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Spectroscopic Observations of VV Cep during the Ingress Phase of the 1976/1977 Eclipse

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Summary. We report about spectroscopic observations of the phase when the hot companion of VV Cep gradually disappeared behind the primary star. The hot companion is surrounded by an extended Balmer line emitting envelope. The variations of the H_β and H_γ lines are followed by a densely spaced time series of spectrograms. The derived variations can be explained by a rotating ring-shaped envelope which gradually disappears behind the primary star.

Key words: VV Cep stars — eclipsing binaries — rotating envelopes — atmospheric eclipse

I. Introduction

VV Cep is the prototype of a small group of supergiant binary systems whose spectra show emission lines of hydrogen and [Fe II] (Cowley, 1969). The primary star in the system is always a K or M supergiant while the secondary is a late O or early B type star. In the visual light the M2 primary star of VV Cep is several magnitudes brighter than the B companion. The observed radiation is therefore mainly due to the M supergiant. McLaughlin (1936) discovered that VV Cep is an eclipsing binary with a period of 20.4 years (7430 days) (Gaposchkin, 1937). The duration of totality is ~450 to ~500 days. This leads to an extraordinary large radius of the main star. According to the recent radial velocity analyses of Wright (1977) the radius of the M star is ~1600 $R_\odot$, while the *B* companion has a radius of ~13 $R_\odot$. The mean separation is ~25 AU, and both stars have the same mass of ~20 $M_\odot$.

Since the hydrogen emission lines disappear at the time of the eclipse, they obviously arise in a region around the hot component. During most of the time the higher Balmer lines show a characteristic reversed P-Cygni profile, i.e. an emission line together with an accompanying redward displaced absorption line. It is generally assumed that these profiles are produced by mass transfer from the M star to its B companion (McLaughlin, 1951). The radius of the hydrogen emitting region is ~650 $R_\odot$ (Wright, 1977). The forbidden emission lines, e.g. [S II] λ4069, [Fe II] λ4245, [Fe II] λ4277, [Fe II] λ4287, are present at all phases. This indicates that they arise in a very extended thin envelope which surrounds the whole binary system.

The first contact of the 1976/77 eclipse was predicted to occur in November 1976. But spectroscopic observations showed that already in 1975 the outermost chromosphere of the M star eclipsed the hot companion (Wright, 1975; Faraggiana, 1976). Observations of Whitney (1976), Howarth (1976) and Skillman and Gradie (1976) show photometric evidence for the beginning of the eclipse early November 1976, the second contact was predicted for December 1, 1976.

The duration of the partial eclipse phase before and after total eclipse is ~30 to 40 days (Larsson-Leander, 1961). The aim of our work was to follow the spectral variations during the gradual atmospheric eclipse phase of the B companion and its envelope. Section II gives a description of the observations. The variations of the H_β, H_γ, H_δ and Ca II H and K lines are described in Section III. The radial velocities of the Balmer lines are given in Section IV. In Section V a simple model to explain the variations of H_β and H_γ is proposed.

II. The Observations

On 21 different nights between October 8, 1976 and January 21, 1977, 45 spectrograms of VV Cep were obtained. The equipment was the newly installed Boller and Chivens Cassegrain spectrograph (Model 26767) attached to the Nasmyth focus of the 72 cm reflector of the Landessternwarte, Heidelberg Königstuhl. Most spectrograms were taken in the blue spectral region (4300 Å central wavelength, IIa-O plates). The dispersion was 55 Å/mm (2nd order), giving a spectral resolution of about 1 Å. Table 1

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Table 1. Spectrograms of VV Cep, 55 Å/mm, 4300 Å central wavelength, plate IIa-O. The exposure time was generally 20 min, the spectrograms marked by L were exposed ~40 min

