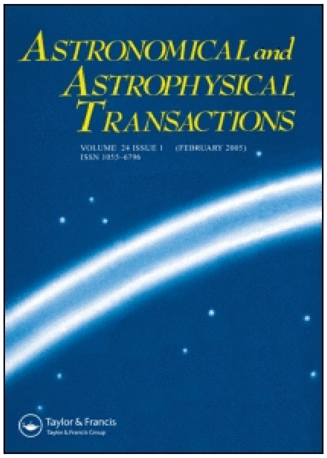

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Photometry of the highly eccentric binary V541 Cyg

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New multicolor photoelectric observations of the highly eccentric ($e = 0.48$) eclipsing star have enabled us to obtain well-founded absolute parameters of the system. The stars seem to be indistinguishable. The new theoretical rate of apsidal rotation follows from the new data.

Keywords: Eclipsing variable; Apsidal motion; Photometric system

1. Introduction

The eclipsing binary V541 Cyg ($P = 15.34^d$, $V = 10.32$, B9.5V + B9.5V) has the highest percentage of relativistic apsidal advance in the overall apsidal motion: $\dot{\omega}_{\rm rel}/\dot{\omega}_{\rm class} = 5.5$, and a unique geometry that forces full eclipses of nearly equal stars [1]. Since only one photoelectric light curve from [1] has been available for the system until now and some discrepancies in the absolute parameters derived by different authors existed [2–4], we have undertaken new photoelectric observations of the star.

2. Observations

The observations were made with 0.6 m Crimean and 0.7 m Moscow reflectors of Moscow University. The UBV photometer (photomultiplier EMI 9789) constructed by I.M. Volkov was used. The measured system dead time was only 30.6 ns. The coefficients of transformation to WBVR system were derived by special observations of the stars from [5]. We prefer W rather then U passband due to its better definition [6], and to that fact that our photometer has ultraviolet sensitivity much closer to W than to U. We found from these measurements that linear transformation from the instrumental system to the standard one is possible: $(M_{\rm stand} - M_{\rm inst}) = K_{\rm passband} \cdot \Delta(B - V)$, where $\Delta(B - V)$ is the difference between instrumental colour index B–V and that of the standard star. The transformation coefficients are: $K_W = -0.023$, $K_{\rm b} = -0.029$, $K_V = -0.028$. One can see that all instrumental passbands are close enough to the standard system, but are moved a little to shorter wavelengths. We used

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Table 1. Magnitudes of V541 Cyg.

Source	V	$U-B$	$B-V$	$E_{(B-V)}$	Sp
[1]	10.32(2)	−0.14(4)	0.08(3)	0.16(5)	B8.6V
[8]	10.350(8)	−0.015(4)	0.035(7)	0.069(9)	B9.5V
[7]	10.336(9)	–	–	0.053(6)	A0V
Present paper	10.322(8)	−0.016(18)	0.046(13)	0.084(20)	B9.5V

the magnitudes of HD186098 and HD186440 from [5] to derive the instrumental magnitudes of V541 Cyg. Then we reduced them to the standard WBV system with the help of the above mentioned transformation coefficients. Then W data were transformed to U taking into account interstellar reddening of the stars under investigation. The details of such transformation can be found in [6]. These data are presented in table 1 along with the results of other authors. Lacy in [7] used a Stromgren photometric system. All these measurements were made between minima. Our data are in close agreement with Lacy [7, 8] photometry but we think that the errors assigned by him to his observations are unjustifiably small. The spectral classes were derived from the standard two-color U–B, B–V diagram. Spectral observations, adduced Lacy in [4], results in A0–B9.5 spectral classes. Photometric observations are not in conflict with the spectra except of the data in the first line in table 1, which should be erroneous. We shall use our B–V colours from the last line of table 1 for the next analysis.

