The higher Balmer lines show a characteristic reversed P-Cyg profile while H_β and H_α show (asymmetric) double emission lines.

The recent eclipse of VV Cep took place in 1976–78. A large number of medium dispersion Cassegrain spectrograms were taken during the different phases of the eclipse. The variations of the Balmer lines during the ingress (1976/77) were described in an earlier paper (Möllenhoff and Schaifers, 1978; Paper I). The present article describes the continuation of these observations during the egress of the binary system. The successive eclipsing of the different emission components sets some constraints for the morphology of the emission envelope. Consequences relating to the model of the VV Cep system are discussed.

2. Observations

The equipment used for our observations was the same as that described in Paper I: A Boller & Chivens spectrograph (model 26767) attached to the Nasmyth focus of the 72 cm reflector of the Landessternwarte Heidelberg. Between September 25, 1977 and August 5, 1979 50 blue and 37 red spectrograms of VV Cep could be obtained. The dispersion was 55 Å mm^{-1} (2nd order) for the blue spectrograms (IIa-O plates) and most of the red spectrograms (103a-F plates). Some of the red spectrograms (those taken

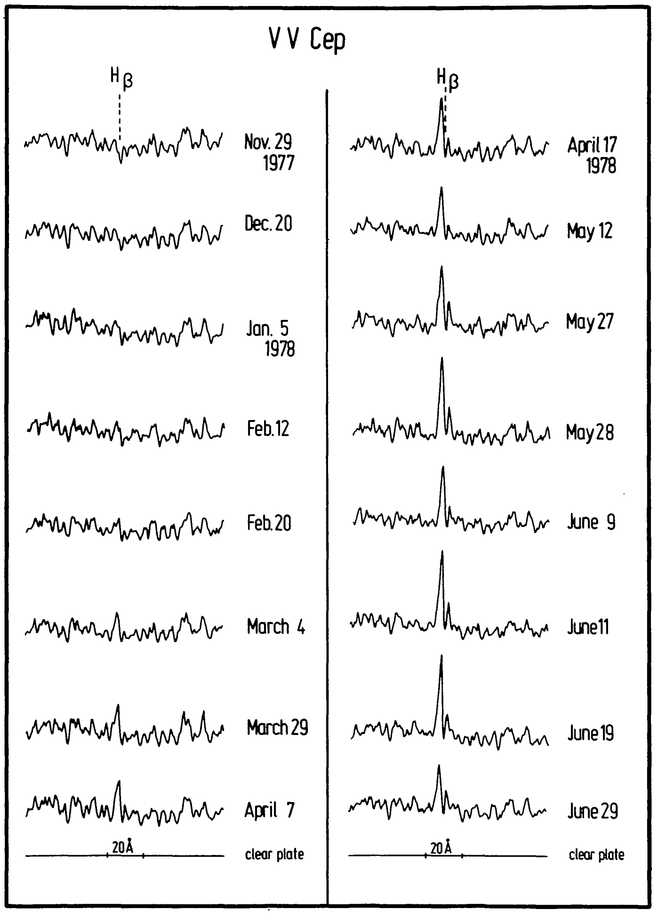

Fig. 1. Increase of the H_β emission lines during the egress of VV Cep. While the blue emission component started its increase already in January, 1978, the red component did not reappear before April, 1978. All tracings are normalized to the same height of the continuum above clear plate (which is only indicated for the bottom tracings). Note the temporary decrease of H_β on June 9 and June 29