No.	Date	Julian Date
2.1	Oct. 8, 1976	244 3060.35
5.1	Oct. 9, 1976	244 3061.33
5.2 *L*	Oct. 9, 1976	244 3061.39
5.3	Oct. 9, 1976	244 3061.45
7.2	Oct. 10, 1976	244 3062.31
7.3 *L*	Oct. 10, 1976	244 3062.35
9.1	Oct. 11, 1976	244 3063.32
9.2 *L*	Oct. 11, 1976	244 3063.35
11.1	Oct. 15, 1976	244 3067.31
12.1 *L*	Oct. 16, 1976	244 3068.45
12.2	Oct. 16, 1976	244 3068.50
14.1	Oct. 22, 1976	244 3074.31
14.2	Oct. 22, 1976	244 3074.33
15.1	Oct. 25, 1976	244 3077.37
15.2 *L*	Oct. 25, 1976	244 3077.39
15.3 *L*	Oct. 25, 1976	244 3077.42
18.1	Oct. 26, 1976	244 3078.36
18.2 *L*	Oct. 26, 1976	244 3078.39
20.1	Nov. 1, 1976	244 3084.29
21.1	Nov. 3, 1976	244 3086.31
21.2 *L*	Nov. 3, 1976	244 3086.33
23.1	Nov. 8, 1976	244 3091.33
24.1	Nov. 20, 1976	244 3103.42
25.1	Nov. 28, 1976	244 3111.31
26.1	Dec. 10, 1976	244 3123.27
27.1	Dec. 15, 1976	244 3128.23
28.1	Dec. 27, 1976	244 3140.22
28.2 *L*	Dec. 27, 1976	244 3140.25
29.1	Dec. 29, 1976	244 3142.22
29.2 *L*	Dec. 29, 1976	244 3142.25
30.1	Jan. 13, 1977	244 3157.21
30.2 *L*	Jan. 13, 1977	244 3157.24
31.1	Jan. 18, 1977	244 3162.28
32.1	Jan. 21, 1977	244 3165.25
80.1	July 1, 1977	244 3326.44
80.2 *L*	July 1, 1977	244 3326.49
85.1	July 3, 1977	244 3328.47
85.2 *L*	July 3, 1977	244 3328.53

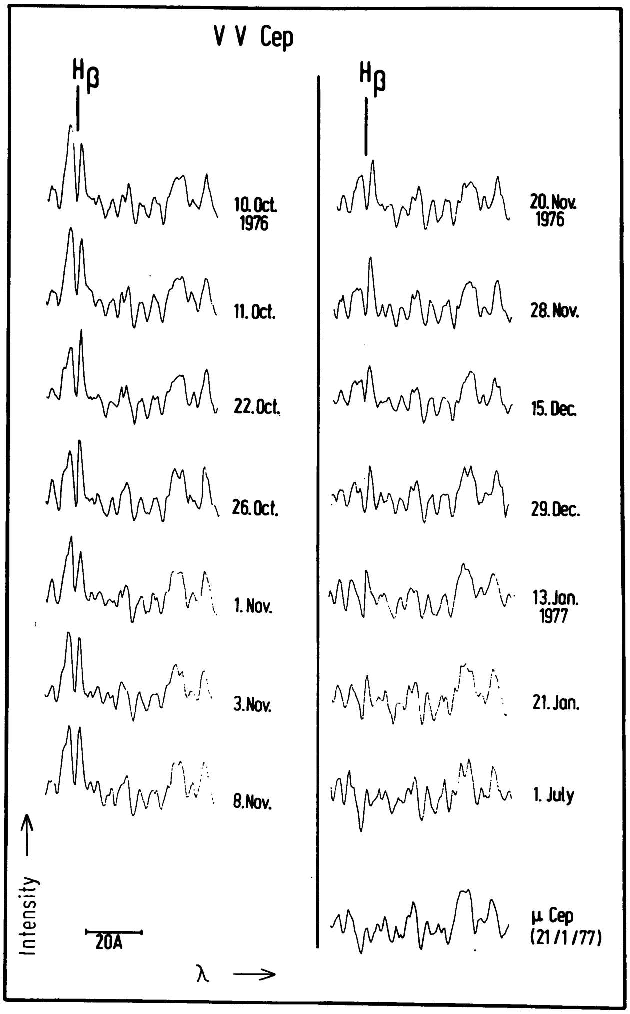

Fig. 1. Intensity tracings of the surroundings of H_β in the spectrum of VV Cep. The sequence shows the time behaviour of the H_β feature during the increasing atmospheric eclipse. The blue emission component started to decrease earlier than the red one. The tracing of July 1, 1977 shows the spectrum during total eclipse. Note the similarity to the spectrum of μ Cep

gives the dates and technical data of the blue spectrograms taken with the Königstuhl equipment. Three different types of exposure times were used:

1) ~20 min exposures which are well exposed in the region ~4000 Å–5050 Å where the strong absorption of TiO molecular bands sets in.

