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The 1997/1998 eclipse of VV Cephei was late

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Abstract. The recent eclipse of the long-period ($P = 7430^{\rm d}$) binary star VV Cephei is studied by means of UBV photometry and optical spectroscopy. Both photometry and variations of the emission lines (Hα and FeII λ 4233) show that the eclipse occured about 68 days later than predicted from the ephemeris. Such a sudden about 1% lengthening of the orbital period between the last two eclipses implies that the generally accepted model of VV Cep with the masses of both the M supergiant and the hot B star of about 20 $M_\odot$ should be revised. The period change due to mass transfer between the components or mass ejection from the VV Cep system can be explained, if one accepts the medium mass model for VV Cep, with the mass of the M star about 2.5 $M_\odot$ and of the B star about 8 $M_\odot$. This model implies that the cool component of VV Cep could be an AGB star rather than a supergiant.

Key words: stars: binaries: eclipsing – stars: individual: VV Cep – stars: supergiants

1. Introduction

VV Cephei (HD 208816, HR 8383) is a well-known massive eclipsing binary consisting of an M supergiant and a hot B type companion. Its optical spectrum is characterized by strong Balmer and [FeII] emission lines (Cowley 1969). Gaposchkin (1937) derived from photometric data the orbital period 7430$^{\rm d}$ (≈ 20.3 yr) which was confirmed later by Wright (1977) and Saitō et al. (1980).

The spectral type of the B star is still uncertain, with the estimates ranging from early B or even O (Hutchings & Wright 1971; Stencel et al. 1993) to A0 (Hack et al. 1989). Adopting an inclination $i = 76^\circ.7$, masses of the both components have been estimated to be about 20 $M_\odot$ (Hutchings & Wright 1971; Wright 1977). According to the orbital elements by Wright (1977), the M supergiant normally does not fill its Roche lobe, but due to the large orbital eccentricity ($e = 0.346$), mass transfer events may take place near the periastron passage when temporary Roche-lobe overflow drives a stream which forms an accretion disk around the hot component (Wright 1977; Stencel et al. 1993). As a result of mass transfer, a disk-like envelope of a radius about 500–650 R$_\odot$ (Wright 1977; Saijo 1981) surrounds the B type star.

Five eclipses of the hot star and its envelope have been recorded photometrically and/or spectroscopically since 1896. The present paper is devoted to the sixth eclipse, mid-point of which was expected to occur at about JD $2\,450\,790$ (December 7, 1997) according to the ephemeris by Gaposchkin (1937) and times of the previous eclipses. Extensive photometric and spectroscopic monitoring of VV Cep which will be shortly described in Sects. 2 and 3, respectively, revealed for our surprise that the eclipse occured by about 68 days later. Some consequences and implications of this time lag will be discussed in Sect. 4.

2. Photometry

The $UBVRI$ photometry of VV Cep was carried out at the Piwnice Observatory of the Toruń Centre for Astronomy, using the 60 cm Cassegrain telescope and the one-channel photometer. The comparison star was 20 Cep.

Photometric UBV data for the 1997/98 eclipse were presented and compared to the previous eclipses by Graczyk et al. (1999) (hereafter GMJ). Fig. 1 (which is an updated version of GMJ Figs. 2 and 3) shows that the totality phase lasted about 450 days in $U-B$ and 475 days in $B-V$ colour. So the last eclipse was similar to the 1957/58 one (Larsson-Leander 1958, 1960), and different from the 1977/78 one which had a shorter totality phase and longer total duration (Saitō et al. 1980). Fig. 1 also clearly shows that the mid-eclipse occured around JD $2\,450\,858$ (Feb. 13, 1998) in both $U-B$ and $B-V$ colours. This is 68 days later than expected from the ephemeris by Gaposchkin (1937).

3. Spectroscopy

3.1. Observations

Spectroscopic observations provide us with complementary information on the duration and mid-point of the eclipse. Consider a disk-like envelope rotating about the hot star in the same direction with the orbital motion. In the beginning of eclipse, the side of the disk which is moving towards us and therefore emitting the blue-shifted component of the emission lines, is eclipsed first. During the totality both emission components should be

