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Causes and cures of the $O - C$ diagram
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Light-Time Effect in Selected Semi-detached and Contact Binaries with Observable Third Components

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Abstract. $O - C$ diagrams of the eclipsing binaries 44i Boo, AH Cep, CW Cep, EM Cep and RY Gem are analyzed. These binary systems have been observed at Tallinn Observatory for a number of years and $UBVR(R)$ phase diagrams have been obtained. $O - C$ analysis is based partially on our data but mostly on published sources. Of all discussed objects with previously unknown third components we find in the case of RY Gem sufficient evidence for the presence of a third body, though more data are needed for an accurate determination of the physical parameters of the invisible component. We discuss the nature of "the fine structure" evident in some $O - C$ diagrams in terms of chromospheric activity of the late-type components.

1. Introduction

Photoelectric observations of the close binary systems discussed in this article constituted a part of a comprehensive project aimed at monitoring of eclipsing binaries and intrinsic variables started as early as 1967 at Tallinn observatory. The observational targets included predominantly long-period eclipsing binary systems with pronounced intrinsic variability and with a strong emission in H_α suggestive of the significant mass transfer between the components or mass loss from the binary. The initiator of the program was a former director of Tallinn Observatory Dr. P. Kalv, who passed away in 2002 (for more details about P. Kalv's activities, see Pustylnik 2003). Observations were obtained with a photoelectric photometer attached to the Cassegrain focus of the 48-cm reflector. At first the measurements in B and V bands were secured and later on measurements in the standard $UBVR$ Johnson system and in H_α were conducted. Details of the reduction procedure for atmospheric extinction, transformation from instrumental to the standard UBV system and other technical peculiarities have been published elsewhere (see Kalv 1975). For the purposes of the current investigation it suffices to say that in all cases measurements of the variable, comparison and check stars lasted for 30 seconds in each of 4 filters and thereafter the sky background was measured for 5 to 10 seconds. The stars were carefully centered in the diaphragm with the aid of the eypiece micrometer of the guider. Usually four individual readings were averaged to get a normal point. Our long experience as well as the comparison with similar observational sets indicate that during the best quality photometric nights we obtain a precision of $0\overset{m}{.}005 - 0\overset{m}{.}007$ in B and V. Considerably higher quality cannot be attained because of an enhanced level of the sky background due to the proximity of the town (notably detrimental in the northern sky).

Table 1. Physical parameters of the discussed binary systems.

	44i Boo	AH Cep	CW Cep	EM Cep	RY Gem
SAO	45357	20247	20401	19718	96912
HIP	73695	112562	113907	108073	36209
HD		216014	218066	208392	58713
Period (days)	0.26781	1.77475	2.72914	0.80618	9.30056
Spectral type	G2V	B0.5VNE	B0.5	B1IVE	A2VE
	G2V	B0.5V	B0.5IV-VEA		K2IV
Mass ($M_\odot$)	1.0	15.3	10.0		2.1
	0.5	13.2	9.8		0.5
a (A.U.)	2.0	18.8	22.2		26.0
R ($R_\odot$)	0.8	5.8	5.9		2.2
	0.6	7.3	4.4		5.3
M (abs., B)	+5.0	-6.3	-5.0		+0.7
	+5.5	-5.8	-4.1		+2.2

2. Selected Binaries

In Table 1 we summarize the data on the orbital periods, spectral classes, luminosity classes and physical parameters of the binaries discussed in the current paper. The derived phases of minimum have been converted to equivalent times (HJD) and listed in Table 2. Figs. 1 and 7 shown $O - C$ diagrams for the listed stars.

Table 2. Types and equivalent times of minimum from our observations.