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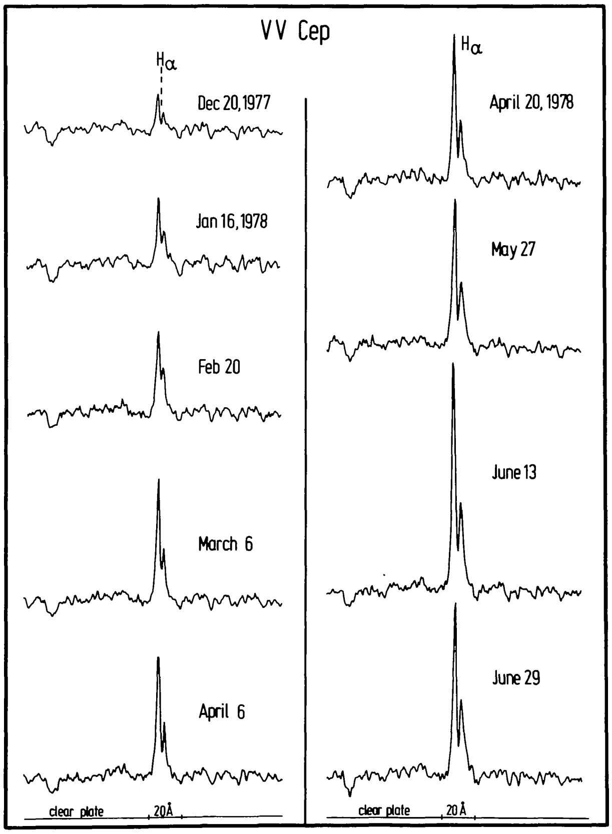

Fig. 2. Increase of the H_α emission lines during the egress of VV Cep. The successive increase of the blue and the red emission component is not as clearly visible as in the case of H_β. Note the temporary increase on June 13

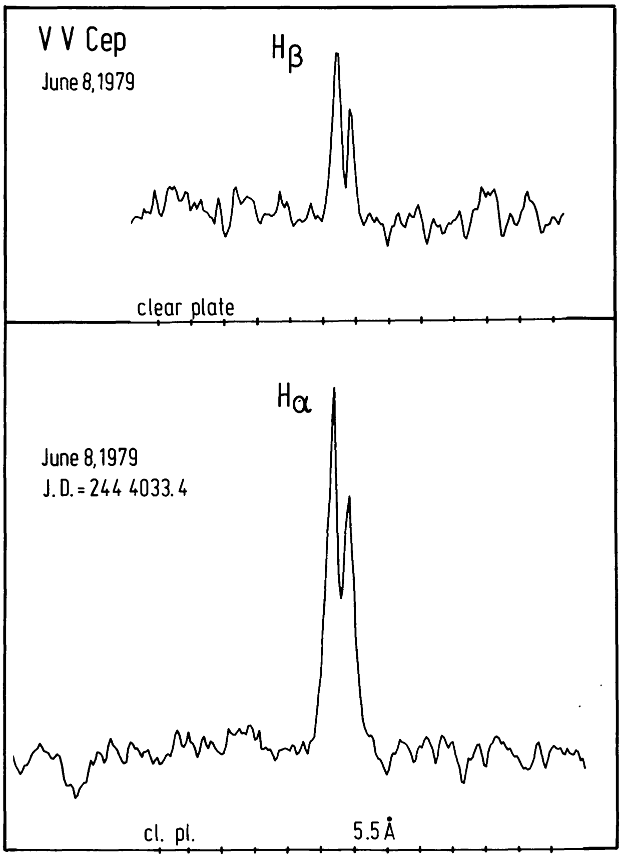

Fig. 3. Typical profiles of H_β and H_α well outside of the eclipse

between Sept. 25 and Dec. 18, 1977) have a dispersion of 110 Å mm^{-1} (1st order). Each plate was calibrated individually by means of a Lyot filter element (Furenlid, 1973; Trefzger, 1976). The plates were traced using a Grant machine.

3. Results

3.1. The H_β Profile

Figure 1 shows the region of the spectrum around H_β at different times. The tracings of Nov. 29 and Dec. 20, 1977 still show the almost pure M spectrum of the main component. H_β shows up as a weak absorption (cf. also Paper I). On Jan. 5, 1978 a small spike appeared in the blue wing of the H_β absorption. This spike gradually grew up to a well developed emission line during March and April 1978. On April 7, 1978 a second emission component appeared on the red wing of H_β. From now on both emission components increased gradually until approximately June/July 1978.

The general increase of the H_β feature was not smooth but it was superimposed on irregular short time variations of both emission components. For example on June 9 and on June 29 both emission lines showed a temporary decrease (Fig. 1).