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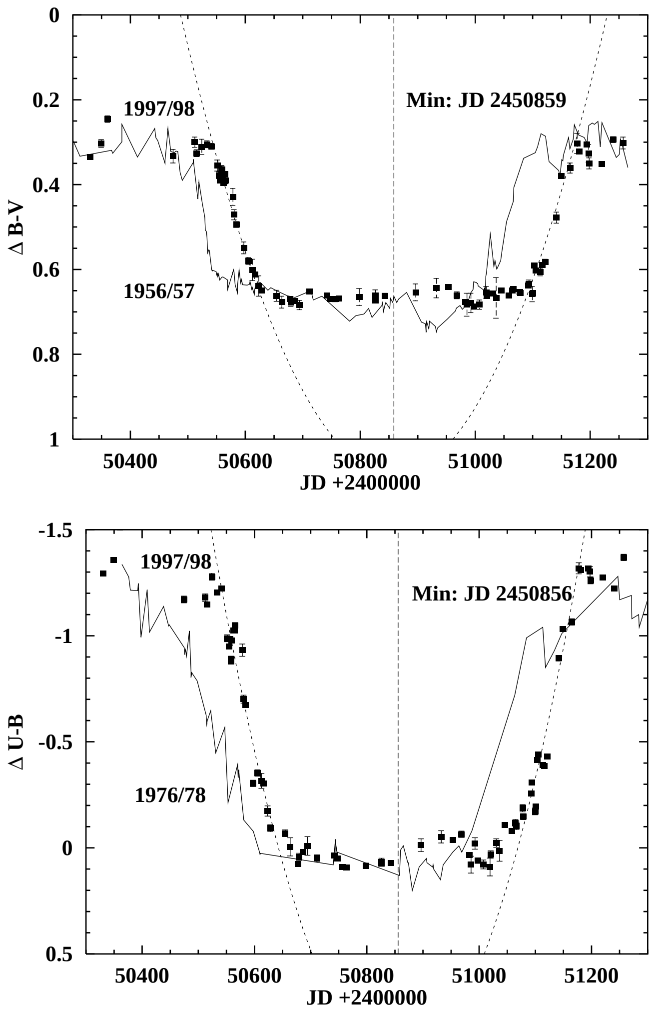

Fig. 1. *(Upper panel)* The 1997/98 eclipse in $B-V$ (black squares) and the 1956/57 eclipse in a similar $P-V$ colour (solid line, Larsson-Leander 1958, 1960) shifted according to Gaposchkin's ephemeris by $2\times7430^{\rm d}$. *(Lower panel)* The 1997/98 eclipse in $U-B$ (black squares) and the 1976/77 eclipse in 3500 Å − 4100 Å colour (solid line, Saitō et al. 1980) shifted by $7430^{\rm d}$. The dashed lines are parabolic fits to the shoulders of the eclipse setting the time of the mid-eclipse at JD 2 450 859 and 2 450 856, respectively

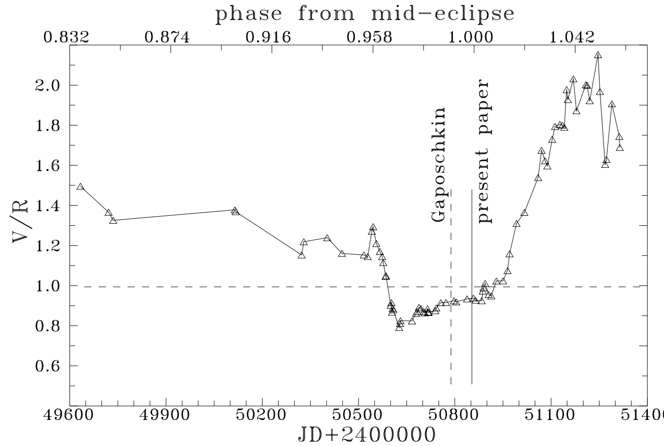

Fig. 2. V/R ratio of the Hα emission line in the spectrum of VV Cep. Times of the mid-eclipse from the ephemeris by Gaposchkin and from the present paper are shown. Phase from mid-eclipse is calculated applying a new possible period $7498^{\rm d}$

suppressed, while in the egress phase the blue-emitting side of the disk emerges first from behind of the supergiant star. Such variations of the V/R ratio are well-known in cataclysmic variables (Greenstein & Kraft, 1959; Young et al. 1981), Algol type binaries (Peters 1989), symbiotic binaries (Leedjärv et al. 1994) etc. Behaviour of the Balmer lines in the spectra of VV Cep during the 1977/78 eclipse was studied by Möllenhoff & Schaifers (1978, 1981), Kawabata et al. (1981) and Saijo (1981), and it was found to be consistent with the rotating disk model.

