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Accretion disc in the massive V448 Cygni system

G. Djurašević,[1,2]★ I. Vince,[1] T. S. Khruzina[3] and E. Rovithis-Livaniou[4]

[1]*Astronomical Observatory, Volgina 7, 11160 Belgrade, Serbia*
[2]*Isaac Newton Institute of Chile, Yugoslavia Branch, Volgina 7, 11160 Belgrade, Serbia*
[3]*Sternberg Astronomical Institute, Universitetski pr. 13, Moscow 119992, Russia*
[4]*Section of Astrophysics-Astronomy & Mechanics, Department of Physics, Athens University, GR Zografos 15784, Athens, Greece*

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ABSTRACT

The *UBV* light curves of the early-type eclipsing binary V448 Cygni, obtained at the Abastumani Astrophysical Observatory from 1964 to 1967, are re-analysed here. The analysis was made assuming the presence of an accretion disc in the system, as inferred from the light-curve shape and spectroscopic characteristics of the system. The Roche model of a binary was used, containing a geometrically and optically thick accretion disc around the hotter and more massive star. By solving the inverse problem, the orbital elements and the physical parameters of the system components and of the accretion disc were estimated. This result is important for understanding the star formation and evolution processes in the systems with massive components.

Key words: accretion, accretion discs – binaries: eclipsing – stars: individual: V448 Cygni – stars: mass-loss.

1 INTRODUCTION

Light variability of V448 Cygni (HD 190967, $\alpha_{2000} = 20^{h}6^{m}10^{s}$, $\delta_{2000} = +35^{\circ}23'10''$) was discovered by Wachmann (1939). Ashbrook (1941) classified it as a β-Lyrae-type eclipsing variable. Its orbital period is about 6.5 days. The spectroscopic classification of V448 Cygni is not quite certain. Various spectral types are assigned to its components. In the Henry Draper (HD) catalogue, it is classified as a B3 spectral type. On the other hand, based on the prominence of O II and Si III lines, Petrie (1956) classified the cooler, less massive component (donor) as B1 and the hotter and more massive component (gainer) as O9.5 V. By combining the spectroscopic orbit and light-curve solutions based on the photographic light curve (Ashbrook 1941), Harries, Hilditch & Hill (1997) determined the masses of components as 25.2 and 14.0 solar masses and the radii as 6.7 and 16.3 solar radii for the gainer and the donor, respectively, considering the orbital inclination to be $83\overset{\circ}{.}2$.

Both components of this binary are massive stars, thus making this system particularly important for our understanding of the star formation processes. The duration of the mass transfer process in the massive close binaries is very short and the mass transfer rate is very large giving rise to unusual physical conditions and chemical composition in such systems. Therefore, a good knowledge of the models of binaries like V448 Cygni is essential, and the determination of their parameters is both important and challenging.

Kumsiashvili & Kochiashvili (2003) published their photoelectric observations of V448 Cygni in three colours (close to *UBV* photometric system) obtained in the period from 1964 to 1967. The orbital phase was rather evenly covered with about 540 observations, providing the light curves of high quality. The maxima of the light curves in quadratures significantly differ and the rising branches of principal minima are steeper than the falling ones. The opposite happens with the secondary minima.

Kumsiashvili & Kochiashvili (2003) modelled the system assuming circular orbits and ellipsoidal components, but this model did not satisfactorily fit the observations. Later on Kumsiashvili, Kochiashvili & Djurašević (2005) introduced a Roche model with spots on the gainer and with the donor filling its Roche lobe. The best fit required two bright-spots (BSs) on the opposite sides of the gainer. The longitudes of spots are measured clockwise (as viewed from the direction of the $+Z$-axis) from the $+X$-axis (the line connecting the stars' centres) in the range 0°–360°. The first spot [hotspot (HS)] with high-temperature factor $A_{HS} = T_{HS}/T_{h} \sim 2$ was at the longitude $\lambda_{HS} \sim 270^{\circ}$. This is the place where the gas flow from the donor almost tangentially hits the surface of the gainer. The second BS was on the opposite stellar hemisphere ($\lambda_{BS} \sim 100^{\circ}$). The authors themselves pointed out the problem of the physical nature and position of the active bright region, necessary for a successful modelling of the light curves. This model seems to be unrealistic and inappropriate. Namely, in the case of a direct hit, the flow of matter generated by the donor hits the gainer in a single point only. Therefore, this Roche model, although formally fitting the observations, seems not to be physically sound, and the presence of two BSs on the gainer cannot be considered as a plausible possibility for explanation of the observed light-curve features.

