EVIDENCE ON HOT SPOT IN CONTACT BINARY VW CEPHEI

I.B. Pustylnik[1], P.G. Niarchos[2]

[1] Department of Astrophysics, Tartu observatory
Tartu region, Toravere 61602, Estonia, *izold@aai.ee*

[2] Department of Astrophysics, Astronomy and Mechanics
Faculty of Physics,University of Athens,GR-157 84
Athens, Greece, *pniarcho@atlas.cc.uoa.gr*

ABSTRACT. We study the nature of asymmetry and the intrinsic variability in the light curves of VW Cep. We analyze our own B,V light curves as well as the other data from literary sources. In view of the presence of significant intrinsic brightness variations at a level of $0^m.01 - 0^m.03$ on time scales comparable to the orbital period we deal only with *individual* light curves sampled possibly in one-two consecutive orbital cycles. The evidence for the presence of the small hot spot region close to the neck connecting both components will be summarized: a) displacements of the brightness maxima from the predicted epochs of elongations suggestive of an additional energy input supposedly of the hot chromospheric origin, b) the overall pattern of asymmetry in brightness maxima and minima, c) systematic colour changes with the orbital phase, d) the presence of significant cosine odd harmonics in truncated series of the observed light curves. We find that the hot spot with a characteristic size of $R \sim 0.7 - 1.2 \cdot 10^{10} cm$ and the temperature contrast $\Delta T/T = 1.3 - 1.4$ located on the surface of a more massive star can explain the afore-mentioned peculiarities whereas model light curves based on our model give rather good fit to the observed data studied so far. The possible physical nature of the hot spot in the light of our results confronted with the spectroscopic data (specifically Mg II resonance doublet) and flare activity signatures are briefly discussed.

Key words:stars:binary: contact; stars: individual: VW Cep.

1. Introduction

The contact binary VW Cephei (*HD 197433 = BD* $+75^o752, 20^h38^m03^s + 75^o25'.0(1950), G5, P = 6^h41^m$) from the moment of its discovery in 1924 till now remains the target of intensive astrophysical research. In recent period the wave-like distortions of the light curves superimposed upon the regular brightness variations caused by mutual eclipses and tidal distortions of both components nearly filling in their respective Roche lobes received considerable attention. New observational data have been accumulating suggestive of a variable chromospheric and coronal activity ,both regular and of a flaring nature (see, for instance, Bradstreet and Guinan 1990, Pustylnik 1995, Choi and Dotani 1998).

There is now consensus among the investigators of close binary systems that AB component of VW Cephei consists of two low mass main sequence stars ($m_1 \simeq 0.9 m_\odot, m_2 \simeq 0.25 m_\odot, R_1 = 0.93 R_\odot, R_2 = 0.5 R_\odot, T_{1\rm eff} \simeq 5000^o K, T_{2\rm eff} \simeq 5200^o K$) (see Hill 1989). By all evidence VW Cep system "oscillates" between the contact and semi-detached configuration. In its present state mass transfer caused by magnetic wind from the low mass component should result in a gradual merging of the components (for details of evolutionary scenarios, see Robertson and Eggleton 1977, Lucy and Wilson 1979).

And yet despite the variety of the observational data the nature of the wave-like distortions of the light curves and their possible connection with the short term orbital period variations remain obscure. To interpret the different brightness maxima heights (O'Connell effect) the idea of dark spots or of circumstellar (circumbinary) matter have been exploited (for more details see Karimie 1983, Hendry *et al* 1992, Pustylnik and Sorgsepp 1975). The purpose of our contribution is to draw attention to a supplementary source of information which in our view may throw an additional light on the nature of asymmetry of the light curves in VW Cephei system: the phase behaviour of the light maxima.