Our spectroscopic observations were carried out at the Tartu Observatory, using the 1.5 meter telescope and the Cassegrain grating spectrograph equipped with a Tek 1024×1024 CCD camera HPC-1 for most of the time. A few spectra before the eclipse were obtained in 1994–1995 with the ST-6 type CCD camera, and since late March 1999 a new Orbis-16 type camera was used. Until March 1997 only spectra in the Hα region were obtained (resolution mostly 0.24 Åpix^{-1}). Since the beginning of the eclipse, also the Hβ region (0.42 Åpix^{-1}) and the blue region (about 3900–4350 Å, 0.47 Åpix^{-1}) have been monitored continuously. Altogether, about 170 spectrograms of VV Cep have been recorded during and around the eclipse. Here we present only some preliminary results from the analysis of the Hα line and the FeII and [FeII] lines. Extensive discussion of the spectroscopic observations remains for a forthcoming paper.

3.2. Hα line

Hα in the spectrum of VV Cep normally is a double-peaked emission line with $V/R > 1$ (Wright 1977). Such an asymmetry may be caused by absorption in the stream of matter between the M supergiant and the B star. As the matter moves towards the B star's envelope, i.e. away from the observer, this absorption is displaced redward from the line centre, thus suppressing the red emission component. Also, an absorption line of the M supergiant may distort the Hα profile.

Fig. 2 demonstrates variations of the V/R ratio before, during and after the eclipse. One can see from Fig. 2 that continuous deep decrease of V/R began at about JD 2 450 540, in a fine agreement with the beginning of the eclipse from the UBV photometry (GMJ). The Hα emission line does not disappear completely during the eclipse, it is probably strong enough to shine through the extended outer atmosphere of the M supergiant. The Hα emission line was not quite symmetric during the totality. At the time of the mid-eclipse derived from the photometry, it had $V/R \geq 0.9$. It reached value 1.0 at about JD 2 450 920, and thereafter rose continuously until value ~ 2.0 by JD 2 451 170. This is actually the end of the eclipse from the photometry. But the V/R ratio of the Hα line continued to vary a little around 2.0, and yet did not reach the usual out-of-eclipse value (1.3–1.5) by the time of writing the present paper. Although determination of the key moments of the eclipse from the variations of the V/R ratio is not unambiguous, the general

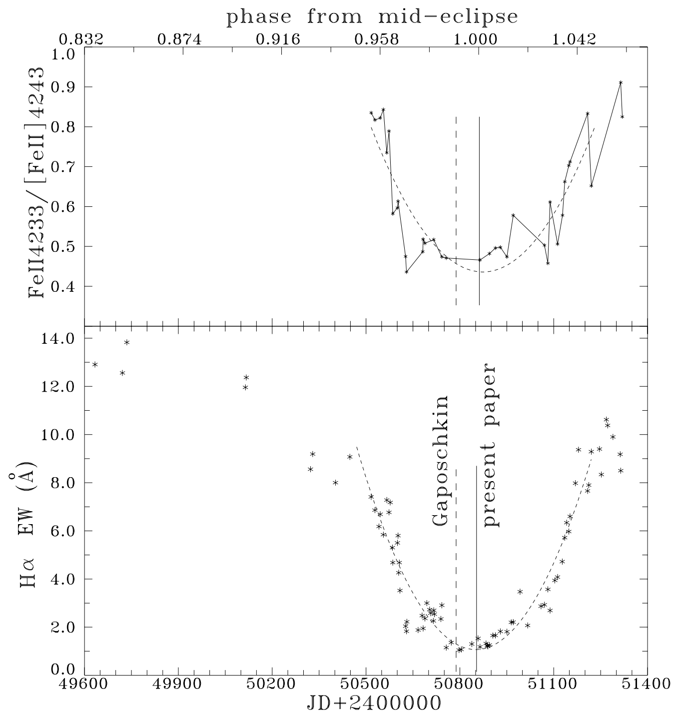

Fig. 3. *(Lower panel)* Equivalent width of the Hα emission line. Parabolic approximation yields the mid-point of the eclipse at JD 2 450 848. *(Upper panel)* Ratio of the EWs of the lines FeII λ 4233 and [FeII] λ 4243. Parabolic approximation yields the mid-point of the eclipse at JD 2 450 868. Note a similarity in the variations of both quantities, in particular around JD 2 450 600

pattern of the variations agrees well with the times determined from the photometry.