Our preliminary analysis of the light curves obtained by Kumsiashvili & Kochiashvili (2003) has shown that also a

★E-mail: gdjurasevic@aob.bg.ac.yu

simplified Roche model, with a single HS formed on the gainer as a result of the direct infall of the gas flow from the donor, is not suitable for this system. Namely, from the light curve of V448 Cyg it is obvious that a HS on the gainer, producing the observed light-curve asymmetry, would have to be located in the longitude interval 90°–110°. If the HS is formed by the direct infall of the gas from the donor to the gainer, the HS should (as a consequence of the effect of the Coriolis force) be located in the longitude interval 270°–360°. Thus, this simplified Roche model is in disagreement with the observations.

By analysing high-resolution spectra of V448 Cygni from 1981 to 1984, Glazunova, Karetnikov & Kutsenko (1986) proposed that the gas streaming through the Lagrangian point L_1 forms a disc around the gainer. Moreover, high-resolution spectroscopic observations of V448 Cygni, made from 1987 to 1989 by Volkova, Glazunova & Tarasov (1993) at different orbital phases, show that the H_α line has a very complex profile. To explain the line profile feature and its variation with phase, the possibility of the formation of a quasi-stationary disc around the gainer was considered. This assumption is supported by a relatively high-mass-loss rate of the donor obtained from the analysis of the continuum absorption of the gas stream ($3 \times 10^{-6} \mathcal{M}_\odot\, \mathrm{yr}^{-1}$) and from the photometric data ($2 \times 10^{-7} \mathcal{M}_\odot\, \mathrm{yr}^{-1}$).

Although the formation of a quasi-stationary disc around the gainer of V448 Cygni could thus be expected, Volkova et al. (1993) objected that the formation of a stationary disc is impossible since the radius of the gainer does not satisfy the criterion of Lubow & Shu (1975). But, as shown in the paper by Kaitchuk, Honeycutt & Schlegel (1985), there are systems with accretion discs, which do not fulfil this criterion. From fig. 2 of that paper it is evident that in the zone where Lubow & Shu criterion is not satisfied there are permanent disc systems, and also, even more numerous, transient disc systems. Moreover, there are systems without accretion disc in the zone where, according to the Lubow & Shu criterion, the systems should have an accretion disc. Recent two- and three-dimensional hydrodynamical modelling of the mass transfer in massive close binary systems (e.g. Bisikalo et al. 2000, Harmanec et al. 2002; Nazarenko & Glazunova 2003, etc.) reveals less restrictive conditions for the formation of the dense accretion disc, allowing disc characteristics that are significantly different from the Lubow & Shu pioneering results.

Another important argument in favour of the accretion disc presence in the system could be the U-band excess and variation of the $U - B$ colour with phase (see Fig. 1, bottom-left panels). Although the radius of the gainer does not fulfil the Lubow & Shu (1975) criterion, taken together, these spectroscopic and photometric characteristics can be considered as indications of the presence of an accretion disc around the gainer in V448 Cygni.

2 ACCRETION DISC MODEL OF THE SYSTEM

The above-mentioned drawbacks of the previous alternative models and indications of the accretion disc presence encouraged us to introduce a Roche model with an accretion disc around the gainer for interpretation of the *UBV* light curves of the close binary system V448 Cyg. The similarity between analysed *UBV* light curves and the more recent *Hipparcos* light curve supports the hypothesis that a long-lived structure (like the geometry of the mass transfer, approximated by an accretion disc model) is responsible for the observed asymmetries in the light curve, rather than the transient phenomena (like starspots).

We reanalyse here the *UBV* light curves of V448 Cygni obtained by Kumsiashvili & Kochiashvili (2003) using the Roche model with an optically thick accretion disc. The disc, lying in the orbital plane around the more massive component, is formed by the gas stream flowing from the donor – Roche lobe-filling supergiant.

Basic elements of the model with a plane-parallel accretion disc and the corresponding light-curve synthesis procedure are given in Djurašević (1992, 1996). The disc edge is approximated by a cylindrical surface. In the current, modified version of the code (Djurašević, Vince & Atanacković 2008), the disc thickness can change linearly with radial distance. The conical form of the disc surface (that can be concave, convex or plane-parallel as a special transient case) is described by the disc radius (R_d), and by the disc thickness at the edge (d_e) and at its centre (d_c). This is a rough but sufficiently good approximation of the disc shape obtained by the current hydrodynamical modelling of mass transfer in close binary systems (see e.g. Bisikalo et al. 2000; Harmanec et al. 2002; Nazarenko & Glazunova 2003, 2006a,b).