2. Epochs of maxima, displacement in respect to elongation

In an earlier paper (Pustylnik and Kreiner 1997) we reported for the first time about the discovery of small but significant phase displacements of light maxima in VW Cep from the predicted epochs of elongation. Recently we have extended the data base including observations by Linnell (1980) and Niarchos *et al* (1998) in our analysis. We used polynomial approximation for normalized brightness $l(T) = \sum_{j=0}^{n} a_j\, T_i^j$ (T_i being the Julian date for the observation considered) and normally $n = 6$ was adopted.The observed moments of brightness maxima have been determined iteratively with the aid of Newton's method solving equation $dl/dt = 0$ (for more details see Pustylnik and Kreiner 1997). We used the data only of high quality with the observational points covering the total light curve and never used average light curves. In this way a number of epochs for the primary and of the secondary maxima have been determined and summarized in Table 1. In all these cases we see small but significant

Table 1: Epochs of the primary E_pr and secondary E_sec maxima and $(O-C)$

E_pr	$O-C$	E_sec	$O-C$
2439467.3288	0.006	2439467.4622	-0.003
2439467.6074	0.004	2439521.4620	0.005
2439521.3184	0.001	2439918.3260	-0.007
2439748.4222	0.004	2439918.6089	-0.004
2439935.4510	0.002	2439935.5836	-0.004
2439964.3967	0.003	2439964.5304	-0.003
2444477.8083	0.002	2444477.6674	-0.001
2448531.4173	0.005	2448152.2112	0.002
2449278.3863	0.005	2449276.4298	-0.004

displacements of the brightness maxima in respect to the predicted moments of elongation. The displacement amounts to $0.^\mathrm{d}005 - 0.^\mathrm{d}008$, i.e $0.03P_\mathrm{orb}$, whereas the formal accuracy of the position of the brightness maximum from the smooth curve is no less than $0.^\mathrm{d}0002 - 0.^\mathrm{d}0003$. We regard thus determined displacements of the brightness maxima as real, since in no cases studied so far we have found displacements of the moments of brightness minima from predicted epochs exceeding $0.^\mathrm{d}001$.

As we see from the data of Table 1, a higher maximum (following the primary minimum) is observed at a later epoch than it follows from the value of the orbital period whereas the lower maximum (preceding the primary minimum) preferentially comes at an earlier epoch. This can be interpreted as an evidence for the asymmetric (in respect to the line of centres) brightness distribution over the hemisphere of a primary component facing its low mass companion. It is obvious that this subtle effect will be smoothed out if one deals with the average light curves in view of the intrinsic light variations. To analyse in more detail brightness changes during maxima we have approximated full light curves with the aid of truncated series

$$L(\phi) = \sum_{j=0}^{n} (A_j\, \cos j\phi + B_j\, \sin j\phi), \qquad (1)$$

and determined the coefficients A_j, B_j for 6 nights for which observational points covered the whole light curve. The results are indicated for 2 nights in Table 2. In addition in the last lines of the Table we are attaching the coefficients of even harmonics of the cosine truncated series tabulated by Rucinski (1995) which approximate the light curves of W UMa type binaries for different angles of orbit inclination i, mass ratios q and fill-out parameter f. Figure 1 illustrates typical

Table 2: Coefficients of the truncated series JD2439000+...

JD467	$-A_1$	$-A_2$	$-A_3$	$-A_4$	$-A_5$	$-A_6$
B	0.022	0.133	0.006	0.024	0.009	0.012
V	0.022	0.124	0.007	0.021	0.009	0.011
JD748	$-A_1$	$-A_2$	$-A_3$	$-A_4$	$-A_5$	$-A_6$
B	0.022	0.132	0.011	0.026	0.010	0.011
V	0.020	0.123	0.012	0.025	0.008	0.011
$f = 0.0$	–	-0.103	–	-0.021	–	-0.008
$f = 0.5$	–	-0.128	–	-0.013	–	-0.005

results for JD2444477 in V colour. Similar results are obtained for other 4 nights.