Star	Type	HJD	Star	Type	HJD
44i Boo	II	2446585.2625	CW Cep	I	2445075.5369
44i Boo	I	2446585.3967	CW Cep	II	2445202.4452
AH Cep	I	2443923.579	CW Cep	I	2445801.4830
AH Cep	II	2443970.609	EM Cep	I	2447064.6942
AH Cep	I	2444516.334	EM Cep	II	2447065.0752
AH Cep	II	2444529.651	EM Cep	II	2451976.3320
AH Cep	I	2445034.562	RY Gem	I	2441155.6195 (B)
AH Cep	II	2445056.746	RY Gem	I	2441155.6212 (V)
AH Cep	II	2446556.373			

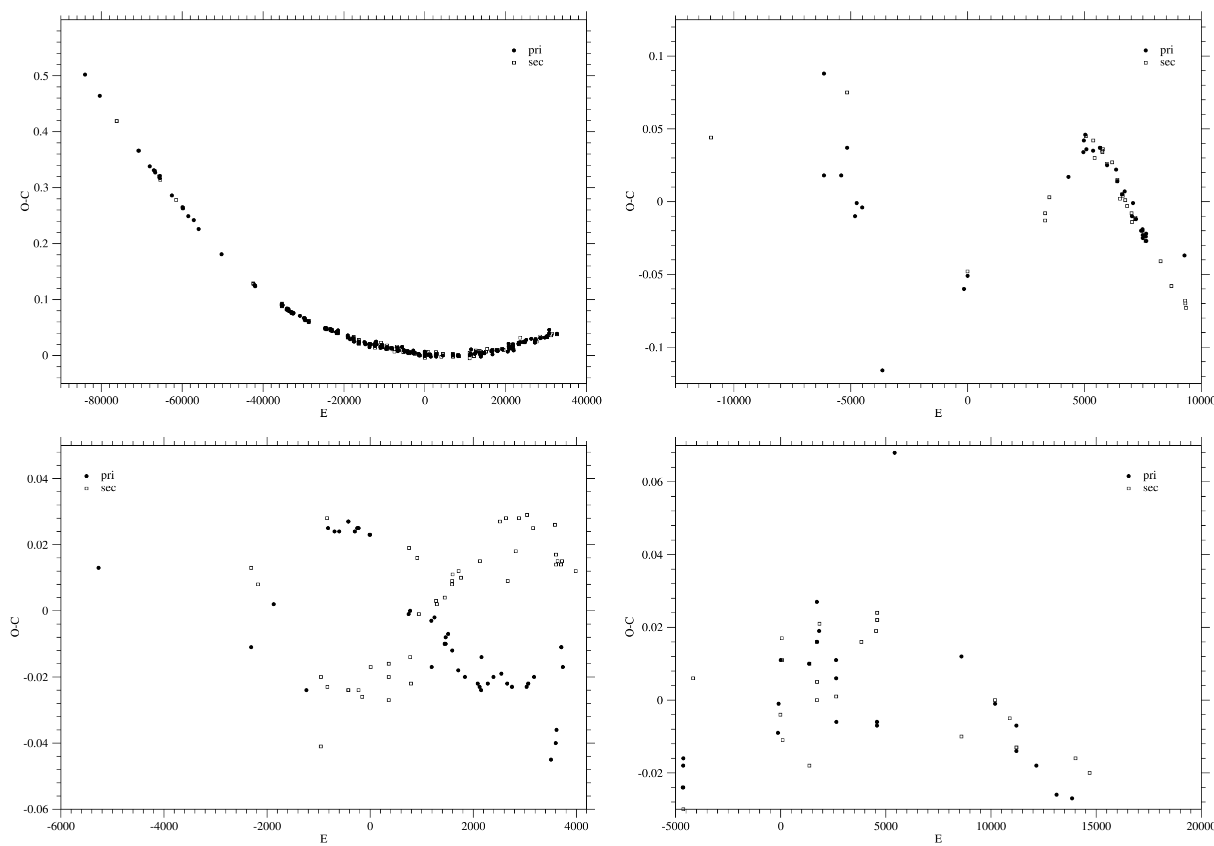

Figure 1. $O - C$ curve of 44i Boo, AH Cep, EM Cep, CW Cep (clockwise).