The total equivalent width (EW) of the Hα line should be better indicator of the duration and the mid-point of the eclipse. Fig. 3 (lower panel) shows that the variations of EW (Hα) are quite symmetric, and the parabolic approximation gives the time of the minimum, corresponding to the mid-eclipse at JD 2 450 848 – again in a good agreement with the UBV photometry. It is seen from Fig. 3 that EW has decreased already about 1.5 times compared to its out-of-eclipse value by the beginning of the photometric eclipse (JD 2 450 540). The decrease started at some time between JD 2 450 120 and 2 450 300, this is about 550–730 days before the mid-eclipse. Assuming that EW will behave symmetrically, one could expect the Hα line to recover its pre-outburst EW between JD 2 451 400 and 2 451 580, i.e. possibly even in early 2000 only. This indicates the total duration of the eclipse (the atmospheric and the stellar ones together) about 1100–1400 days (15–18% of the orbital period).

3.3. Permitted and forbidden lines of FeII

Forbidden [FeII] emission lines are characteristic features of all the VV Cep type stars. These lines do not vary considerably throughout the orbital cycle. This is indicating their origin in an extended envelope surrounding the whole binary system. The permitted lines of FeII are more variable, and are present in the spectra of some VV Cep type stars only for some time around the periastron passage (Cowley 1969; Leedjärv 1998).

In the present paper we study the narrow region in the spectrum of VV Cep containing the lines of FeII λ 4233 and [FeII] λ 4243. The forbidden line (which actually is a blend) is more or less symmetric narrow single-peaked emission line showing no significant intensity variations during the eclipse. Profile of the FeII λ 4233 line is more complicated, at times showing additional blue-shifted (and perhaps also red-shifted) emission component. One could suspect that the blue-shifted component actually is the [FeII] line at $\lambda = 4231.56$ Å which according to Mammano & Martini (1969) has been detected in the spectra of the VV Cep type stars WY Gem and W Cep. Kawabata & Saitō (1997), however, have not identified this line in their extensive study of the forbidden line spectrum of VV Cep. Also, our measurements of the radial velocities show that the component shortward of FeII λ 4233 emission line probably cannot be [FeII] λ 4231 line.

Therefore we tend to prefer the interpretation by McLaughlin (1951) and its development by Hagen Bauer et al. (1991) according to which there is a narrow emission line of FeII λ 4233 (and UV lines of FeII) arising in a circumsystem envelope like the [FeII] emissions, but it is accompanied by a weaker emission with a width and structure similar to those of hydrogen Balmer lines. This wide component most likely arises in a rotating disk and the region of its origin should be eclipsed similarily to that of the hydrogen lines. Many of our blue-region spectra are too noisy for monitoring the behaviour of the V/R ratio of the λ 4233 line during the eclipse. However, variations of the overall emission intensity (EW) are well detectable, and Fig. 3 (upper panel) presents the time-dependence of the ratio of the EWs of the lines FeII λ 4233 and [FeII] λ 4243. In spite of some scatter, the general pattern of the variations is well recognizable, and it is very similar to that of the Hα line. Also the mid-point of the eclipse JD 2 450 868 derived from Fig. 3 is in agreement with that obtained from the Hα line and from the UBV photometry. This confirms the common place of origin of the hydrogen and the wide FeII emission lines.

Table 1. Contact times for the last eclipse in VV Cep from UBV photometry and spectroscopy of the Hα and FeII λ 4233 emission lines. The times are given in JD $-2\,400\,000$

	1st	2nd	3rd	4th	mid-point	totality
		contact				(days)
$B-V$	50545	50630	51100	51180	50859	470
$U-B$	50545	50620	51070	51170	50856	450
Hα	50520	50620	51085	51210	50848	465
FeII	50550	50625	51110	51200	50868	485
Mean	50540	50624	51091	51190	50858	467

4. Discussion

Table 1 summarizes the important time moments for the last eclipse of VV Cep. The times of the 4th contact from spectroscopic data are quite uncertain, as the emission lines have not yet achieved their pre-eclipse intensity. Durations of the partial and total phases of the present eclipse were similar to the 1957/58 eclipse (Larsson-Leander 1958, 1960), while the total phase of the 1977/78 eclipse was about 100 days shorter (Möllenhoff & Schaifers 1981; Saitō et al. 1980). But the most surprising feature of the last eclipse was its late occurence – 68 days later than expected from the ephemeris by Gaposchkin (1937). There are two possible reasons for such a phenomenon: (1) inappropriate orbital elements or (2) the real change of the orbital period. Inspection of the O−C diagram for the past five eclipses (see Fig. 4 in GMJ) shows no systematic deviations from the Gaposchkin's elements, except the 1936 eclipse which was about 25 days late. There is too limited statistics to conclude from this fact that some cyclic variations of the orbital period could take place. It seems more likely that the orbital period of VV Cep has increased by almost 1% between the last two eclipses.