As one can see from the plot there is in general a good agreement between the observations and approximation by truncated series except for the phase interval $\phi = 0.95 - 1.05P$, i.e. the bottom of the primary minimum. The coefficients of even harmonics A_2, A_4, A_6 are in good agreement with the values found from Rucinski's paper. But in addition to even harmonics considerable odd harmonics are present. Their sums are $C_1 = A_1 + A_3 + A_5$. For JD2439748 we have respectively $C1 = -0.043, -0.040$ (in B and V), JD2439467 -0.037, -0.038(B and V), JD2439918 - 0.030, -0.052(B and V), JD2444472 -0.020,-0.034,-0.063, - 0.008 (B,V,R,I respectively), JD2444477 -0.034,-0.033 (B and V). We interpret it as the contribution from the "hot spot" which would have been best visible at the phase angle value $\phi = 0.5P$ but it is hidden (at least partially) because of the transit eclipse of a more massive component. The value of C_1 is very close to the amplitude of the colour curves and the differences in brightness minima depths.

3. Estimate of the parameters of the hot spot

Displacement of the maxima positions from elongations along with the pronounced overall asymmetry of the light curves can be interpreted as an evidence of an additional energy input (apparently of non-thermal origin) which affects the regular light variations caused by the tidal distortions of both components nearly filling in their Roche lobes. Whatever is the nature of mechanism responsible for the observed asymmetry, to cause the displacement in phase of maximum by $\Delta\phi$ an additional energy input is needed $L \geq C\, \frac{dl}{d\phi}\, \Delta\phi$ where the value $dl/d\phi$ can be estimated with the aid of the theoretical light curve and the constant C should be of order $C \simeq 1 - 10$. Taking use of the data for the effective temperatures and the radii of the components from Hill(1989) we have found $L = 2 \cdot 10^{29} ergs/s$ and $L = 2 \cdot 10^{30} ergs/s$ for $C = 1$ and $C = 10$ respectively. An average value of the difference between the heights of the adjacent maxima for the Julian dates given in Table 1 yields the estimate $L = 3.5 \cdot 10^{30} ergs/s$. Next assuming that mutual eclipses and tidal distortions fully determine the shape of the light curve for a standard limb darkening law we shall attempt now to estimate the size and the temperature of the putative spot. In doing that we neglect small differences in temperature between the component stars (according to various authors $\Delta T \sim 150°K$) and the gravity darkening effect. Since in U, B, V colours and even in R and I we can safely use Wien's approximation a simple expression holds for the total luminosity of the binary in wave-length λ_j for the phase angle ϕ in orbit

$$L_{\lambda\, j}(\phi) = \frac{c_1}{\lambda_j^5} \exp(-\frac{c_2}{\lambda_j\, T_{\rm st}})\, [S_{\rm 1st}(\phi) + S_{\rm 2st}(\phi)] +$$

$$\frac{c_1}{\lambda_j^5} \exp(-\frac{c_2}{\lambda_j\, T_{\rm sp}})\, S_{\rm sp}(\phi), \qquad (2)$$

where $T_{\rm st}$ and $T_{\rm sp}$ are respectively the effective temperatures of the components and the spot whereas $S_{\rm 1st}, S_{\rm 2st}, S_{\rm sp}$ are projected areas upon the plane of the sky of the components and the spot. Now introducing the temperature contrast $\delta T_{\rm sp} = (T_{\rm st} - T_{\rm sp}/T_{\rm st})$ and relative area $\delta_{\rm sp}(\phi)$ in units of the total area of a binary visible at a given phase angle ϕ in orbit we can easily find that

$$\delta_{\rm sp}(\phi) = 0.921034\, [\Delta m_{\lambda\, j(\phi,0)} -$$

$$-2.5\, \lg(L_{\lambda\, j}(0)/L_{\lambda\, j}(\phi))]\, \exp(-\frac{c_2\, \delta T_{\rm sp}}{\lambda\, j\, T_{\rm sp}}) \qquad (3)$$

where $\Delta\, m_{\lambda\, j} = m_{\lambda\, j}(\phi) - m_{\lambda\, j}(0)$ is the observed difference in stellar magnitudes of VW Cep for phase angles 0 and ϕ. Taking the data for the full amplitude of the light curves in U,B,V,R,I from the paper of Linnell (1980) the orbital elements from the paper of Hill(1989) and calculating from the model light curves $L_{\lambda\, j}(0)/L_{\lambda\, j}(\phi)$ we arrive at the below-given values for $\delta_{\rm sp}(\phi = \pi/2)$,(see data in Table 3) for different assumed values of the temperature of the hot spot. Applying (3) to the luminosity of VW Cep, for instance, in B and V colors we have the following relation between the relative size of the hot spot $\delta_{\rm sp}(\phi)$ and the colour change $\Delta(B - V)$ between maximum and primary minimum