2.1. 44i Boo

The peculiar eclipsing binary 44i Boo which is one of the components of the visual binary ADS 9494, is a very frequently observed object. This variable displays strong variations and certain period changes. We obtained a single night light curve of 44i Boo on 3–4 June 1986. The observations were carried out with the two–channel photon–counting photoelectric system attached to the 48-cm reflector of the Vilnius Obsevatory High–Altitude station on Mount Maidanak (near Samarkand). This system has been specially designed for searching rapid variations by simultaneous measurements of a variable and a comparison star. The V-filter of the UBV-system and an integration time of 100 seconds were used. The standard error of an individual observation is $0^{\rm m}_{.}003$. The star 47k Boo served as comparison star. The observations were corrected for differential extinction in a usual way (for more details see Harvig 1990a). Figure. 2 shows the phase diagram of 44i Boo. We treat small deviations from the otherwise smooth $O-C$ diagram (see Fig. 1) as a real effect and we discuss its probable nature in Section 7 of the current paper.

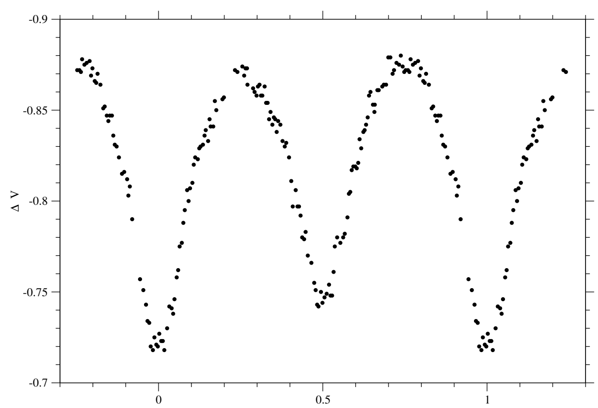

Figure 2. Phase diagram of 44i Boo (HJD= $2443614.4987 + 0.2678173\ E$).

2.2. AH Cep

AH Cep is an early-type eclipsing binary system. UBV photoelectric measurements of AH Cep have been obtained during 103 nights between August 1978 and November 1982 and in addition in the spring of 1986. Detailed description of observational material and analysis of the light curves including determination of the orbital and physical parameters were published in Harvig (1990b). A sample of light curves in B and V bands is shown in Fig. 4. Mayer & Wolf 1986 concluded from their $O-C$ analysis that there is a third component with a period $P_3 = 62.3$ yr and assuming a total mass of the binary of 25M$_\odot$ they esimated the mass of the third component as $M_3 = 8{\rm M}_\odot$. In addition from the residuals, they found a periodicity in $O-C$ diagram pointing to the presence of the fourth body in the system with $P_4 = 1.83$ yr and the mass of this component $M_4 = 7{\rm M}_\odot$. Considerable scattering of the points and pronounced asymmetry of the light curves and a displacement of the epoch of the secondary minimum from phase 0.5 leave little doubt that intrinsic variability and circumstellar matter in AH Cep should influence also $O - C$ diagram. We thus conclude that deviations from a smooth run in $O - C$ diagram of AH Cep (see Fig. 1) is a consequence of these effects. In view of these results, it seems that the conclusion about the presence of four bodies in the system of AH Cep made by Mayer & Wolf is premature.

2.3. CW Cep

CW Cep is an early-type eclipsing binary system with an eccentric orbit ($e = 0.056$, Petri 1947). The binary was observed in *UBVR* and $H\alpha$ from October 1981 till April 1982 at Tallinn Observatory during 38 observing nights. In addition, a number of observations in the Vilnius multicolor photometric system has been secured at Vilnius Observatory Maidanak observing station. Observational material collected both in Tallinn Observatory and Maidanak including comparative critical discussion of orbital elements and physical parameters of the components has been published elsewhere (Harvig 1990c). In the same paper the period of the apsidal motion $P_{\rm aps} = 44.9$ years was deduced and an estimate of the probable age of the binary has been proposed (2 million years). This estimate is based on the assumption that CW Cep belongs to the stellar association Cep III. The light curves in U, B, V, R and H_α are shown in Fig. 3.

