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MODELING THE ECLIPSING BINARY SYSTEM VW CYGNI

K. A. Antonyuk[1] and E. A. Antokhina[2] UDC: 520.85

Five color UBVRI photometric and polarimetric measurements of the eclipsing binary VW Cyg are reported. It is shown that in the primary minimum the luminosity is attenuated (at short wavelengths) even after passage of the second contact. This fact is interpreted as evidence of gaseous structures in the system. The exchange of matter among the system components is also confirmed by the O-C curve constructed from data covering nearly a hundred years. Polarimetric analysis makes it possible to isolate the intrinsic (P=0.030±0.02) and interstellar components of the polarization. The UBVRI light curves of VW Cyg have been resolved. This was done using an algorithm for synthesizing theoretical light curves in the Roche model. Good agreement was obtained between the theoretical curves and observations in the V, R, and I bands, but the observed minimum depths in the U and B bands exceed the theoretical values. This appears to be caused by gas flows in the system.

Keywords: (stars): eclipsing - stars: individual: VW Cygni

1. Introduction

The eclipsing binary VW Cyg ($\alpha_{2000} = 20^h15^m12^s.3$, $\delta_{2000} = +34^o30'48''$) was discovered by Williams in 1906 [1]. Later it was studied by Nijland [2] in order to determine its photometric elements. Spectroscopic observations were made by Struve [3]. He showed that the bright component is a main sequence star of spectral class A3. Photometric observations of this object were subsequently made. The light curve was analyzed using Russell's method. It has been assumed that the secondary component of this system is a G5 star. However, the results of different authors differ greatly for various reasons [4,5]. The light curve of this variable has primary and secondary maxima owing to mutual eclipsing of the components. In addition, the shape of the light curve is complicated by the existence of gaseous structures in the system.

[1] Crimean Astrophysical Observatory, Ukraine, e-mail: antoniuk@crao.crimea.ua;
[2] P. K. Shternberg State Astronomical Institute, Russia, e-mail: elant@sai.msu.ru.

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2. Observations

Photometric and polarimetric UBVRI observations of VW Cyg have been made on the 1.25 m AZT-11 reflecting telescope at the Crimean Astrophysical Observatory using a Finnish dual beam modulating photometer-polarimeter designed by Piirola [6]. A total of 12 thousand determinations of the brightness and 1500 determinations of the polarization were obtained over a period of 37 nights. The observations were made between 2001 and 2003. The error in the brightness estimates was within $\pm 0^m.02$. The star with coordinates $\alpha_{2000} = 20^h15^m19^s$, $\delta_{2000} = +34^\circ 35' 12''$ was used as a comparison star, for which we obtained *UBVRI* indices of $10^m.72$, $10^m.87$, $10^m.66$, $10^m.40$, and $10^m.25$, respectively, by calibration to Johnson system photometric standards. The instrumental component of the polarization was taken into account through regular measurements of standards with high and low polarizations.

Complete eclipsing occurs at the principal minimum. Figure 1 shows that after the onset of the full eclipse phase a further attenuation of the brightness is observed. This effect is noticeable only in the blue bands. An analysis of the part of the light curve outside the eclipsed portion shows that there is no secondary minimum in the *U* and *B* bands. Its depth in the *V* band is less than $0^m.08$. It has a significant depth in the *R* and *I* bands. Furthermore, while the part of the light curve outside the eclipses is flat in the blue bands, in the *R* and *I* band an ellipsoidal shape of the star can be discerned. This is caused by a significant contribution to the overall brightness of the system from the luminosity of a subgiant which occupies its Roche cavity.