2) In addition we took plates with longer exposure times (~40 min) in order to get the region near Ca H and Ca K well exposed.

3) A small number of red spectrograms (1st order, 110 Å/mm, 103a E plates) was obtained in order to get the region near H_α.

III. Line Variations during the Atmospheric Eclipse

The most characteristic features of the system are

1) the M2 spectrum of the primary component,

2) the forbidden emission lines from the common envelope,

3) the hydrogen emission lines which are produced in the H II region surrounding the hot secondary B-component.

At the beginning of our observations (October 9, 1976) the Balmer lines H_α, H_β, H_γ and H_δ still appeared in emission. H_α showed the characteristic structure of a broad emission with a narrow central absorption described by Wright (1977). H_β appeared as a nearly symmetric double emission. However, the blue emission component was stronger (Fig. 1). H_γ and H_δ showed the usual (McLaughlin, 1951; Peery, 1966) reversed P-Cygni profiles. During the following weeks gradual variations of H_β and H_γ lines occurred due to the progressing eclipse. In detail the following changes were observed:

a) The H_β*-Line*

Figure 1 shows the development of the H_β feature between October 10, 1976 and January 21, 1977. For comparison the corresponding region of a spectrogram from July 1, 1977, i.e. well deep in the eclipse and furthermore a spectrogram of the M2 supergiant μ Cep (obtained with the same equipment) is also given. At the beginning of our sequence H_β consists of a broad blue shifted emission line (cf. radial velocity measurements in the following section). The blue component shows some irregular variations, but there is a distinct general tendency of decrease. The red component seems to remain constant until approximately the middle of November, when it starts to decrease too. On January 21, there remain only two small relics of the H_β emission lines. The central absorption between the two emission components does not disappear but sinks below the continuum when the emission lines disappear.

The spectrogram of July 1, 1977 shows the blue emission more or less of the same strength as on January 21st, while the red emission can hardly be distinguished from the continuum. The absorption has still increased. A comparison of the July 1, 1977 spectrogram of VV Cep and the spectrum of μ Cep (cf. Fig. 1) now shows that at this phase the spectra are practically identical. Thus, the hydrogen emitting region was indeed totally eclipsed at the end of January 1972.

Figure 2 shows the time development of the equivalent width of the emission components of H_β (with "equivalent width" EW we denote here simply the area below the emission line, measured in arbitrary units above an arbitrarily adopted continuum). The blue component of H_β was already decreasing when we started our observations on October 9, 1976. It must have been stronger before that date. This is in good agreement with reports (Peery, 1966) that normally the blue emission component is much stronger than the red one. The red component, on the other hand, started to decrease not before November 10. Obviously the region of the H II envelope (around the secondary star) which emits the blue emission peak of H_β began the atmospheric eclipse earlier than the red emitting part of the envelope. On January 21, 1977 the equivalent width of the blue component had nearly reached its value of the total eclipse (indicated in Figure 2 by the broken line which corresponds to the observations of July 1 and 3, 1977), while the red emission component is still slightly above that value. An interpretation of these phenomena will be given in Section V.

b) The H_γ*-Line*

Figure 3 shows sections of our spectrograms which include the H_γ line. The blueward displaced emission component starts to decrease at the beginning of November 1976, leaving only a broad absorption at the end of December 1976. The time development is roughly parallel to that of H_β. However, the emission feature is too weak to derive more accurate quantitative information. For comparison, again the same section from the spectrogram of μ Cep is given. Compared to spectrograms outside of the eclipse (Peery, 1966; Cowley, 1969) the H_γ emission seems rather weak. This is in accordance with the low intensity of the blue H_β emission component. Probably both lines are emitted from the same region, which was already partly eclipsed at the beginning of our observing run.