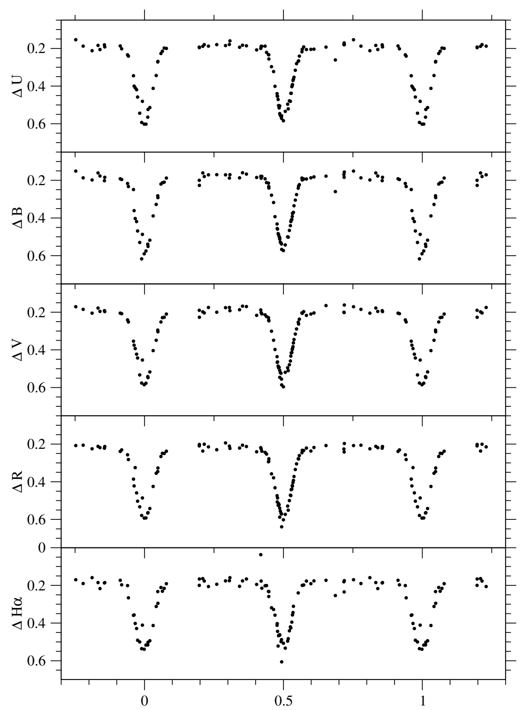

Figure 3. Phase diagram of CW Cep (HJD= $2441669.5726 + 2.72913933\ E$).