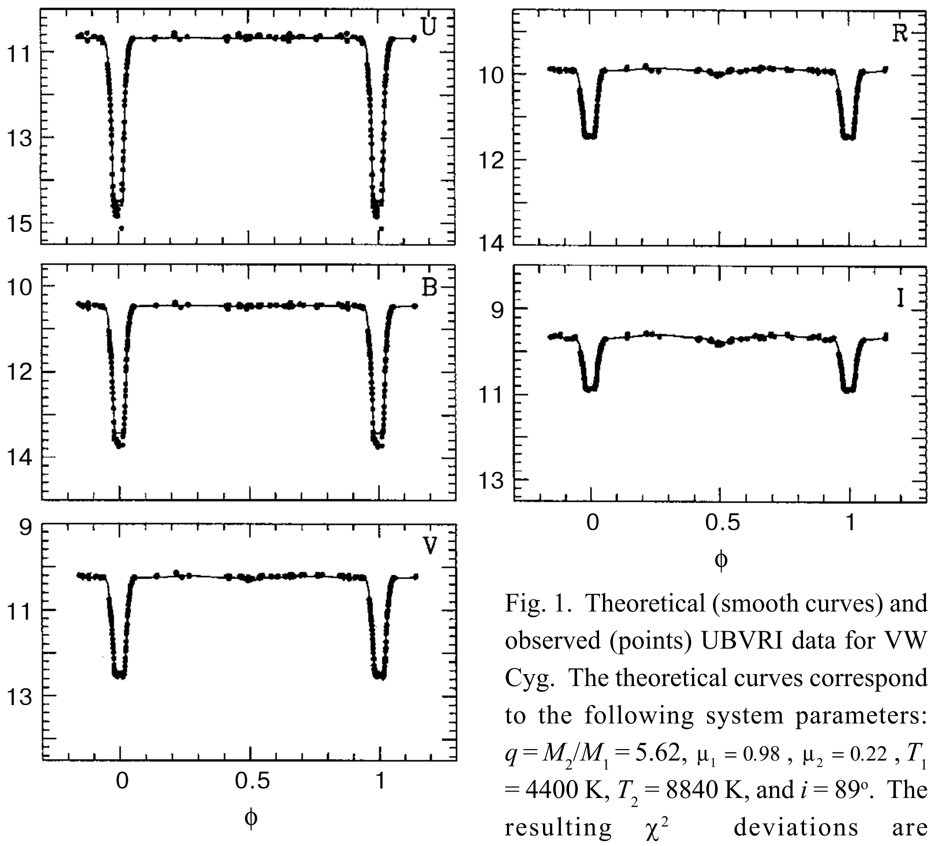

Fig. 1. Theoretical (smooth curves) and observed (points) UBVRI data for VW Cyg. The theoretical curves correspond to the following system parameters: $q = M_2/M_1 = 5.62$, $\mu_1 = 0.98$, $\mu_2 = 0.22$, $T_1 = 4400$ K, $T_2 = 8840$ K, and $i = 89^\circ$. The resulting χ^2 deviations are fx = 0.6268E + 04.

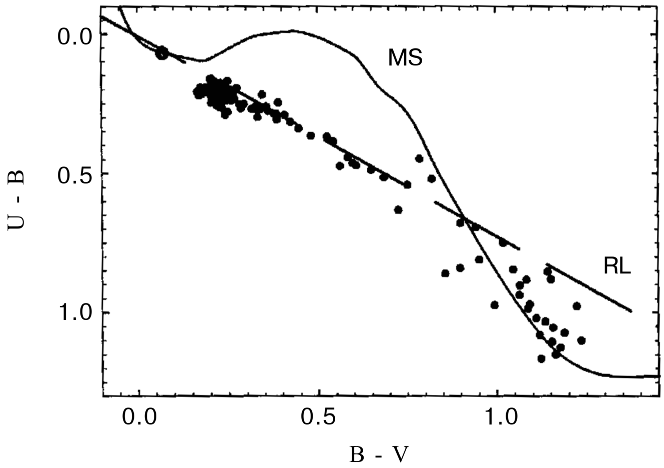

Fig. 2. The relationship of the color indices (*B-V*) and (*U-B*) in various states of the brightness. The smooth curve corresponds to the main sequence and the dashed curve to the reddening line.

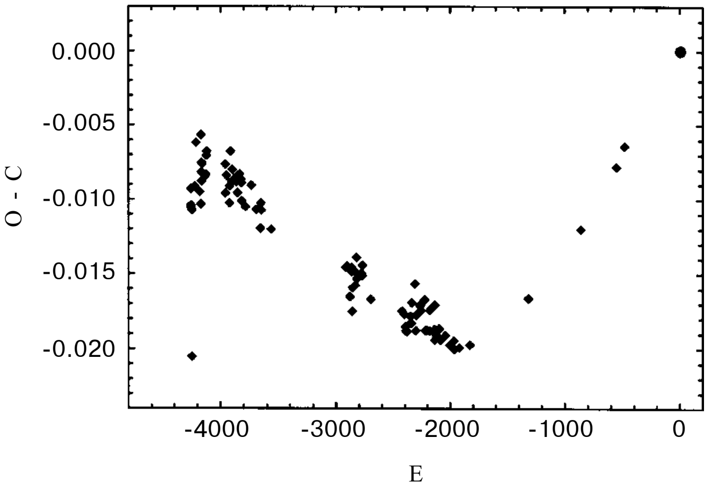

Fig. 3. The O-C diagram.