3.2. The H_α *Profile*

In contrast to H_β the H_α emission lines did not disappear completely during the recent eclipse, a phenomenon which was also observed during the earlier eclipses. Even during maximum eclipse a small nearly symmetric H_α emission with a central absorption was observed [compare also the H_α profiles of the 1956/57 eclipse shown in Wright (1977)]. Figure 2 shows a series of some H_α profiles during the egress phase. Both emission components seem to increase more or less simultaneously. The comparison of this behaviour with the different results for H_β will be discussed in Sect. 4. The H_α line too showed sudden variations in intensity, e.g. a strong increase on June 13, 1978 (Fig. 2).

During summer 1979 (well outside the eclipse), several spectra were taken for comparison purposes. Figure 3 shows the typical out-of-eclipse H_β- and H_α-emission lines from June 8, 1979.

In order to get a better and a quantitative understanding of the behaviour of H_β and H_α during the eclipse, the equivalent widths of the blue and red emission components above the M star continuum were measured. In cases where the two emission components were not completely separated (H_α), a rough Gaussian fitting for both emission components was done. In Fig. 4 these measurements are plotted as a function of time. The crosses refer to the blue emission components while the dots show the increase of the red emission components. The absolute values of the equivalent widths of the emission lines were obtained by comparison with the continuum of VV Cep. For an estimate of the continuum luminosity at the corresponding wavelengths the absolute flux units for M stars given in Allen (1973) and $V \approx 5.3$ for VV Cep were used.

