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Research Note

Photometric study of the contact binary star V861 Herculis[⋆]

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Abstract. First Cousins $V(RI)_C$ light curves of the W UMa-type eclipsing variable star V861 Herculis are presented. The system was observed in 2000 and 2003. The light curves obtained at different epochs showed significant deviation from each other. The O'Connell effect was about $\Delta V = 0.05$ mag in 2000 but it vanished in 2003 (except the night of February 22/23, 2003 when we observed a small O'Connell effect ($\Delta V = 0.02$)). Further peculiarities of the light curves are also discussed. The light curves were solved with the Wilson-Devinney code and the spot parameters were determined. The system seems to be a W-type contact binary system with at least one active component. This is strongly supported by the fact that the system is brighter by 0.45 mag through an Hα filter than the MS stars with the same colour index in the open cluster NGC 7790. This deviation can be explained by chromospheric activity of one of the components.

Key words. techniques: photometric – stars: individual: V861 Her

1. Introduction

Light curve variations are common features of contact binary stars. These light curve variations occur on time scales of the order of months to years (Maceroni & van't Veer 1996). Moreover, Pustylnik & Niarchos (2000) found variations on time scales comparable to the orbital period in the case of the contact binary star VW Cep. These variations are often explained by spot activity. Because of the very small number of well-studied cases, further observational studies are needed on more systems and it would be necessary to make *follow-up observations* to detect changes of spot activity photometrically.

The light variation of V861 Her was discovered by Antipin (1996) who classified it as a W UMa-type eclipsing variable star. The colour index of the V861 Her system is very similar to the solar value: $(B-V)_\odot = 0.64$ for the Sun and $B-V = 0.63$ for V861 Her (Antipin 1996) (the interstellar reddening in the direction of V861 Herculis is quite small, $E(B-V) = 0.02$ (Schlegel et al. 1998) and therefore we neglect it throughout the paper). Antipin (1996) gave an ephemeris and $V_{\max} = 13.09$. There is no light curve solution nor spectroscopic study of this system available. Several times of minima were reported in Csizmadia et al. (2002) and in Borkovits et al. (2003).

In this paper the light curves in 2000 and 2003 of the contact binary star V861 Herculis were studied. Light curves obtained at different years and nights were compared to each other. The geometrical and physical parameters of the system were determined by the Wilson-Devinney code. The residuals of the fitting are explained by spots.

2. Observations

2.1. Instruments and reduction procedure

V861 Herculis was observed at the Konkoly Observatory in 2000 and in 2003 to obtain a precise multicolour light curve. The observations were carried out with the 1 m RCC telescope of the Konkoly Observatory located at the Piszkéstető Mountain Station at 964 m above the sea level. The log of the observations can be found in Table 1. Cousins $V(RI)_C$ filters were used. Two different CCD cameras were applied. During the observations in 2000 the detector was an electronically cooled 1024 × 1024 pixels Photometrics CCD camera ($T_{\rm CCD} = -41$ °C, pixel size is 19 × 19 micron). Usually 30, 15 and 10 s exposure times were used in $V(RI)_C$, respectively, and a 2 × 2 binning on the chip was applied to reduce the readout time and to reach a nearly optimal *FWHM* (generally it was 4.5 pixels). During observations in 2003 a 770 × 1152 pixels Wright In. CCD camera, cooled by Peltiers ($T_{\rm CCD} = -70$ °C, pixel size is 22.5 × 22.5 micron), were used with the same filters and telescope. Typical exposure times were 30 s in each filter with this camera and no binning was applied. All frames

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[⋆] Table 3 is only available in electronic form at the CDS via anonymous ftp to `cdsarc.u-strasbg.fr (130.79.128.5)` or via `http://cdsweb.u-strasbg.fr/cgi-bin/qcat?/A+A/417/745`

Table 1. Log of observations and number of individual data points on each night.