The relationship of the color indices is shown in Fig. 2. Clearly, the secondary component has a later spectral class than assumed previously (G5) and probably belongs to the K-subgiants.

All the available published data have been used to construct an O-C diagram (Fig. 3). Our observations (the circle) supplement the other data well. The O-C curve has a complicated time variation that may be caused by intense gas flows in the system.

3. Results

The averaged polarimetric observations are plotted in Fig. 4. The difference in the polarizations corresponding to the eclipsed and uneclipsed phases can be seen from this figure. The increased polarization at the time of the minimum

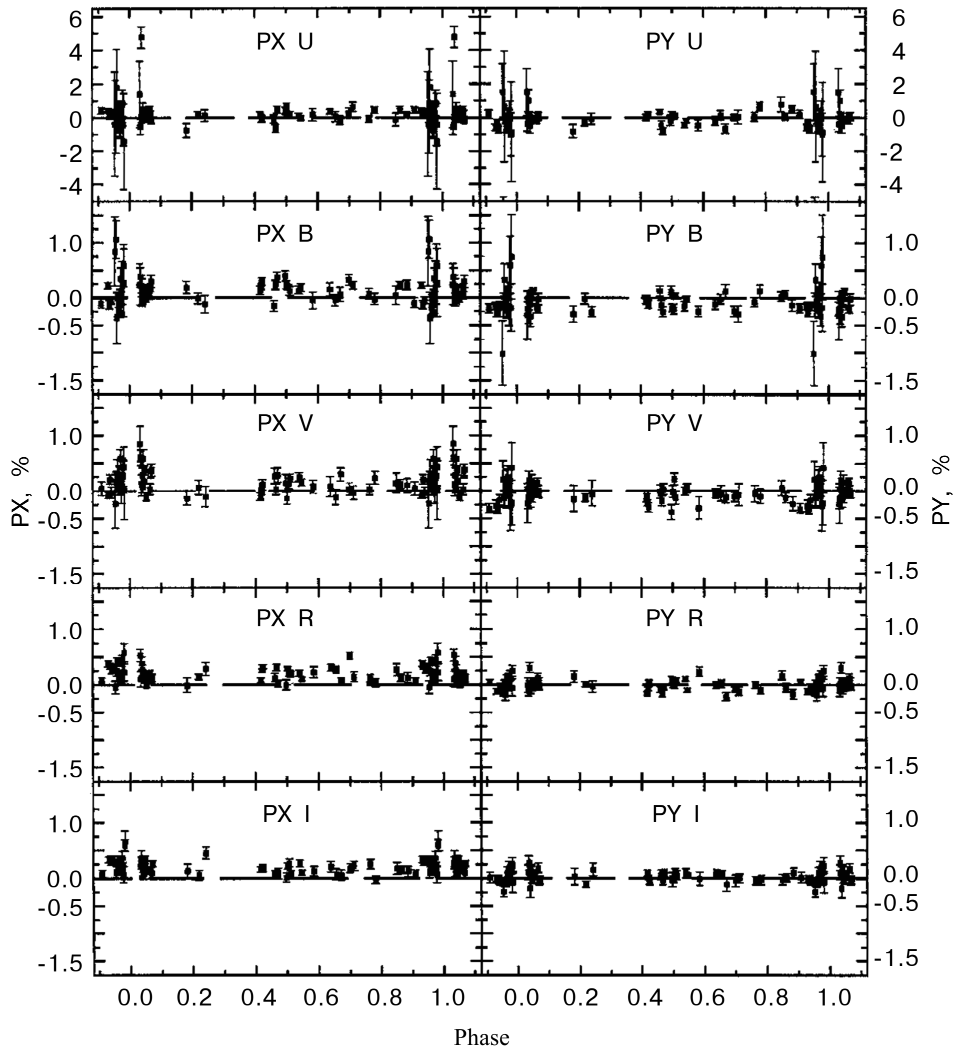

Fig. 4. The parameters *Px* and *Py* of the linear polarization as function of phase in the five colors.

is caused by a contrast effect— an increase in the contribution from polarized light scattered on the optically thin gas. Individual details can be seen in the region of the primary minimum which are caused by the gaseous structure surrounding the brighter component. In order to separate the intrinsic and interstellar polarizations we first postulate that the interstellar polarization obeys the Serkowsky law. We shall also assume that the intrinsic polarization arises in the optically thin hydrogen plasma through electron scattering and is, therefore, independent of wavelength. Here we choose parameters of the interstellar polarization (position of the maximum, degree of polarization, and position angle) such that the vector sum of the intrinsic and interstellar polarizations best fits the observations in all five bands. This yielded the following values for the intrinsic polarization of the system: $P = 0.30 \pm 0.02$ and $PA = 26^{\circ} \pm 2^{\circ}$.