Table 3: Relative size of the hot spot

$T_{sp}(K)$	U	B	V	R	I
6000	0.063	0.053	0.041	0.038	0.020
7000	0.021	0.024	0.023	0.023	0.016
8000	0.012	0.014	0.014	0.017	0.012

$$\Delta(B - V) = 1.086\delta_{\rm sp}\, [\exp(-\frac{c_2\, \delta T_{\rm sp}}{\lambda_b\, T_{\rm sp}}) - \exp(-\frac{c_2\, \delta T_{\rm sp}}{\lambda_v\, T_{\rm sp}})]. \qquad (4)$$

Because of a crude nature of the estimate we have neglected possible differences in the size of the spot in different colors when deriving relation (4). Applying it to different colors we find the amplitudes of color changes for different values of $T_{\rm sp}$. The results are summarized below in Table 4. In the last line the average observed values are indicated for VW Cep. As we see there is a good agreement between the observed and model color indices, if one assumes that $T_{\rm sp} = 7000°K$. The derived parameters of the hot spot depend on the adopted orbital elements, notably on the value of fill-out parameter f. The above-given values of δ were obtained assuming $f = 0.05$. However, the results are not specially sensitive to the assumed value of f. For instance if one takes $f = 0.4$, one finds δ smaller by about 20 per cent than those given-above.

Table 4: Full amplitudes of colour changes

$T_{sp}(K)$	$\Delta(B-V)$	$\Delta(U-B)$	$\Delta(V-R)$	$\Delta(V-I)$
6000	0.020	0.031	0.016	0.10
7000	0.038	0.070	0.029	0.049
8000	0.057	0.117	0.040	0.064
Δ_{obs}	0.040	0.072	0.030	0.044

To verify how the hot spot with the above-given parameters can be helpful in interpreting the observed light curves of VW Cep we used commercially available computer package *BINARY MAKER* and modelled with its aid the light curves of VW Cep assuming the orbital and physical parameters from Hill (1989) and changing only the inclination angle $i \simeq 65° - 67°$.

We have found the best fit for the following values of the hot spot parameters:$R_{\rm sp} = 7° \pm 1°, \delta T/T \simeq 1.35 - 1.4, L_3 = 0.02 - 0.03$ (the third light),$f = 0.05, l = 80° \pm 2°, \chi = 357° \pm 2°$ (l being the latitude and χ the longitude of the centre of the hot spot upon the surface of more massive component). Figure 2 illustrates results for light curve in V for Julian date 2439467. Although the agreement between the observed and model light curves is not fully satisfactory, we see that the model light curves reproduce the observed phase displacements of maxima and produce the overall observed pattern of asymmetry.

We find especially encouraging that the derived value of the temperature of the hot spot is practically coincident with the temperature needed to generate $MgII\lambda 2795, 2802\dot{A}$ strong resonance doublet feature, whereas both the flux in this feature and the phase of its maximum are in good accord with the above given estimate of the luminosity of the hot spot and its location(for details see Pustylnik 1995 and the graphical data in Bradstreet and Guinan 1990 for $MgII\lambda 2795, 2802\dot{A}$ and H_α line composite profile). To summarize, we find the proposed hot spot is an essential cohesive element of the model for VW Cep because it solves an old enigma of the color changes on one hand and gives natural explanation to small differences in depths of minima for practically equal effective temperatures of the components on the other. With its application the discrepances between the photometric and spectroscopic data find natural explanation.