Date	JD	V	R	I
2000 May 24/25	2 451 689	69	70	69
2000 May 25/26	2 451 690	107	107	110
2000 May 30/31	2 451 695	119	120	120
2000 July 03/04	2 451 729	30	30	30
2000 July 04/05	2 451 730	10	10	10
2003 Feb. 22/23	2 451 693	28	28	28
2003 Feb. 23/24	2 451 694	64	64	62
2003 Feb. 25/26	2 451 696	42	42	42
2003 Feb. 26/27	2 451 697	45	45	45
Total	9 nights	514	516	516

were bias-subtracted and dark corrected, although only a small dark current was measured. Flat-field correction was also done using dome flats. To determine the raw magnitudes of stars in the frames, aperture photometry was performed using the IRAF/DAOPHOT package (Stetson 1990). On the frame we selected a comparison star (GSC 3079-194) and a check star (GSC 3079-192) and they showed a sufficient stability in each colour (standard deviation of their magnitude differences is 0.005 mag). Then differential photometry was done defining the variable's brightness as $\Delta m = m_{\rm var} - m_{\rm comp}$.

The two primary and two secondary minima calculated from these observations have been published elsewhere (Csizmadia et al. 2002; Borkovits et al. 2003). 514 points in V, 516 in R and 516 in I were collected in total.

2.2. Data homogenization

Instrumental magnitudes were transformed into the standard Cousins system via Eqs. (1)–(6). In the case of Photometrics camera we used the following set of equations:

$$\Delta V = 1.003 \Delta v \tag{1}$$

$$\Delta(V-R) = 0.900 \Delta(v-r) \tag{2}$$

$$\Delta(V-I) = 1.072 \Delta(v-i). \tag{3}$$

For the Wright camera other equations were applied:

$$\Delta V = 1.036 \Delta v \tag{4}$$

$$\Delta(V-R) = 0.913 \Delta(v-r) \tag{5}$$

$$\Delta(V-I) = 1.111 \Delta(v-i). \tag{6}$$

In these transformations capitals mean magnitudes in the standard system and lowercase means the instrumental magnitudes. The transformation coefficients were determined using the standard stars listed in Joner & Taylor (1990) and via the method described in Henden & Kaitchuck (1982). No effect of differential extinction was found. Evidently, this is due to the fact that the field of view of the instrument is quite small (only $5' \times 5'$ for the Photometrics and $4' \times 7'$ for the Wright camera) and therefore both comparison and check star are very close to the variable.

Table 2. Colours of V861 Herculis at the main phases.

Phase	$V-R$	$V-I$
0.0	0.36	0.77
0.25	0.34	0.75
0.5	0.34	0.76
0.75	0.34	0.74

Since the observations were carried out with different detectors, data have to be homogenized. The simplest way is to transform all of the data into the standard system, however, the transformation generally causes an accuracy not better than several hundredths of a magnitude.

We checked the results of the standard transformation the following way: twenty CCD frames of V861 Her were selected, ten of them were obtained by the Photometrics CCD camera and the other ten frames were obtained by the Wright CCD camera. Instrumental magnitude differences of nine stars on these frames were determined ($\Delta m_{ij} = \frac{1}{10}\Sigma(m_i - m_j)_k$, where k was the number of the frame, i, j were the numbers of the two stars). In this way we had 36 instrumental differential magnitudes obtained by one of the two CCD cameras and this was repeated in the case of the other camera. Then the instrumental magnitude differences were transformed into the standard photometric system applying Eqs. (1)–(6). The standardized differential magnitude of a stellar pair should be the same measured by the two CCD cameras. The standard deviations of the magnitude differences measured by certain cameras were smaller than 0.008 mag. As the agreement was excellent we did not make any further correction of the data.

The colour indices of the variable are listed in Table 2 at certain phases. All individual data points (pairs of heliocentric Julian Dates and standard magnitudes) are published in Table 3.