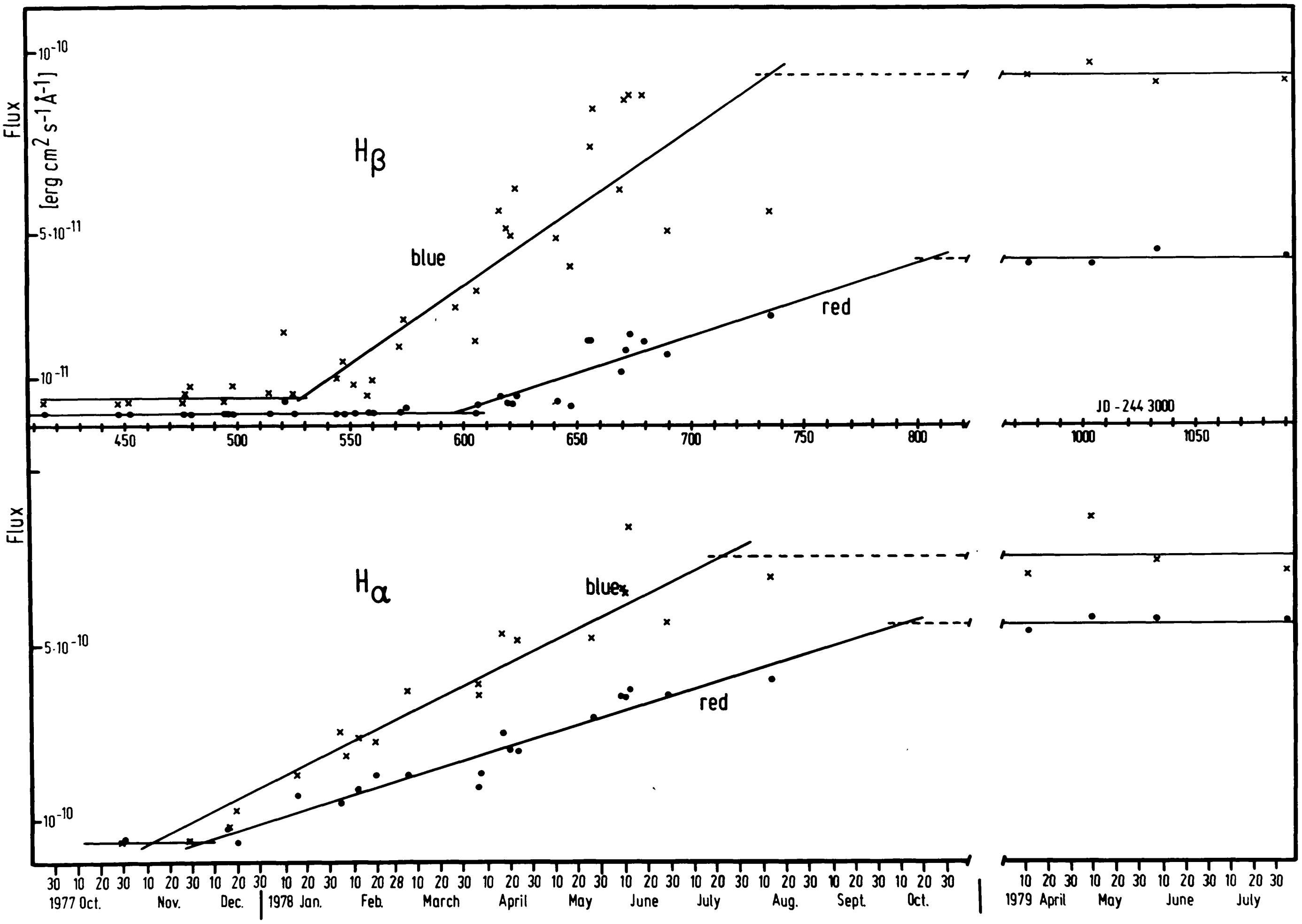

Fig. 4. Equivalent widths of the different emission components during the egress phase. Crosses refer to the blue component, dots to the red one. Note the gap in the time axis between October 1978 and April 1979. The coincidence of the fourth contacts of the blue and red emission components indicates that H_β and H_α origin from the same spatial region. Note the temporary simultaneous increase of H_β blue and H_α blue in April and May 1978

The points in Fig. 4 show a considerable scatter which cannot be explained by the observational errors (which are ≈5%). These irregular variations of the emission line intensities are intrinsic. Linear least square regression were fitted to the rising parts of the observed equivalent width vs. time relation. In a similar way horizontal lines were constructed to fit the relations before and after the egress phase. From Fig. 4 it can be seen that the principal behaviour of H_α was not different from that of H_β: the red emission component of H_α reached its end value (fourth contact) later than the blue one. The time lag is practically the same as in the case of H_β. In a similar manner the red component of H_α started its reappearance (third contact) later than the blue component. However, here the time lag was considerably smaller than in the case of H_β. Interestingly, both emission components of H_α started their egress from the eclipse earlier than the H_β components. An interpretation for this is given in Sect. 5.

4. Interpretation of the Behaviour of H_β and H_α

During the ingrees of the recent eclipse the blue emission component of H_β disappeared before the red one (cf. Paper I). This was interpreted in the following way: the emission nebula around the hot companion of VV Cep is assumed to be a rapidly rotating oblate envelope (similar to envelopes of Be stars). Then, the blue emission component is produced by that part of the envelope which moves towards the observer, the red component by the receding part. Angular momentum conservation requires the sense of rotation of the envelope to be the same as that of the orbital revolution. Therefore, that part of the envelope which moves towards the observer is occulted first. Similar models of rotating envelopes are described in Hutchings and Wright (1971) and in Wright (1977), however these authors prefer an envelope with less equatorial concentration of matter.

The new observations of the egress showed the blue emission components of H_β and H_α to reappear first, followed by the red emission component. This agrees very well with the proposed model of the rotating envelope.

We consider in Fig. 4 the intersections of the rising branches of the fitting curve with the horizontal branches as the contact epochs of the corresponding emission line components. Due to the linear fitting procedure the uncertainty of these epochs is approximately ±15 d.

In Table 1 we have compiled all contact epochs for the eclipse of the different emission components of H_α and H_β. The corresponding J.D. numbers have been taken from Fig. 4 and from Fig. 2 in Paper I (where the same linear least square regression was