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References

Bradstreet D.H., Guinan E.F.: 1990, *In: Active Close Binaries,* ed. C.Ibanoglu (Dordrecht: Kluwer), 467.
Choi C.S., Dotani T.: 1998, *Ap.J.*, **492**, 761.
Hendry P.D., Mochnacki S.W., Collier Cameron A.: 1992 *Ap.J.*, **399**, 246.
Hill G.: 1989, *Astron. Astrophys.*, **218**, 141.
Karimie M.T.: 1983, *Astrophys. Space Sci.*, **92**, 53.
Linnell A.P.: 1982, *Astrophys.J. Suppl.Ser.*, **50**, 85.
Lucy L.B., Wilson R.E.:1979, *Astrophys.J.*, **231**, 502.
Niarchos P.G., Hric L., Manimanis V., Theodossiou E.: 1998, in: *Proc. of the 20th Stellar Conference of the Czech and Slovak Astr. Inst.*, 89.
Pustylnik I., Sorgsepp L.: 1975, *Publ. Tartu obs.*, **43**, 130 (in Russian).
Pustylnik I.: 1995, in: *Stellar Surface Structure, IAU Symp.* **176**, Wien, Poster Proceedings, ed. K.G.Strassmeier, 215.
Pustylnik I., Kreiner J.: 1997, in: *"Astronomical Time Series",* ed. D.Maoz, A.Sternberg, E.Leibowitz, Kluwer Publishers, 207.
Robertson J.A., Eggleton P.P.: 1977, *Monthly Not. Roy. Astr. Soc.*, **179**, 359.
Rucinski S.M.: 1995, *Astron. J.*, **109**, 2690.

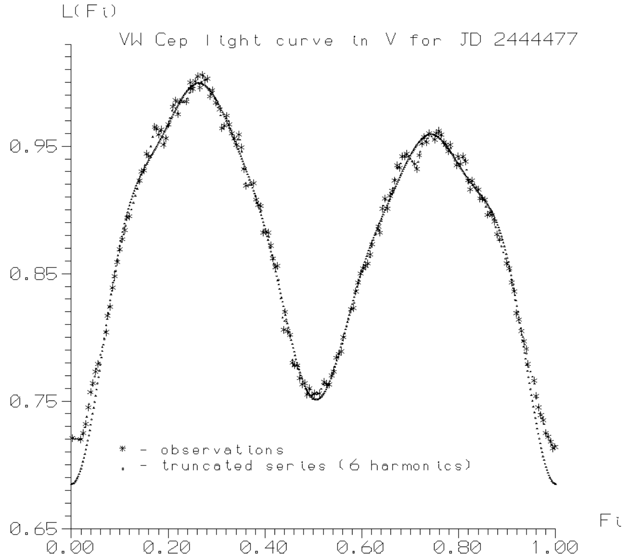

Fig. 1. Observed V light curve of VW Cephei for *J.D.*2444477 and approximation by truncated series(see formula (1) in text).

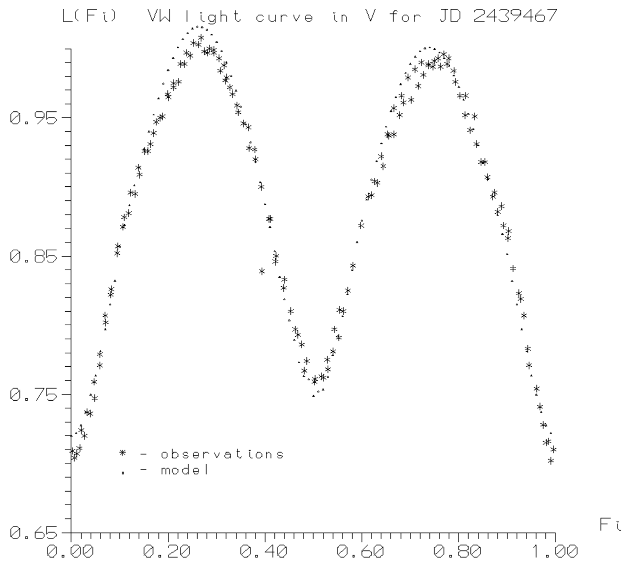

Fig. 2. Observed V light curve of VW Cephei for *J.D.*2439467 and the model light curve assuming presence of a small hot spot upon the surface of the primary component close to the neck region.The physical parameters and location of the spot are given in the text.