2.3. Hα measurements

Hα emission is a good indicator of chromospheric activity, therefore the brightness of V861 Her in Hα was checked on August 11/12, 2003 at phase $\varphi = 0.33$. The 60/90/180 cm Schmidt-telescope of the Konkoly Observatory was used to compare the system's magnitude through an Hα filter (centered at 656.8 nm with a band-width of 8 nm) to ones of the stars in the galactic cluster NGC 7790. Both the system and the open cluster were observed on the same night. No standard transformation was applied to the Hα data, but we determined the atmospheric extinction coefficient. Then all the Hα data were corrected for atmospheric extinction via the equation $m_0({\rm H}\alpha) = m({\rm H}\alpha) - kX$. ($k = 0.070 \pm 0.007$ was determined.) Ten stars were selected from NGC 7790. The values of the $V-I$ were in the range of 0.59−1.14. These ten stars showed a colour index of $\langle R-{\rm H}\alpha \rangle = -0.31 \pm 0.05$ and they did not show dependence on $V-I$. We measured $R-{\rm H}\alpha = -0.65$ for V861 Herculis which means that it is significantly brighter in Hα than the ten selected stars in NGC 7790. The ten comparison stars have

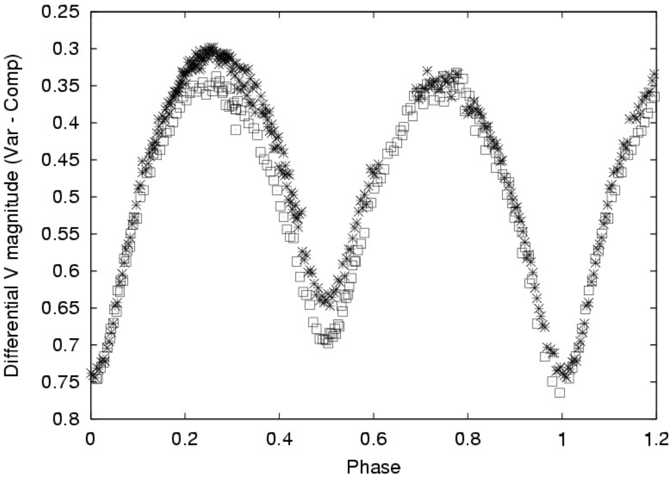

Fig. 1. V light curves of V861 Herculis, phased by the new ephemeris given by Eq. (8). Asterisks mean the data in 2000 while squares are used to represent the data in 2003.

Table 4. Times of minima of V861 Herculis. Sources: 1 Csizmadia et al. (2002), 2 Borkovits et al. (2003). $E_{1,2}$ represent the cycle number of the different ephemerides (see Eqs. (7) and (8)).

E_1	E_2	HJD	Error	Type	(O−C)$_1$	(O−C)$_2$	Source
23231	0	51 690.5276	0.0002	I	+0.0517	0.0000	1
23245.5	14.5	51 695.5268	0.0006	II	+0.0540	-0.0007	1
26141.5	2909	52 693.6196	0.0004	I	+0.0919	-0.0010	2
26150	2917.5	52 696.5519	0.0004	II	+0.0949	+0.0003	2

$\langle R \rangle = 12.6$ while V861 Her has $\langle R \rangle = 12.7$. Then the differences in $\langle R - \mathrm{H}\alpha \rangle_{\mathrm{NGC\ 7790}} - (R - \mathrm{H}\alpha)_{\mathrm{var}} = +0.34$ yields $\mathrm{H}\alpha_{\mathrm{var}} = \langle \mathrm{H}\alpha \rangle_{\mathrm{NGC\ 7790}} - 0.45$, so V861 Herculis showed an Hα excess of ~50% compared to the normal stars in NGC 7790.

3. Period determination

O−C values were calculated applying Antipin's (1996) ephemeris:

$$\mathrm{Min}\ I = 2\,443\,684.325 + 0.3446322 \times E \qquad (7)$$

and they are referred as (O−C)$_1$ values in Table 4. These O−C residuals show an increase with time suggesting a longer period.

We searched for a new period with the Phase Dispersion Method (Stellingwerf 1978). $P = 0.344824$ was found to be a good value to construct an appropriate phase-diagram (see Fig. 1). The new ephemeris is:

$$\mathrm{Min}\ I = 2\,451\,690.5276 + 0.344824 \times E \qquad (8)$$

where the epoch is our first minimum observation and the period is from our PDM-analysis. We computed the new O−C values listed as (O−C)$_2$ in Table 4. The O−C values scatter around zero. We used this ephemeris hereafter.