3. Photometric solution

The first column of table 2 presents the results of the photometric solution obtained in [4] from [1] V observations. We used the differential corrections method [9] to obtain the photometric solution in the second column for our V observations. The intrinsic errors for two data sets are comparable. This enables us to combine both sets with equal weights. The result is shown in the third column of table 2. Some portion of the extra light was useful to reduce the average residuals of the solution and forced the darkening coefficients to become closer to their theoretical values. We found $u_1 = 0.42$ and $u_2 = 0.35$ for $L_3 = 0.007$. So we fixed the darkening coefficients according to their theoretical values [10] and found the final solution presented in the last column of table 2. We hope that we managed to reduce the systematic errors of the two data sets, though the average residuals have increased! The final photometric elements are well-founded, see the behaviour of the residuals at the bottom of figure 1. No systematic deviations can be seen. The components of V541 Cyg are just indistinguishable. We have made several CCD frames of the stars under investigation and have found that the

Table 2. Photometric solutions for V observations.

Parameter	[4] from [1] observations	Our observations	Combined data, $L_3 = 0.0$	Combined data, $L_3 = 0.0115$
r_1	0.0440(4)	0.0428(12)	0.0437(2)	0.0436(2)
r_2	0.0419(4)	0.0439(11)	0.0421(2)	0.0426(2)
i, deg	89.88(3)	89.881(2)	89.880(1)	89.921(1)
e	0.479(4)	0.449(7)	0.469(3)	0.467(2)
ω, deg	262.82(11)	262.182(3)	262.610(1)	262.585(1)
L_1	0.520(22)	0.494(24)	0.518(3)	0.5045(29)
u_1	0.32(7)	0.51(9)	0.33(7)	0.41
u_2	0.32(7)	0.40(13)	0.33(9)	0.41
J_2/J_1	1.018(15)	0.974(20)	1.003(12)	1.005(9)
σ_{o-c}	0.01186^m	0.01128^m	0.01506^m	0.01499^m

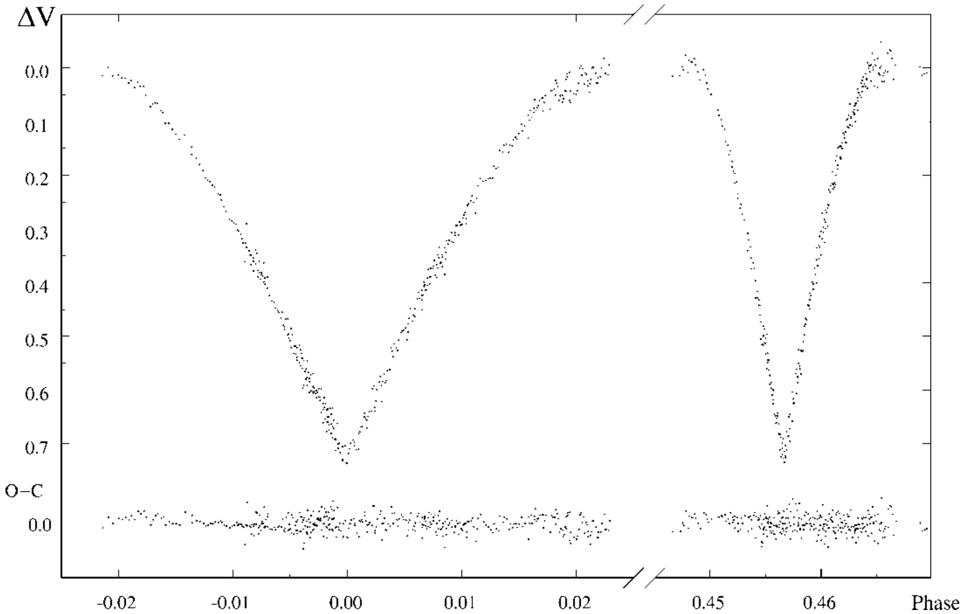

Figure 1. All available photoelectric observations of V541 Cyg in minima. Comparison with the model from the last column of table 2 (O–C) is presented at the bottom of the graph.

third light in the system could follow from the phone star $V = 15.6^{\mathrm{m}}$ at a distance of $13''$ to the north-east from the variable as we used $d = 27.5''$ diaphragm in our photoelectric observations. From our final solution follows $L_3 = 0.0115$, which corresponds to the star of $V = 15.17^{\mathrm{m}}$, close enough to the observed value. We should note here that the light of such a star could be systematically measured together with the light of the sky, especially in the Milky Way area. In this case, some amount of negative third light, $L_3 < 0$, could be formally included into the final solution.