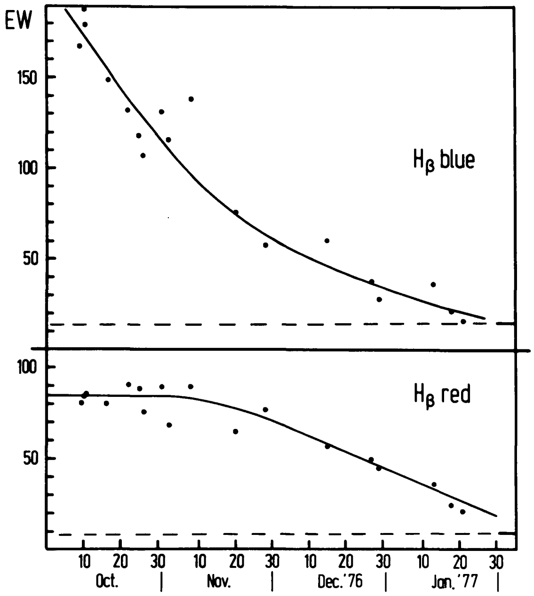

Fig. 2. Equivalent width of the blue and red emission component of H_β during the increasing atmospheric eclipse. The decrease of the blue component must have been started already before the beginning of our observation run, i.e. more than 30 days before the decrease of the red emission. The dashed lines correspond to the equivalent widths during total eclipse (spectrograms of July 1 and 3, 1977)

c) The Ca II H *and* K *Lines*

As mentioned already some of our spectrograms were exposed long enough to show the spectrum of VV Cep down to ~3800 Å. Figure 4 gives the section of two of these spectrograms between ~3850 and ~4230 Å. The first one was taken on October 16, i.e. before the first contact, the other one was taken on December 27, i.e. after the second contact of the B star. Ca II H and K show striking changes. During ingress they became broader and a number of satellite absorptions showed up. It should be noted that the same phenomenon was observed by Wright (1972) in the K line of 31 Cyg during ingress. Normally the B star partly fills the H and K absorption, but during ingress satellite absorptions appear due to clouds or prominences in the outer atmosphere of

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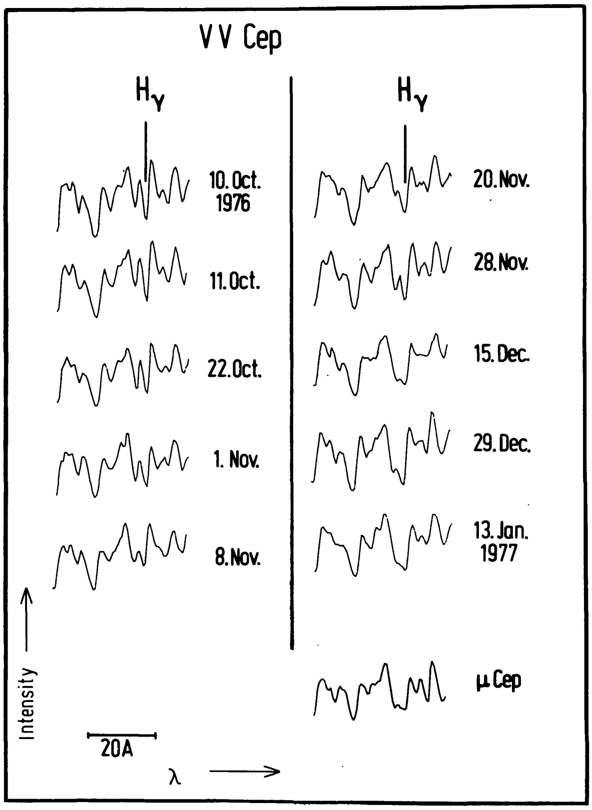

Fig. 3. Intensity tracings of the surroundings of H_γ in the spectrum of VV Cep. The sequence shows the time behaviour of the H_γ feature during increasing atmospheric eclipse. The H_γ emission decreases in a similar way as those of H_β. For comparison the same section of a spectrum of μ Cep is shown

the primary star. Finally, during totality only the undisturbed H and K lines of the M star are visible.

Finally it should be noted that a certain decrease of the ultraviolet continuum due to the eclipse of the B star is also detectable on Figure 4 (cf. Cowley, 1969).