The orbital period of the binary stars can be changed by (1) mass transfer between the components, (2) ejection of some mass from the system or (3) presence of a third body. The sudden increase of the period suggests the first or the second possibility. As already discussed by GMJ, the generally accepted model of VV Cep with the mass ratio $q = M_{\rm M}/M_{\rm B} \approx 1$ and total mass of the system about 40 $M_{\odot}$, implies incredibly high mass loss rates for the M supergiant. When considering mass transfer between the components, a rate of $5 \cdot 10^{-2} M_{\odot} {\rm yr}^{-1}$ is needed for $q = 1$. In the second case, the total ejected mass should be of the order of 0.1 $M_{\odot}$ to account for the period change. This implies the mass loss rate of $5 \cdot 10^{-3} M_{\odot} {\rm yr}^{-1}$.

We think that one should not rely too much on the spectroscopic solution for the hot component of VV Cep by Wright (1977), as the disk surrounding the hot star may distort the spectroscopic appearance of the star significantly. GMJ have proposed a medium mass model with the mass ratio $0.2 \leq q \leq 0.3$, and masses of about 8 $M_{\odot}$ and 2.5 $M_{\odot}$ for the B star and for the M star, respectively. In this case, the mass loss rates required to explain the period change would be $5 \cdot 10^{-4} M_{\odot} {\rm yr}^{-1}$ and $4 \cdot 10^{-4} M_{\odot} {\rm yr}^{-1}$ for the mass transfer and mass ejection, respectively. These rates are nearly consistent with the estimates of the upper limits of mass loss rate from the M-star by Stencel et al. (1993) and Kawabata & Saitō (1997). On the other hand, a 2.5 $M_{\odot}$ star would be an AGB star rather than a supergiant, and it is still difficult to obtain such an high mass loss rate from the AGB star. Interaction of the components in the binary system, however, may enhance the mass loss and mass transfer processes. Also, thermal pulses of the AGB star may be responsible for the increasing mass loss rate.

One of the main goals of the present paper was to draw attention to the controversy between the apparent period change and the generally accepted model of VV Cep. If really some dramatic mass transfer or mass ejection events took place in the VV Cep system during the last 20 years, there could be some observable signatures of these processes, especially in the high-dispersion spectra. All interested observers are encouraged to look through the archival data on VV Cep which together with future multi-wavelength observations could help to solve the problem of nature and evolutionary status of VV Cep (and possibly about 20 more VV Cep type stars).

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References

Cowley A.P., 1969, PASP 81, 297
Gaposchkin S., 1937, Harvard Coll. Obs. Circ. No. 421
Graczyk D., Mikołajewski M., Janowski J.L., 1999, IBVS 4679 (GMJ)
Greenstein J.L., Kraft R.P., 1959, ApJ 130, 99
Hack M., Engin S., Yilmaz N., 1989, A&A 225, 143
Hagen Bauer W., Stencel R.E., Neff D.H., 1991, A&AS 90, 175
Hutchings J.B., Wright K.O., 1971, MNRAS 155, 203
Kawabata S., Saitō M., 1997, PASJ 49, 101
Kawabata S., Saijo K., Sato H., Saitō M., 1981, PASJ 33, 177
Larsson-Leander G., 1958, Arkiv Astron. 2, 135
Larsson-Leander G., 1960, Arkiv Astron. 2, 301
Leedjärv L., 1998, A&A 338, 139
Leedjärv L., Mikołajewski M., Tomov T., 1994, A&A 287, 543
Mammano A., Martini A., 1969, In: Non-Periodic Phenomena in Variable Stars. IAU Colloq., Budapest, p. 415
McLaughlin D.B., 1951, ApJ 114, 47
Möllenhoff C., Schaifers K., 1978, A&A 64, 253
Möllenhoff C., Schaifers K., 1981, A&A 94, 333
Peters G.J., 1989, In: Batten A. (ed.) Algols. Space Science Reviews 50, p. 9
Saijo K., 1981, PASJ 33, 351
Saitō M., Sato H., Saijo K., Hayasaka T., 1980, PASJ 32, 163
Stencel R.E., Potter D.E., Bauer W.H., 1993, PASP 105, 45
Wright K.O., 1977, JRASC 71, 152
Young P., Schneider D.P., Shectman S.A., 1981, ApJ 245, 1035