The disc edge's cylindrical surface is characterized by its temperature T_d. The radiation from the conical surface of the disc depends on the radial temperature profile. Among the variety of simple power-law radial temperature distribution profiles of the disc (Djurašević et al. 2008) here we chose, as optimal, the following one:

$$T(r) = T_\mathrm{d} + (T_* - T_\mathrm{d})\left[1 - \left(\frac{r - R_*}{R_\mathrm{d} - R_*}\right)\right]^{a_T}. \tag{1}$$

Equation (1) was obtained by modifying the temperature distribution proposed by Zola (1991). We assumed that the disc is in physical and thermal contact with the central star. Thus, the inner radius and temperature of the disc were set equal to the radius and temperature of the star (R_*, T_*). The temperature of the disc's edge (T_d) and the radial temperature distribution exponent (a_T) were taken to be free parameters. Besides, the radii of the star (R_*) and of the accretion disc (R_d) also appear as parameters.

In order to explain the light-curve asymmetry, we introduced a HS region on the disc edge at the place where the gas stream from the donor falls on the disc. The HS increases the flux around the orbital phase 0.75. Due to the infall of an intensive gas stream, the disc surface structure in the region of the HS can be deformed, producing a local distribution of radiation which deviates from the uniform azimuthal distribution. Such kind of deformation in the HS region was evidenced by Mason et al. (2000) for the system WZ Sge. In the code, this effect is described by the angle θ_rad between the line perpendicular to the local disc edge surface and the direction of the HS's maximum radiation. Depending on the θ_rad, the maximum of the HS flux can be slightly shifted in the orbital phase, changing the light-curve asymmetry around the secondary maximum and in the region of the primary minimum. The preliminary analysis showed that a HS region somewhat improved the fit but could not explain the light-curve asymmetry completely, especially in the light-curve minima and in the range of the first maximum (around the orbital phase 0.25).

By introducing an additional BS region, larger in size and located at nearly opposite side of the disc, the fit becomes much better. The large area and the high temperature of the BS produce a significant flux increase in the brighter quadrature around the phase 0.25, enabling successful fitting of the light-curve minima too. We have to point out that the BS only is not sufficient to fit the light curve in the region of the secondary maximum, so that we need both spots for good light-curve modelling.