Figure 5 is a diagram of the normalized Stokes parameters q and u for the observations (solid circles), and for the interstellar (P') and intrinsic (P^*) polarizations and their vector sum (P_c). Given the observational errors, the agreement between the calculated and observed values is rather better.

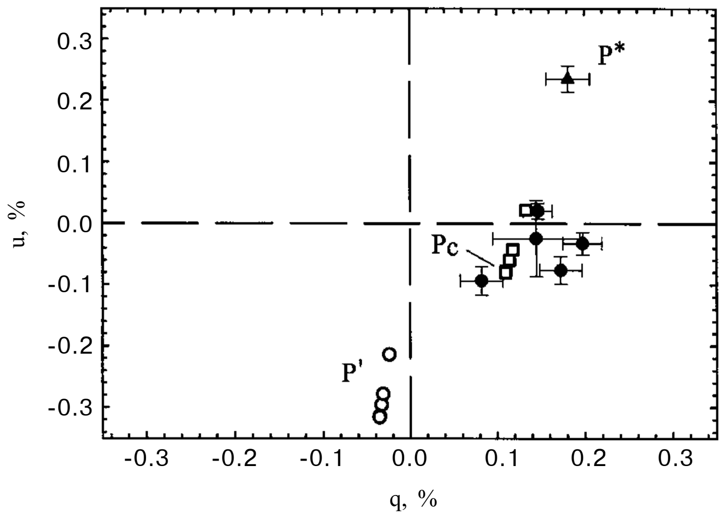

Fig. 5. A plot of the normalized Stokes parameters q and u.

4. Discussion

The *UBVRI* light curves of VW Cyg were analyzed using the algorithm for synthesis of theoretical light curves in Roche's model [7,8]. It is similar to the well known algorithm of Wilson [9], which is widely used these days for studying the light curves of close binary systems. The basic idea behind the methods for synthesizing the light curves for close binaries involves breaking up the complicated tidally distorted surfaces of the stars into thousands of elementary areas and calculating the emerging radiation from each of them. Then the contributions of these areas is summed taking their visibility at the star in difference phases, including the eclipses, into account. A detailed description of the algorithm we have used is given in an article by Antokhina [8]. Here we briefly summarize the elements of the model.

It is assumed that stars with thin atmospheres move around the common center of mass of the system in elliptical orbits. (In the case of VW Cyg the special case of a circular orbit is considered.) The shape of each star is described by an equipotential surface in the Roche model. The effects of gravitational occultation and limb darkening, as well as the heating of the star's atmosphere by incident radiation from the satellite (the "reflection" effect), are taken into account. The input parameters for the synthesis of theoretical light curves of close binary systems according to the Roche model are listed in Table 1.

Some of the parameters can be set using the available information on the system. In accordance with the data of Milano et al. [4] who analyzed the light curves of VW Cyg in B and V filters, we established the temperature of the hot A3 star (T_2 = 8840 K) and the ratio of the masses in the system, $q = M_2/M_1 = 5.62$. The coefficients of gravitational occultation are taken to be the standard values for stars with convective envelopes and with radiative energy transfer—for a cold star $\beta_1 = 0.08$ and for a hot star $\beta_2 = 0.25$. The "reflection" coefficients are A_1=0.5 and A_2=1.0 for cold and hot stars, respectively. The limb darkening coefficients were chosen depending on the filter wavelength [10]. It was assumed that the stars rotate synchronously with their orbital revolution ($F_1 = F_2 = 1$) and that there is no "third light" in the system.

The fit parameters were: the angle i of inclination of the orbit, the degrees of filling μ_1 and μ_2 of the Roche

TABLE 1. Input Parameters for the Program for Synthesizing Theoretical Light Curves for a Binary System with a Circular Orbit