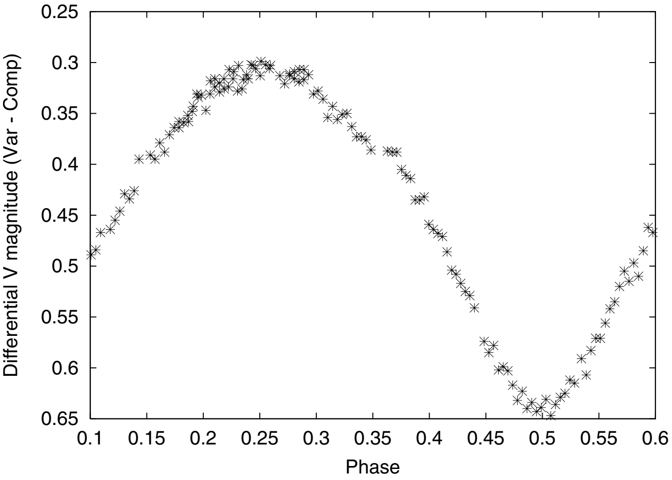

Fig. 2. A well seen standstill on the light curve in 2000 around $\varphi = 0.37$. See Sect. 4.1 for details.

4. Light-curve solution

4.1. General remarks

The characteristics of the light curve can be summarized as follows:

i) The O'Connell effect is present in year 2000. The first maximum is higher by about 0.05 mag (in V) than the second maximum (Fig. 1.). The two maxima are equally bright and there is no obvious O'Connell effect on the nights of February 23/24, 25/26 and 26/27, 2003. However, comparing the observations on February 22/23 2003 to the data on the above three nights, we found a small O'Connell effect ($\Delta V = 0.02$ mag, see Fig. 4).

ii) The heights of the maxima were different in 2000 and 2003. This is a consequence of the disappearance of the O'Connell effect in 2003.

iii) There is a standstill on the light curve in 2000 around the phase 0.37. This standstill is present in the three colours and it is covered by at least 3 points in each colour. Therefore it is a real feature and not an observational error (see Fig. 2). Note that a similar feature can be seen e.g. on the light curve of AD Cancri (Yang & Liu 2002).

iv) Light minima are of various depths at different epochs. The depths of the minima were closer to each other in 2003 than in 2000. Note that the difference between the primary minima is much smaller than in the case of secondary ones.

v) The descending branch of the primary minimum was deformed by a dark spot on February 22/23, 2003. This part of the light curve was different on February 22/23 and 23/24, 2003 (see Fig. 4).

An observational origin of the differences of light curves obtained in 2000 and in 2003 can be excluded. The data homogenization procedure showed that the 3σ limit is not more than 0.02 mag in the transformed data points and the differential magnitudes of the comparison and check stars showed the stability of the observing equipment. Also, the changes in the light curve shapes had higher rate than the observational error.

4.2. *Modeling the light curve*

4.2.1. Unspotted solution

We selected the data in 2003 that is free from the O'Connell effect. The modeling of this light curve is easier and reliable. These data are very close to each other in time (maximum difference between their epochs is ~5 days) and therefore one can assume that there were no large variations in the distribution of the surface brightnesses of the components.

The 1998 version of the Wilson-Devinney code (Wilson 1998) was used for light curve solution. The background geometry and physics are described in Wilson & Devinney (1971) and Wilson (1979). For different kinds of binary stars different modes of the code can be used; mode 3 was chosen to analyze the light curve. In this mode the components are in geometrical but not in thermal contact, i.e. the dimensionless surface potentials Ω (see Kopal 1959; Wilson 1979) of the components are equal to each other but there can be some temperature difference between the components.

Unfortunately, the spectroscopically determined mass ratio is not known for the system. Therefore we fixed the mass ratio at different values between 0.05–10.0. The following parameters were adjusted: inclination (i), fractional luminosity of the primary ($L_1/L_{\rm tot}$), dimensionless surface potentials ($\Omega_1 = \Omega_2$), secondary's temperature (T_2) and phase shift ($\Phi_{\rm sh}$).