4. Absolute elements and apsidal motion

Using the data from the last column in table 2 and the spectroscopic orbital elements from [4], one can derive the absolute parameters of the double star. We present these data in table 3. The temperatures of the components were derived from our unreddened (B–V) colour between

Table 3. Absolute parameters.

Parameter	Primary	Secondary
Mass, M	$2.295 \pm 0.080 M_{\odot}$	$2.292 \pm 0.075 M_{\odot}$
Radius, R	$1.879 \pm 0.025 R_{\odot}$	$1.837 \pm 0.031 R_{\odot}$
Luminosity, $\lg L/L_{\odot}$	1.493 ± 0.019	1.477 ± 0.020
Surface temperature, K	9960 ± 100	9980 ± 100
Spectral type, Sp	B9.5V	B9.5V
Surface gravity, (cm s^{-2}), $\lg g$	4.250 ± 0.010	4.269 ± 0.010
Absolute bolometric magnitude	$0.96^{\mathrm{m}} \pm 0.05$	$1.00^{\mathrm{m}} \pm 0.05$
Absolute visual magnitude	$1.21^{\mathrm{m}} \pm 0.05$	$1.25^{\mathrm{m}} \pm 0.05$
Semi major axes of the orbit	$43.1 \pm 0.1 R_{\odot}$	
Interstellar absorption, A_v	$0.28^{\mathrm{m}} \pm 0.02$	
Distance, pc	820 ± 35	

minima and the surface fluxes ratio in V from the final light curve solution according to [11] calibration. This ratio shows that the second star should be 20 K hotter than the primary. We took this into account when calculating the absolute magnitudes of the components. The bolometric corrections, the temperature of the Sun and the absolute magnitude of the Sun were assumed from [11]. The errors for the temperatures were assigned according to the uncertainty of the colour index calibrations, not to our errors of the observations which are significantly smaller. In this work we confirm the observed apsidal motion rate from [12]: $\dot{\omega}_{\rm obs} = 0.86(5)$ deg/100 year. But the theoretical value should be changed according to the new absolute parameters derived in the present investigation. We find the new absolute parameters of the system internal structure constants $k_{21} = k_{22} = 0.0046$ [13]. To derive the Newtonian apsidal motion rate due to tidal and rotational distortion of the components, one needs to know the axial rotation of the stars. There are two available derivations, one by [4]: $v_1 \sin i_1 = v_2 \sin i_2 = 24(2)$ km/s and the second by [3]: $v_1 \sin i_1 = v_2 \sin i_2 = 20(5)$ km/s. If the system is synchronized in periastron the rotational velocities should be: $v_1 \approx v_2 \approx 20$ km/s. Note that Lacy in [4] derived $v_{\rm synchronization} = 6$ km/s, which is valid only for circular orbit. So we conclude that the condition of synchronization is fulfilled. Newtonian apsidal motion rate should be $\dot{\omega}_{\rm class} = 0.12(2)$ deg/100 years. The general relativistic rate is $\dot{\omega}_{\rm GR} = 0.74(2)$ deg/100 years, so the total value should be $\dot{\omega}_{\rm theor} = 0.86(3)$ deg/100 years. There is no discrepancy between theoretical and observed rates of apsidal motion.

Another interesting feature of this star is that due to its orbit inclination very close to 90° and the equal sizes of the components $r_2/r_1 \approx 1$, surface brightnesses $J_2/J_1 \approx 1$, the darkening coefficients could be derived with appreciable precision. A few numbers for eclipsing variables allow such a possibility. We plan further multicolour observations of the star in order to derive the darkening laws for the system and to find accurate values of the internal structure constants from apsidal motion observations.

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