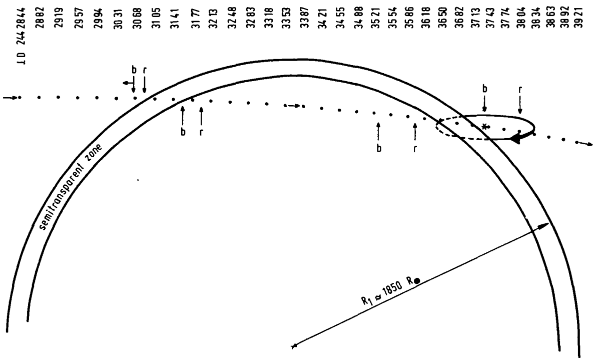

Fig. 5. The primary star of VV Cep and the companion's orbit as they appear projected against the sky. The orbit is indicated by dots, the corresponding Julian Dates are on top. The contact times for H_β blue (*b*) and H_β red (*r*) are indicated. The equator of the rotating emission envelope is drawn at the position of the fourth contact for H_β blue

done as in Fig. 4). The photometric contact dates were taken from Nakagiri and Yamashita (1979). They coincide fairly well with the dates of other observers (Böhme, 1978; Hayasaka et al., 1977).

The mid eclipse (in time) of the blue H_β emission component occurred before J.D. 2443345, the photometric mid eclipse (mainly due to the eclipse of the B star itself) occurred approximately on J.D. 2443360, while the mid eclipse of the red H_β component occurred on J.D. 2443398. The time sequence of these dates fits the proposed model of a different spatial origin of the blue emission components, the B star continuum and the red emission component. (A comparison with H_α is not possible here as the first and second contacts for H_α were not observed.)

5. Estimates of the Dimensions of the Envelope

We assume that the H_α- and H_β-emitting regions have the same sizes. This is supported by the close coincidence of the fourth contacts of H_α blue (J.D. 2443714) and H_β blue (J.D. 2443735) and of H_α red (J.D. 2443795) and H_β red (J.D. 2443806). The differences of 21 and 11 d respectively are within the error limit. However, the time differences between the fourth contacts of red and blue are 81 (H_α) and 71 (H_β) d respectively, a significant difference. At the fourth contact of the blue components all parts of the envelope which contribute to the blue emission are not eclipsed (i.e. that parts of the rotating envelope which move towards us). Correspondingly, at the fourth contact of the red components the whole envelope is not eclipsed. This gives an estimate for the radius of the envelope:

Figure 5 shows the M star and the orbit of the B star (with envelope) as they appear projected against the sky. This figure is based on the orbital elements (from numerous radial velocity measurements) given by Wright (1977). The Julian Dates of the different places of the B star in its orbit are marked at the top (based on Wright's time of periastron passage: J.D. 2438461 ± 48). Furtheron the different contact times of the H_β emission components are indicated. From the positions of the third and fourth contacts and the interpretation given above the radius of the rotating envelope has to be approximately 300–$320 R_\odot$. If we consider the first and second contacts this value may even be smaller. However, the dates of the first and second contacts are not as well determined as the third and fourth ones. The radius derived in this way is nearly half that given by Hutchings and Wright (1971) (who derived $650 R_\odot$). Note that these authors favoured a nearly spherical shell and assumed that the bifurcation of the emission lines is totally due to absorption).

Here we have to consider the following argument: The outer boundary of a red supergiant is not a sharp occulting edge, but the optical density increases only slowly with decreasing radius. The region between optical depths from $\tau = 10^{-2}$ to $\tau = 1$ is approximately 5% in radius (Scholz, 1979). Nakagiri and Yamashita (1979) estimate from photometric observations the scale height of the semitransparent outer region. They get a value of ≈15% of the radius of the M star. The envelope has no sharp outer edge either. Thus the eclipse starts and ends by a gradual extinction. Therefore the time difference between the third and fourth contacts appears longer than the corresponding dimension of the envelope

This supports the tendency towards a smaller envelope. This extinction effect may also be responsible for the different behaviour of H_α and H_β during the total eclipse. From the measurements of the equivalent widths we get $H_\alpha/H_\beta \approx 9$ to 10 outside of eclipse. Therefore it seems plausible that H_α is strong enough to shine through the outer atmosphere of the M star, even at maximum eclipse. This is true at least for those parts of the envelope which are only obscured by the semitransparent outer region of the M star (Fig. 5). From this argument it is also plausible that H_α starts its ingress earlier than H_β, and that the third contacts of H_α blue and H_β red nearly coincide.