IV. Radial Velocities of H_β and H_γ

Measurements of the radial velocities of the different emission and absorption components of the Balmer lines are important to clarify the structure of the H II region surrounding the B star. Close to the eclipse the velocity of both stars should be equal to the systemic velocity: $V_0 = -20.2$ km s^{-1} according to radial velocity measurements of the M star (Wright, 1977). For control reasons radial velocity measurements were carried out not only for H_β and H_γ but also for a number of metal lines arising from the M star and from the common envelope. Nine spectrograms (Nos. 9.2, 12.2, 14.2, 20.2, 24.1, 25.1, 27.1, 30.1, 32.1) were measured using the Grant machine. The results are given in Table 2. Because of the large number of line blends in the M-spectrum some care is necessary to select lines which are suitable for radial velocity measurements (Wright, 1955; Peery, 1966). The laboratory wavelengths λ_0 were taken from Moore (1945) or from Wright (1955) (for the blends).

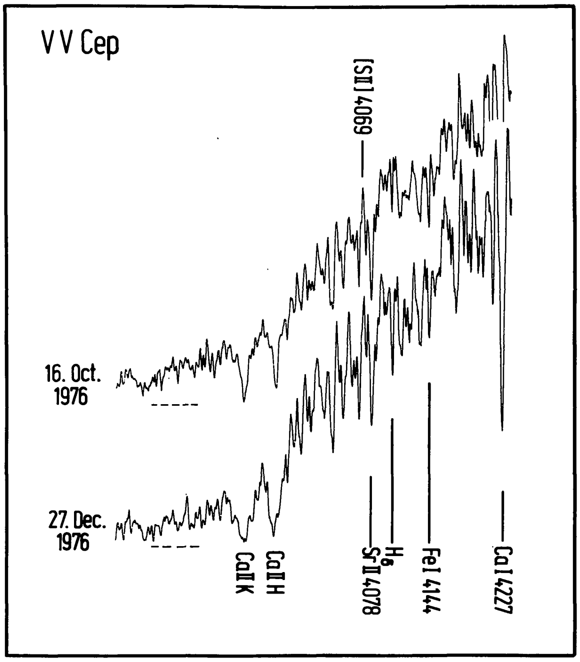

Fig. 4. Part of spectrograms of VV Cep at the beginning of the atmospheric eclipse (top) and at (nearly) totality (bottom). The broad Ca II H and K lines show up during eclipse, normally they are partly filled by the B companion. Note the increase of the H_δ absorption during eclipse. The intensity level of the clear plate is marked by a dashed line

The systemic velocity of VV Cep is reproduced satisfying well by our measurements (cf. the errors listed in Table 2). Therefore, the velocities for H_β and H_γ seem reliable. The H_γ absorption shows the velocity of the system. The H_γ emission is displaced shortward and shows a velocity of -110 km s^{-1} relative to the system. This velocity is very similar to the velocity of the blue H_β

Table 2. Radial velocities of some selected metal lines and of the emission and absorption features of H_β and H_γ in the spectrum of VV Cep (mean value of spectrum Nos. 9.2, 12.2, 14.2, 20.2, 24.1, 25.1, 27.1, 30.1, 32.1)

Ion	λ_0 Å	Velocity km s^{-1}	σ km s^{-1}
Ca I	4226.728	− 20.3	± 3.8
Cr I	4254.315	− 20.5	3.8
[Fe II]	4287.40	− 24.1	3.2
Fe I, Ca I, Ti II	4307.892	− 23.6	4.4
Ti I	4715.295	− 20.9	3.7
H_γ Abs.	4340.468	− 18.2	4.1
H_γ Em.		−130.9	5.5
H_β Abs.	4861.332	− 8.6	3.4
H_β Em. blue		−144.8	13.7
H_β Em. red		+ 94.7	3.0

emission ($-125\,\mathrm{km\,s^{-1}}$ relative to the system). The red H_β emission is displaced nearly symmetrically to the red: $+115\,\mathrm{km\,s^{-1}}$. The H_β absorption does not coincide exactly with the systemic velocity but shows a relative velocity of $+12\,\mathrm{km\,s^{-1}}$.