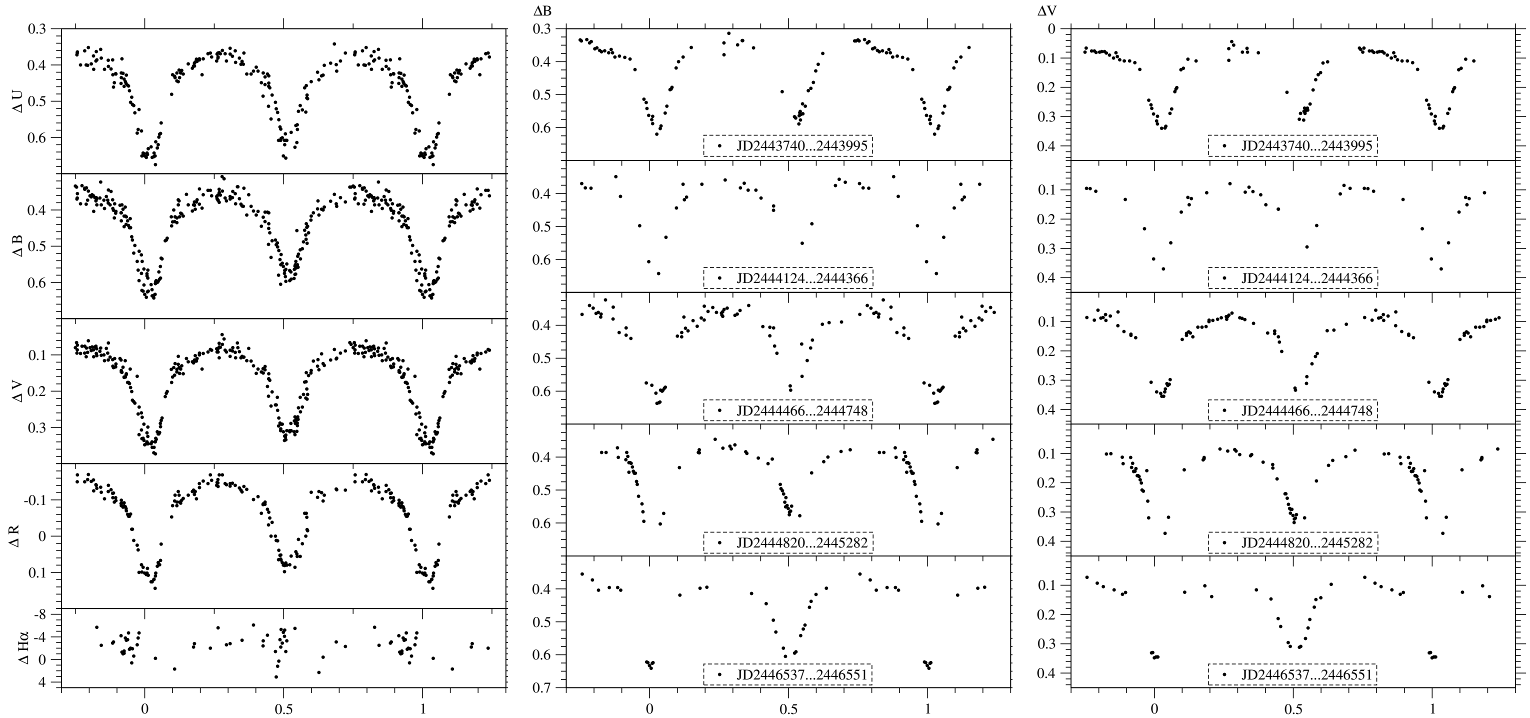

Figure 4. Phase diagrams of AH Cep (HJD= $2434989.4548 + 1.7747474\ E$). Left to right: $UBVR$Hα, and BV (1978–1982).

2.4. EM Cep

EM Cephei is a rare short-period Be star. This variable was observed by us at Mount Maidanak (along with 44i Boo). The observations were carried out using the two–channel photon–counting photoelectric system attached to the 48-cm reflector of the Vilnius Observatory. We observed this star additionally at Tallinn Observatory with the SBIG ST7 CCD camera attached to the 48-cm telescope. The light curve is displayed in Fig. 5. The $O-C$ diagram of EM Cephei shows a considerable scatter, a similar scattering can be seen in the $O-C$ diagram of Kreiner et al. (2000).

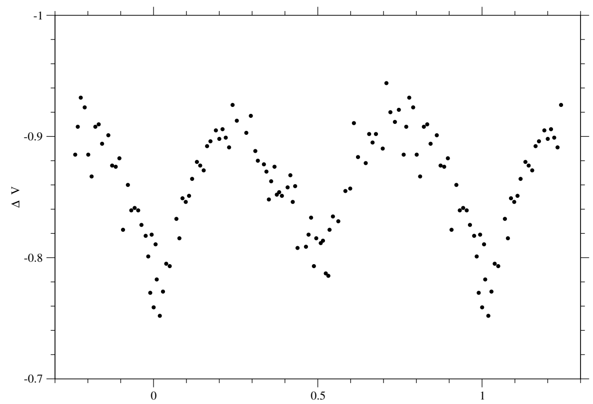

Figure 5. Phase diagram of EM Cep (HJD= 2440134.7329 + 0.80618298 E).

2.5. RY Gem

RY Gem is an Algol type semi–detached eclipsing binary with a gas ring discovered around A2 main-sequence primary component from spectroscopic detection of $H\alpha$ emission by Struve & Huang (1956). *UBV* photoelectric measurements of RY Gem have been obtained during 103 observing nights between 1967 and 1975 (for more details, see Kalv 1980). Earlier reports about the appreciable eccentricity ($e = 0.16$, Mc Kellar 1950) have not been confirmed and displacement of the secondary minimum from the phase of 0.5 in all probability is caused by the circumbinary gas structure. The light curves in B and V are shown in Fig. 6. An enhanced scatter of the observational points close to the bottom of the primary minimum is clearly visible in the light curve both in B and V. Since the line of sight almost exactly coincides with the plane of orbit, the observed light in the primary minimum comes only from the K type secondary component. It implies that the scattering should be caused by the interplay between the activity of the secondary and the mass transfer from this component. This effect should be responsible also for the visible asymmetry between the descending and ascending branches of the light curve seen during partial phases of the primary minimum. We tried to approximate the $O-C$ diagram by a parabolic and sinusiodal curves, see Fig. 7. Both approximations give similar results and for the time being it is virtually impossible to discriminate between two options.