6. The Diameter of the M Star

The primary star of the VV Cep system has the largest measured stellar diameter known so far. However, the actual estimates varied considerably during history, depending on the improvement of the orbital elements (see e.g. Cowley, 1969; Wright, 1977). From an analysis of the H_α profiles Wright (1977) gave $R_1 = 1600 R_\odot$ as the best value. From a photometric analysis during the recent eclipse Saito et al. (1979) obtained $R_1 = 1900 R_\odot$

Table 1. Contact times for the eclipse of the different emission components of H_α and H_β. Column 3 contains the photometric contact times given by Nakagiri and Yamashity (1979)

Contact	H_α blue	H_β blue	Photometric	H_α red	H_β red
1st	–	<JD 2443060	JD 2443055	–	JD 2443087
2nd	–	3159	3200	–	3195
Mid eclipse	–	3345	3360	–	3398
3rd	2443460	3530	3514	2443485	3600
4th	3714	3735	3670	3795	3806

Table 2. Durations of the phases of the eclipse of the different emission components of H_α and H_β. The photometric durations are from Nakagiri and Yamashita (1979)

Phase	H_α blue	H_β blue	Photometric	H_α red	H_β red
Ingress	–	> 99 d	145 d	–	108 d
Totality	–	381	314	–	405
Egress	246	205	156	310	206
Whole eclipse	–	675	615	–	719

while Nakagiri and Yamashita (1979) obtained $R_1 = 1700 R_\odot$. From Fig. 5 we get a best fit with $R_1 = 1850 R_\odot$ and the geometrical mid eclipse was at J.D. =2443370. Because of the semitransparent outer layers of the M star this value is only a rough estimate. However, when comparing the above results it should be considered that the M star is a semiregular variable, where radius variations due to pulsations may well occur.

7. Epochs and Duration of the Eclipse

Gaposchkin (1937) gave the epoch of the mid-eclipse of VV Cep by J.D. $= 2421070 + N \times 7430$. This leads to J.D. 2435930 for the 1956/57 eclipse which coincides with the observationally determined epoch [J.D. 243 5931 according to Larsson-Leander (1957) and 243 5931.4 according to Wright (1977)]. Using Wright's (1977) period (7430.5 d) this leads to J.D. 244 3363 for the recent eclipse. The latter value fits very well with our value from Fig. 5 (J.D. 244 3370) and with the photometric value of Nakagiri and Yamashita (J.D. 244 3360).

In Table 2 we have collected the durations of the partial and total phases of the recent eclipse for the different emission components. We see that the ingress phase for H_β was approximately 104 d (99 days for the blue component and 108 d for the red one), while the egress phase was 205 d (for both components). The different duration of the first and second partial phase was already observed by Larsson-Leander (1957) in the photometric data of the 1956/57 eclipse. The reason for this difference is not clear. It may be explained by an asymmetric distribution of gas between the stars (gas streams). However, this is very speculative.

In earlier papers the duration of the totality of the eclipse was given by 450–550 d while the partial phases were only 20–40 d (Cowley, 1969). Our spectroscopic observations as well as the photometric observations of Nakagiri and Yamashita (1979) indicate that the totality is shorter: approximately 400 d (314 d), while the duration of the whole eclipse is longer: approximately 700 d (615 d; the values in parenthesis are from Nakagiri and Yamashita; see Table 2).

8. Conclusions and Discussion

The above considerations, using simple geometric conditions during the eclipse of the VV Cep system, provide strong constraints for models of the emission envelope of the B star. The successive fading and reappearance of the different emission components support the proposed model of a rapidly rotating envelope (or a rotating ring). From the time difference between the contact dates follows that the radius of the envelope is about $320 R_\odot$.

The radial velocity displacements of the blue and red emission component of H_β are approximately -100 and $+100 \mathrm{~km~s^{-1}}$ (Paper I). These values correspond to a Keplerian velocity at a distance of $\approx 380 R_\odot$ from the secondary star. This radius is compatible with the dimensions given above.

Even in view of the new results we are still far from a self-consistent model of the VV Cep system, which should include mass transport, radiation transport etc. The statement of Wright and Larson (1969) that "VV Cep is one of the least understood of the well observed stellar systems" still appears to be valid.

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