McKellar et al. (1957) observed the radial velocity of ultraviolet Fe I lines during the 1956/57 eclipse. They found systematic variations ($5\,\mathrm{km\,s^{-1}}$) from the computed velocity curve and were able to make statements about the beginning of totality. As our spectrograms were made with a dispersion of 55 Å/mm the scattering from one plate to another is too high to verify this trend.

V. Discussion

How can the observed variations of the H_β-profile be explained? We start from the following rough picture: VV Cep is a binary consisting of a M supergiant and a late O or early B type star. There exists a common extended envelope around both stars (producing the [Fe II] emission) and there exists mass transfer from the M star to its companion. The hot companion is surrounded by an H II region (radius $\sim 650\,R_\odot$, Hutchings and Wright, 1971).

In order to explain the H_β-profile and its variations during ingress we propose the following qualitative model: The mass streaming from the M star into the gravitational potential of the B star will generally contain angular momentum. Therefore, it will not fall directly onto the B star but will accumulate in a rotating ring-like envelope around the star. This ring (or oblate envelope) is heated up by the B star (H II region) and is therefore emitting Balmer recombination radiation. Hutchings and Wright (1971) used such a model to explain the H_α-profiles which they observed. Note also the arguments of Sahade and Struve (1957) who proposed a rotating ring to explain the structure of the H_α-feature of AZ Cas shortly before its eclipse. This geometry produces a broad emission line, possibly with a central depression. The central depression depends on the rotation law, the density distribution, and the radiation transport in the radiating envelope.

The asymmetry of the Balmer lines may be explained in the following way: Outside of the hot ring cool matter (H I) from the M star will stream (in spiral orbits) towards the ring. The part of the cool matter which is situated between the radiating envelope and the observer causes an absorption in the Balmer profiles. As the matter moves towards the ring, i.e. away from the observer, this absorption will be redward displaced. Furthermore the M star contributes an absorption line (note that the H_β and H_γ absorption lines are still clearly visible during eclipse; see Figs. 1 and 3).

The combination of the emission and absorption features described above yields a Balmer line profile consisting of a strong, blue shifted emission and a weaker red shifted emission component. This is just the shape of profile which H_α and especially H_β generally showed (Wright, 1977; Peery, 1966; McLaughlin, 1951). If the absorption is still stronger, this model could even explain the reversed P-Cyg profiles of the higher Balmer lines.

If this interpretation of the emission profiles is correct, then the displacement (approximately $\pm 100\,\mathrm{km\,s^{-1}}$) of the emission components of H_β should correspond to the Kepler velocity of the H_β emitting ring. Together with a mass of $20\,M_\odot$ for the B star this leads to a radius of $\sim 380\,R_\odot$ for the ring. This value is comparable to the value of $\sim 650\,R_\odot$ for the H_α emitting region (Hutchings and Wright, 1971).

The blue emission component of H_β arises in that region of the rotating envelope which moves towards the observer. After the beginning of the atmospheric eclipse this part is occultated first. This explains our result that the blue emission component of the H_β line starts its decrease earlier than the red one. If this interpretation is correct then the time difference between the first contacts of the regions contributing respectively to the blue and the red emission components should give a measure for the diameter of the envelope. Since we obviously missed the first contact of the blue emitting region (see Sect. III) we can only give a lower limit for this diameter. The time difference was more than 30 days; together with the duration of the total eclipse (~ 498 days, Larsson-Leander, 1961) and the radius of the M star ($\sim 1600\,R_\odot$, Wright, 1977) this yields a lower limit of $96\,R_\odot$ for the radius of the H_β radiating envelope. As could be expected during total eclipse only the absorption line of H_β (formed in the atmosphere of the M star) is visible.

This very rough and qualitative model should be considered only as a first approximation to the interpretation of the observed phenomena. It is surely too simple to give a full explanation to the highly complex spectrum and the spectral variations of VV Cep. A first simple test is possible at the end of the eclipse: During egress the blue shifted emission component of H_β should reappear first. It should develop nearly to its full strength before the red-shifted emission line will become visible. To test the validity of the proposed model intensive spectroscopic observations of the phenomena during egress as well as quantitative calculations are intended.

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