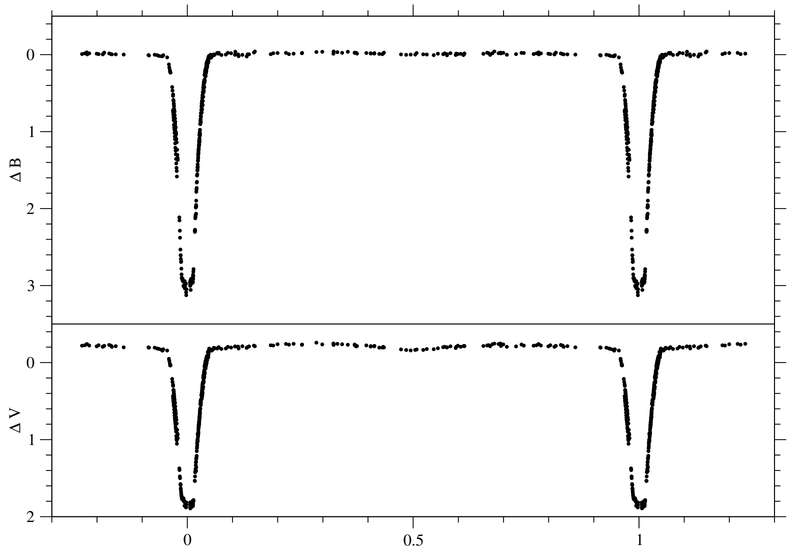

Figure 6. Phase diagram of RY Gem (HJD= $2439732.6123 + 9.300681\ E$).

The presence of the third body in the system seems to be probable but more observations are needed to make firm conclusions.

3. The Fine Structure in $O - C$

In some cases $O - C$ diagrams of close binary systems display significant deviations from a smooth curve on time scales embracing $10^1 - 10^3$ orbital periods. To make definite conclusions about their reality, one needs a long time monitoring of the binary system. In practice this can be accomplished relatively easily for W UMa type stars in view of their short orbital periods permitting to obtain a full light curve in one night. Since in these types of binaries we observe various manifestations of surface activity associated with spots, it seems very probable that we deal here with a real effect which is caused by the combination of interrelated phenomena: 1) asymmetry of the light curve due to the contribution from the flares into the total luminosity of the primary, 2) the presence of the dark spots or the large scale structure of the ambient gas. Both are transient and aperiodic or quasi-periodic phenomena and due to differential rotation (non-synchronism with orbital revolution) they should, in principle, cause small displacements from the otherwise smooth $O - C$ trends provided that the amplitude of the effect is sufficiently high to influence broad-band photometric measurements. Period changes in W UMa type stars have a typical scale of $\delta P/P \simeq 3 \cdot 10^{-5}$ and very much look like random-walk variability with the alternate sign of δP suggestive of magntic cycles 10–50 years long (see, for instance, Rucinski 1993). Most recent X-ray data for a close-by system 44i Boo (for details see Brickhouse & Dupree 1998) from Chandra firmly supports this view at least for one binary system. Although flares have been discovered in several Algol type systems and contact binaries it is not clear whether flaring regions are necessarily connected