The fixed parameters were set as follows. $T_1 = 5785$ K was calculated from Antipin's (1996) colour index $(B - V) = 0.63$ and to transform $B - V$ to temperature we used Flower's (1996) tables. Since Antipin (1996) did not give the error of the $B - V$, it is difficult to estimate the error of this temperature approximation. Assuming a probable error of ±0.05 in his $B - V$, the error of temperature is approximately ~200 K. Applying Bessell et al.'s (1998) formulae, the newly observed $(V - I)_{\rm C} = 0.74$ yielded 5574 ± 230 KK. An average value of 5680 K was then assumed for the primary's surface temperature with an error about ±200 K. Note that Bessell's (1990) table gave $(B-V)_0 = 0.654$, $(V-R)_0 = 0.388$ and $(V-I)_0 = 0.746$ for a G5V star. These are very close to the observed values and a G5V type star has a surface temperature of 5780 K (Popper 1980). However, the secondary star can slightly modify the observed colours if it has a different temperature. Such a slight difference can be expected from the different depths of the minima, which we found to be less than 330 K. This modified the colour index only a few hundredths of a magnitude which is within the error of our colour index measurements. So, 5680 K can be assumed for T_1. Linear limb-darkening coefficients were taken from van Hamme's (1993) tables. Gravity darkening exponents and albedos were fixed at 0.32 and 0.5, respectively. This is the usual choice for convective stars (Lucy 1967; Rucinski 1969), and V861 Her consists of convective stars, because the temperature of the primary suggested a spectral type of mid-G.

For each value of the fixed q the solution was searched for by the differential correction method. The solutions converged in each case. The sum of squares of residuals (SSR), which measures the goodness of the fit, is plotted as a function of the mass ratio (see Fig. 3). The fitting is evidently better if $q > 1.0$ and it has the best value close to $q = 2.5$ However, the minimum of SSR is wide and all solutions between $q = 1.50$–2.50 would be acceptable.

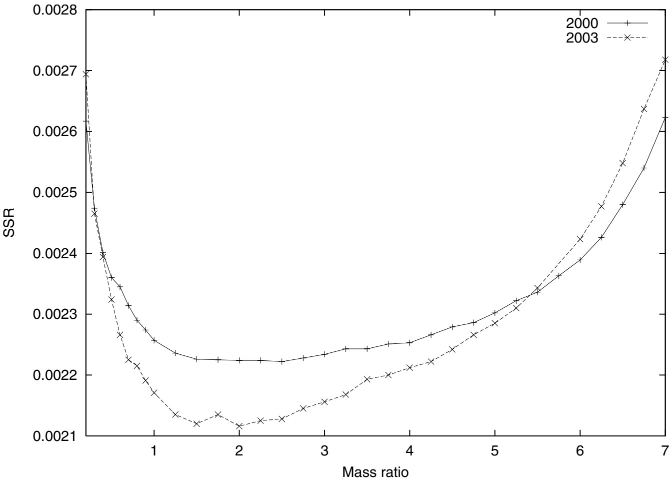

Fig. 3. Sum of squared residuals as a function of the mass ratio.

Modeling of contact binary stars with the O'Connell effect is difficult. Testing how the O'Connell effect affects the solution, we gave a solution for the light curves in 2000. The second and third night data from 2000 were selected, because they overlap, but show a strong O'Connell effect. Our free parameters were as the previous ones (i, $L_1/L_{\rm tot}$, Ω_1, T_2 and $\Phi_{\rm sh}$). The mass ratio was fixed at several different values between 0.1–10.0 and the same procedure was applied as in the previous paragraph. The resulting q-SSRs diagram is very similar to that in the spot-free case and the two curves are topologically fully equivalent. We concluded that, in this particular case, the solutions of spotted and unspotted light curves yielded the same parameter set.