$q = M_2 / M_1$	Mass ratio of the stars
i	Orbital inclination
μ_1, μ_2	Filling coefficients for the Roche cavities by the stars, $\mu = R / R^*$, where R and R^* are the polar radii for partial and complete filling of the critical Roche cavities ($0 < \mu \leq 1$)
F_1, F_2	Ratios of the rotation velocities of the stars to their synchronous rotation velocity
T_1, T_2	Average effective temperatures of the stars
β_1, β_2	Gravitational occultation coefficients (such that the temperature of a surface element of the first star $T = T_1 \cdot (g / g_0)^{\beta_1}$, where g and g_0 are the local and average values of the acceleration of gravity)
A_1, A_2	Bolometric albedo (reprocessing coefficient for incident radiation by the satellite)
$u_1(n), u_2(n)$	Limb darkening coefficient for different wavelengths $\lambda(n)$
$l_3(n)$	"Third light" in relative units of the total monochromatic flux from the system for different wavelengths
$\lambda(n)$	Effective wavelengths for the theoretical light curves

cavities by the stars, and the temperature T_1 of the cold star. The best fit of the theoretical light curves relative to the observed points along the stellar magnitude axis was determined separately for each of the five filters. The theoretical light curves were compared with observations using the χ^2 criterion. A solution was sought simultaneously for the 5 filters. The solution of the inverse problem was found using the standard "simplex" algorithm— the Nelder-Mead method for finding the minimum of a function over a deformed polyhedron [11,12].

Table 2 lists the parameters of the solution for the UBVRI light curves of VW Cyg together with the confidence intervals for the fit parameters per the χ^2 criterion at a 1% significance level. Figure 1 shows both the theoretical light curves for the best fit parameters and the observed light curves.

The system parameters obtained here indicate that the hottest and most massive A3 star has a small radius and lies deep inside its Roche cavity, while the evolved cold, and currently less massive, star is close to filling its Roche cavity. The orbital inclination i is close to 90%. At the principal minimum the hot star is completely eclipsed. An analysis of the light curves shows that it is not possible to describe the observational curves for all five colors simultaneously with a single parameter set. With a good fit of the theoretical to the observed curves for the *V, R*, and *I* filters, the observed

TABLE 2. Parameters of the Solution for the Lght Curves of VW Cyg

$q = M_2 / M_1$	5.62	$L_1/(L_1 + L_2)(U)$	0.040
i	$89^{\circ} \pm 0.3^{\circ}$	$L_2/(L_1 + L_2)(U)$	0.960
μ_1	0.98 ± 0.01	$L_1/(L_1 + L_2)(B)$	0.090
μ_2	0.22 ± 0.01	$L_2/(L_1 + L_2)(B)$	0.910
T_1, K	4400 ± 50	$L_1/(L_1 + L_2)(V)$	0.171
T_2, K	8840	$L_2/(L_1 + L_2)(V)$	0.829
F_1	1	$L_1/(L_1 + L_2)(R)$	0.287
F_2	1	$L_2/(L_1 + L_2)(R)$	0.713
β_1	0.08	$L_1/(L_1 + L_2)(I)$	0.386
β_2	0.25	$L_2/(L_1 + L_2)(I)$	0.614
A_1	0.5	$u_1(U)$	1.00
A_2	1	$u_2(U)$	0.41
r_1(pole)	0.2206	$u_1(B)$	1.00
r_1(point)	0.2883	$u_2(B)$	0.56
r_1(side)	0.2289	$u_1(V)$	0.86
r_1(back)	0.2574	$u_2(V)$	0.47
r_2(pole)	0.1091	$u_1(R)$	0.67
r_2(point)	0.1092	$u_2(R)$	0.38
r_2(side)	0.1091	$u_1(I)$	0.55
r_2(back)	0.1092	$u_2(I)$	0.30

depths of the minima for the *U* and *B* filters exceed the theoretical values. This appears to be related to gaseous flows within the system.

5. Conclusion

An extensive set of observational data has been obtained for the eclipsing binary VW Cyg and this has yielded a number of conclusions. Reliable photoelectric light curves in five colors have been obtained and these show that the amplitude of the variability is greatest in the *U* band and falls off in the direction of longer wavelengths. It has been shown that in the principal minimum the attenuation of the luminosity (at short wavelengths) continues beyond passage of the second contact. This has been interpreted as evidence of the existence of gaseous structures in the system. The exchange of matter between the components of the system is also confirmed by the O-C diagram, which has been constructed from data encompassing almost a hundred years.

An analysis of the polarimetric data shows that the polarizations differ in the phases of the principal minimum and of the regions outside the eclipse. The changes in the polarization in the principal minimum phases are caused by a contrast effect— an increase in the contribution from polarized light scattered on the optically thin gas. It was possible to distinguish the intrinsic (P = 0.30±0.02) and interstellar components of the polarization.

The *UBVRI* light curves of VW Cyg have been modelled. This was done using an algorithm for synthesizing theoretical light curves in the Roche model. Good agreement between the theoretical and observed curves was obtained for the *V, R*, and *I* filters. The observed depths of the minima for the *U* and *B* filters exceeded the depths of the theoretical curves. This appears to be related to the presence of gaseous flows in the system.

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