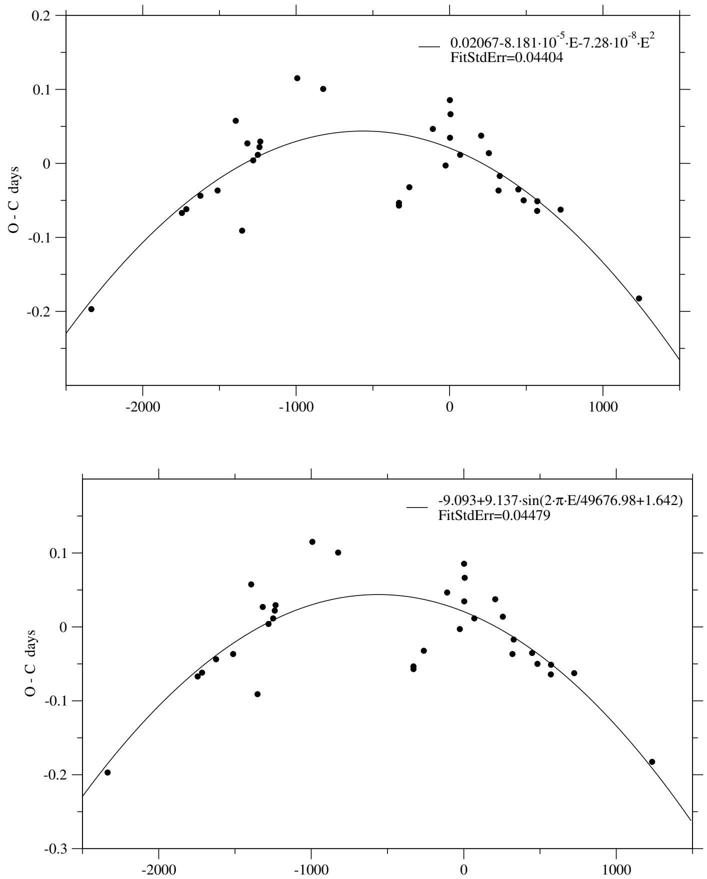

Figure 7. $O - C$ curve of RY Gem (HJD= $2439732.6123 + 9.300681\ E$).

with dark spots[1]. At least durations of the flares detected in extreme UV and X-ray regions in several contact binaries (see McGale et al. 1996, Rucinski 1998) do not contradict the theoretical estimates of the characteristic size of convective cells. Thus, according to Choi & Dotani (1998), the linear size of the flaring region in VW Cep is $\sim 5.5 \cdot 10^{10}$ cm. This estimate is free from any models of the flare since it is based on the observed time of eclipse egress in the X ray light curve dip present near phase 0.5.

After these general remarks we shall look more closely at the data for two close-by bright contact binaries – VW Cephei and 44i Boo. In our detailed investigation of the active contact binary VW Cephei (Pustylnik & Kreiner 1997, Pustylnik & Niarchos 2000), we combined long time series in UBV or $UBVRI$ obtained by Albo, Sorgsepp & Pustylnik between 1962–1968 (see Pustylnik & Sorgsepp 1975), Linnell (1982) and Niarchos et al. (1984) with the data on

[1] J.M. Saxton "Recent observations of 44 Bootis", `http://www.britastro.org/vss/boo44.html`

flares observed in the extreme UV and X-ray region to find evidence for the hot spot region which causes small but significant displacements of maxima from predicted epochs. This idea proved to be productive and enabled us to interpret the observed pattern of $B-V$ changes from minimum to maximum (the binary looks bluer in both maxima compared to its color in the minima). Since the optical center of the putative hot spot appears to be displaced from the line of centres for VW Cephei, the light curve displays asymmetry: the ascending branch is systematically more steep than the descending branch. As $P_{\rm orb} = 6^{\rm h}\,41^{\rm m}$ and we deal with transient phenomena, we have used in our analysis only individual light curves obtained during one observing night. There is a serious danger that averaging over several nights smears out the transient effect and thus it escapes detection. Whatever is the nature of the mechanism responsible for the displacement in phase of maximum by $\Delta\phi$, an additional energy input is needed $L_{\rm add} \geq C\,dl/d\phi\,d\phi$ where the value of $dl/d\,\phi$ can be estimated with the theoretical light curve whereas the constant C must be of order $C \sim 1-10$. With the known orbital elements, physical parameters of the components and the distance to VW Cephei ($d = 23.2$ pc) we found $L_{\rm add} = 2\cdot 10^{29}{\rm erg\,s^{-1}}$ and $L_{\rm add} = 2\cdot 10^{30}{\rm erg\,s^{-1}}$ for $C = 1$ and $C = 10$, respectively. A similar estimate was found as average difference between the heights of the adjacent maxima. Next assuming that mutual eclipses and tidal distortions fully determine the shape of the light curve of VW Cephei for a standard limb-darkening law, we estimated the relative size and the temperature of the putative hot spot. We have achieved a good quantitative agreement with the observed pattern of color changes $\Delta(B-V)$ and $\Delta\,(V-I)$ for the temperature of the hot spot $T_{\rm sp} = 7000$ K and its relative size $R_{\rm sp} \sim 0.02$ (in terms of the total area of the primary component). It is worth mentioning that both $R_{\rm sp}$ and $T_{\rm sp} = 7000$ K were found to be practically in agreement in all five $UBVRI$ bands. Finally, using the data on flares in extreme UV (Rucinski 1998), assuming that both the volume and emission measure during the flare roughly remain constant and taking at the top of the flare $T_0 = 1.5\cdot 10^5$ K (as a characteristic temperature for the transition region) and at minimum $T_{\rm sp} = 7000$ K (the hot spot is treated as the "photospheric burn" at the bottom of the flare) we have found for the total duration of the flare in the extreme UV $\Delta\,t_{\rm fl} = 860$ sec, the electronic density in the flaring region $N_{\rm e} = 1.75\cdot 10^{11}$ cm^{-3}. With these figures in hand one can calculate the wavelength integrated luminosity during the flare for optically thin plasma. In this way we have found for VW Cephei the energy released during the flare and showed finally that $L_{\rm fl}/L_{\rm bol} \sim 0.02-0.03$. Thus, intrinsic colour changes of order $0^{\rm m}.01 - 0^{\rm m}.02$ from one observing night to the other can be readily reproduced.