To smooth the light curve solution the free parameter set was then expanded by q and the final solution was searched for by differential correction analysis. During the smoothing the 2003 LC was used again. The final parameter set is listed in Table 5. The fit is satisfactory and it is shown in Fig. 4.

4.2.2. Spot modeling

At least one of the components is chromospherically active as was proved by the Hα measurement. This excess was observed at a different epoch, however, the chromospheric activity allowed us to introduce stellar spots to explain the O'Connell effect in 2000.

Since there is a strong correlation between the spot's radius and temperature (Hrivnak et al. 1995), we fixed the temperature factor ($TF = T_{\rm spot}/T_{\rm photosphere}$) at 0.67. A TF of 0.67 is a typical value for the Sun with nearly the same spectral type as V861 Her's primary component. This solution is not the only possibility: Maceroni & van't Veer (1993) noted that if a synthetic light curve was generated by polar spots, the WD code puts the spot close to the stellar equator which seems to be a feature of the code. Whilst spot parameters were adjusted and other parameters were fixed, we iterated until convergence.

Table 5. Photometric solutions of V861 Herculis, based on 2003 LC. For details see Sect. 4.2.

Parameter	Value	Error
$L_1/(L_1+L_2)$		
V	0.3736	±0.0033
R	0.3610	±0.0031
I	0.3519	±0.0028
$x_1 = x_2$		
bolometric:	0.520	
V	0.644	
R	0.556	
I	0.470	
$q = M_2/M_1$	2.460	±0.017
i	66.17	±0.23
Φ_{sh}	−0.0306	±0.0004
$A_1 = A_2$	0.50	
$g_1 = g_2$	0.32	
$\Omega_1 = \Omega_2$	5.8414	±0.0228
T_2	$5332K$	$\pm 220K$
r_1(pole)	0.2876	±0.0022
r_1(side)	0.3004	±0.0027
r_1(back)	0.3357	±0.0046
r_2(pole)	0.4351	±0.0018
r_2(side)	0.4650	±0.0024
r_2(back)	0.4933	±0.0031
$\Sigma w(l_{\mathrm{obs}} - l_{\mathrm{comp}})^2$	2.22×10^{-3}	

Table 6. Spot parameters for V861 Herculis. Latitude during solving data in 2000 was fixed.

Year	Star	Latitude	Longitude	Radius	Temperature factor
2000	Primary	0°	48 ± 3°	21 ± 1°	0.67
2003	Secondary	48° ± 11°	239 ± 6°	10 ± 1°	0.67

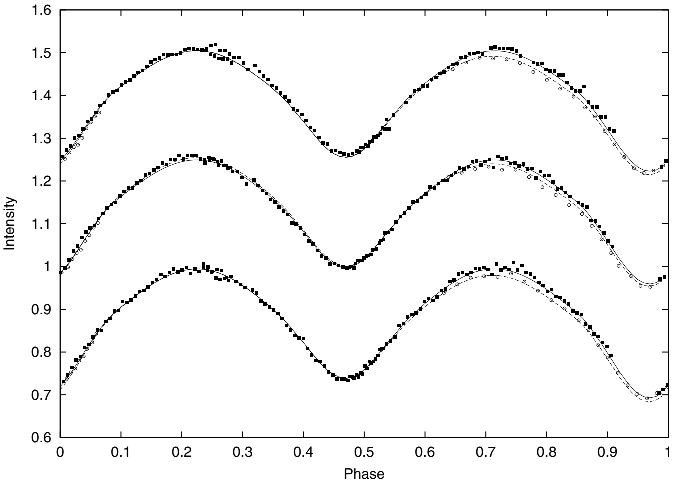

Fig. 4. Fitting of the light curve of V861 Herculis, obtained in 2003. From bottom to top: intensity in V, R and I. For clarity, R and I curves were shifted by 0.25 and 0.50 intensity unit, respectively. Continous lines show the fit with parameters listed in Table 5. Dashed lines represent the spot solution and valid for February 22/23, 2003 data. Individual points of this night are denoted by open squares.