We now turn to 44i Boo. In Table 3 we summarize some comparative data on physical parameters and the surface activity in UV and X ray region for VW Cephei and 44i Boo. These data leave little doubt in the close resemblance between characteristics of the plasma region in both contact binaries. In addition, element abundance of O, Mg and Fe found from the flare spectrum in 44i Boo are almost identical with those for VW Cep, while Ne and Si are higher by a factor of 1.5–2 than in the case of VW Cep (for more details see Choi & Dotani 1998). It is symptomatic in the context of the discussed aspects of the fine structure seen in the $O-C$ diagram that Chandra data explicitly indicate the region of enhanced activity in X rays dominant on the hemisphere of the primary component of 44i Boo facing the companion star (for more details see Brickhouse & Dupree 1998). In Saxton's detailed $O-C$ analysis of 44i Boo (which embraces almost 80 years since 1920) both the changes of $P_{\rm orb}$ due to the presence of the third component and the secular change of the orbital period have been accounted for. The $O-C$ residuals (see the plot reproduced from the paper of Hollis 1995) clearly indicates the enhanced scatter after 1960. It is very pronounced around 1960, between 1965 and 1975, also around 1980, a fact that in all probability must be attributed to the surface activity in 44i Boo especially pronounced after 1960. It would be interesting to make a dedicated search in archived broad-band photometric data for 44i Boo in an attempt to find the traces of asymmetry of the light curve suggestive of the enhanced activity during the periods when small amplitude $O-C$ variations are in evidence.

Table 3. Comparison of activity parameters in X-ray and UV between 44i Boo and VW Cep. Compiled on the basis of ROSAT data in McGale et al. (1996), IUE data in UV for the CIV 1550 Å chromospheric activity indicator from Rucinski & Vilhu (1983) and extreme UV from Rucinski (1998).

Diagnostics	44i Boo	VW Cep	Comments
Intensity of $CIV\lambda1550$	117	75	$L_l/L_{\rm bol}\cdot 10^7$
$L_{\rm x}$	4.4	7.9	In units of $10^{29}{\rm erg\,s^{-1}}$ (0.15–0.24 Kev)
$L_{\rm x}/L_{\rm bol}$	2.12	4.0	
EM	0.78	1.8	Emission measure in units of $10^{52}{\rm erg\,s^{-1}}$
$Lu_{\rm fl}/Lu_{\rm qu}$	2.7	2.7	Ratio flare amplitude in extreme U to quiescent luminosity

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Izold Pustylnik questioning the speaker