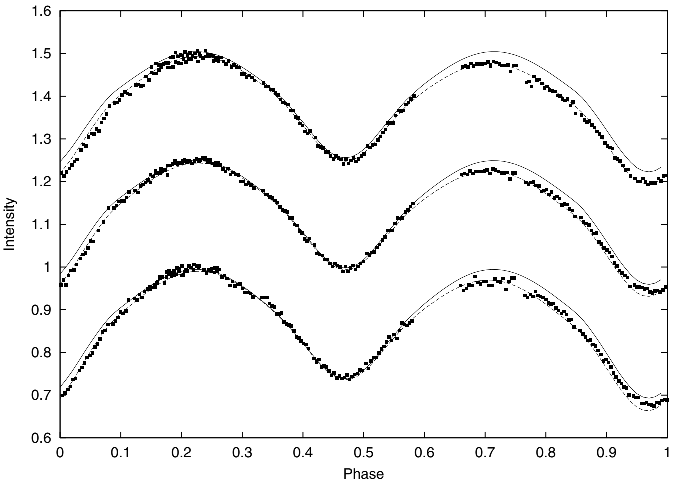

Fig. 5. Fitting of the light curve of V861 Herculis, obtained in 2000. From bottom to top: intensity in V, R and I. For the sake of clarity, R and I curves were shifted by 0.25 and 0.50 intensity units, respectively. Long dashed lines show the fit with parameters listed in Table 5, while the dotted lines show the result of a fit with one circular spot. Note that the spot model eliminated the residuals of the unspotted fit and only the scatter of observations remained (except the residuals of the transient event during the primary minimum which can be seen only in V and R, but is absent in I.

On February 22/23, 2003 was indication for presence of a dark spot. This part of the light curve was modeled and a small dark spot was found. The other data obtained on February 23/24, 25/26 and 26/27 did not yield a physical spot solution (spot diameter became negative). We then analyzed the data in 2000. In Fig. 5 the dashed line represents the unspotted light curve solution based on the data in 2003. The fitting significantly differs from the observations. Assuming only one circular spot, a good fit was obtained (representing by the continuous line) and this spot generated the O'Connell effect. Only one part of the light curve in 2000 (the bottom of the primary minimum) is not well fitted. This segment could not be fitted by introducing more spots. It is very likely a kind of transient event, e.g. a flare. The deviation between the fit and the light curve is higher in V and smaller in R, and it is almost completely missing in I. Flares are high temperature events and hence they are brighter in shorter wavelengths. This wavelength dependence might be observed here. If a flare caused deviation, the quantitative analysis of the deviations is in good agreement with flare hypothesis. However, due to the lack of U and B data it is difficult to identify the flare event undoubtedly.

5. Conclusions

The first multicolour Cousins VRI photometry of the W UMa-type eclipsing variable star V861 Herculis was presented and analyzed by the Wilson-Devinney code. The data were collected over nine nights in 2000 and 2003. A new ephemeris for V861 Her was computed. The grid solution of the spotted data in 2000 and the unspotted data in 2003 yielded the same results.

We found remarkable variations and peculiarities of the light curves in all colours, listed in Sect. 4. The rate of the O'Connell effect was $\Delta V = 0.05$ mag in 2000 but it was missing in 2003 (however, on February 22/23, 2003 it reached about 0.02 mag. This is close to the error limits, but all points observed on this night were systematically below the unspotted nights. We checked the stability of the photometry and we did not find any change in the differential magnitudes of the comparison and check stars.) We concluded that the O'Connell effect has a variable rate from year to year, and likely night to night in V861 Her. Depth variation of the secondary minimum was detected when comparing the light curves in 2000 and 2003.

In the year 2000 a spot with a 21 degree radius modified the light curve and caused the observed O'Connell effect as our modeling showed. The spotted area was approximately 13% of the surface of the primary star in 2000, and 9% of the surface of the secondary star in 2003. The system has at least one chromospherically active star, because V861 Her showed 50% excess in Hα 2003.

The observations of times of minima of V861 Herculis is important to establish a reliable rate of period variation or to exclude period variation. To obtain complete light curves to detect its variation is also important for studies on the changes in spotted area as well.

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