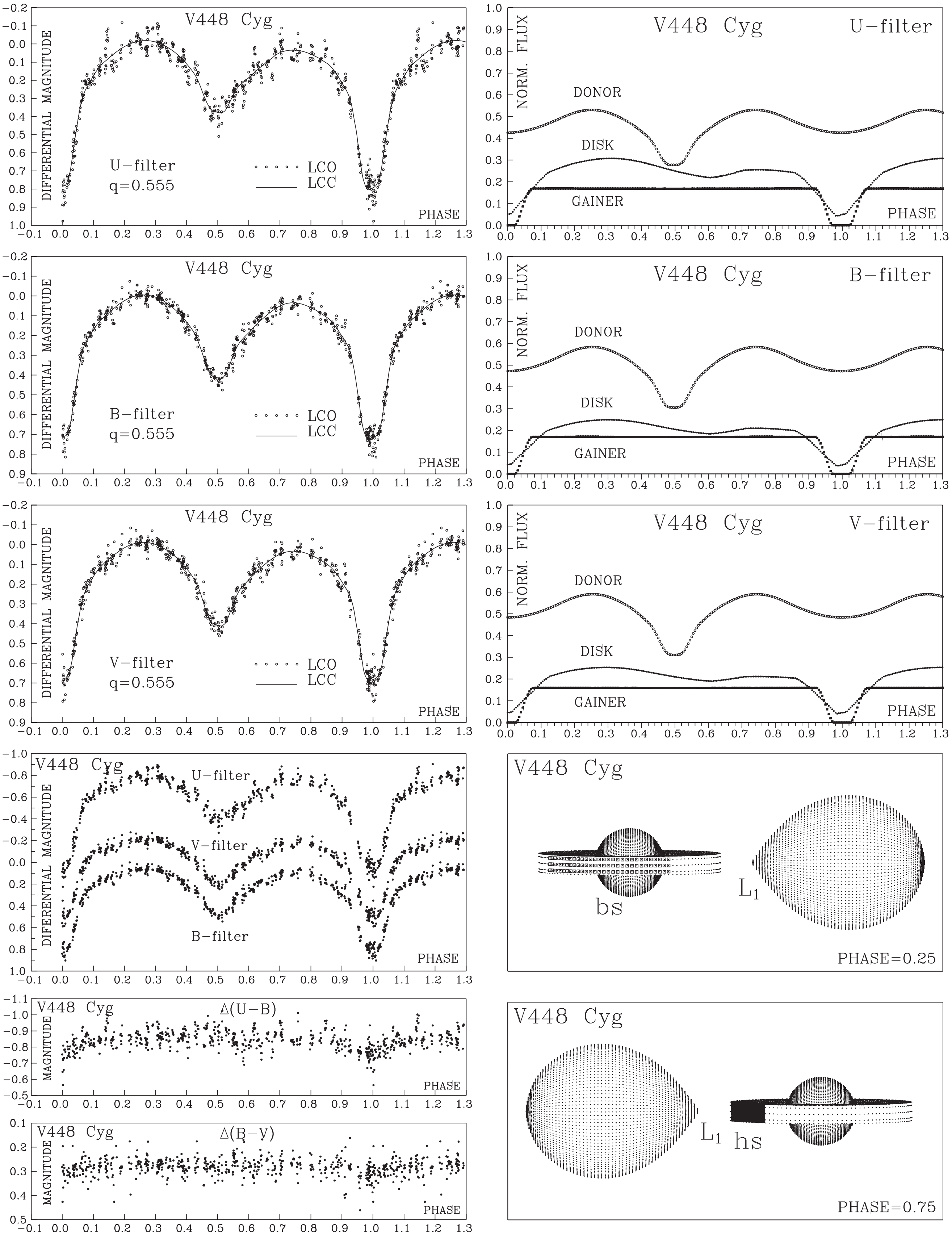

Figure 1. Left-hand panels: *UBV* observed (LCO) and synthetic (LCC) light curves of V448 Cygni. Right-hand panels: *UBV* fluxes of components and of the accretion disc. Bottom-left panels: *UBV* observations and corresponding variations of the $\Delta(U-B)$ and $\Delta(B-V)$ colour indices with orbital phase. Bottom-right panels: the optimal model at orbital phases 0.25 and 0.75.

3 LIGHT-CURVE ANALYSIS AND RESULTS

For the light-curve analysis, we used the published photoelectric observations of V448 Cygni in three colours (close to *UBV* photometric system) by Kumsiashvili & Kochiashvili (2003). The light-curve analysis was performed by applying the inverse-problem method (Djurašević 1992) based on the simplex algorithm. In this way, we estimated the optimal system parameters yielding the best fit of the observations.

In order to ensure the convergence of the iterative procedure of the inverse-problem solution, it is necessary to restrict the number of free parameters of the model. This can be done by fixing some of them in advance on the basis of an independent information or plausible approximation of the V448 Cygni elements. Thus, we assumed the following:

(i) the spectroscopic mass ratio is fixed to $q = \mathcal{M}_c/\mathcal{M}_h = 0.555$, based on the radial velocity study by Harries et al. (1997). The subscripts (h,c) refer to the hotter gainer and the cooler donor, respectively;

(ii) the temperature of the gainer is fixed to $T_h = 30\,490$ K consistently with its spectral type O9.5 V and the revised theoretical $T_{\rm eff}$-spectral-type calibration (Martins, Schaerer & Hillier 2005);

(iii) according to the temperature of the gainer and preliminary estimated temperature of the donor, we set the gravity-darkening coefficients and component's albedos at their theoretical values ($\beta_{h,c} = 0.25$, $A_{h,c} = 1.0$), corresponding to von Zeipel's law for fully radiating shells and complete re-radiation;

(iv) the filling factor for the critical Roche lobe of the donor was set to $F_c = 1.0$, since we assumed that this component completely fills its Roche lobe and loses mass through the Lagrangian point L_1;

(v) the rotation of the components is synchronous with their orbital revolution. Therefore, we adopted $f_{h,c} = \omega_{h,c}/\omega_K = 1.00$, where $f_{h,c}$ is the ratio of the rotation rate ($\omega_{h,c}$) to the Keplerian (ω_K) orbital rate.

In our new code we applied the non-linear limb-darkening approximation given by Claret (2000). For the effective wavelengths of the corresponding *UBV* filters, the limb-darkening coefficients were interpolated from Claret's tables according to the current values of the stellar effective temperature $T_{\rm eff}$ and surface gravity $\log g$ in each iteration. More details concerning the interpolation procedure can be found in Djurašević et al. (2004). The disc limb darkening was applied in the same way, except that for $\log g$ we used the value corresponding to the middle of the disc radius. Another possibility provided in our code is to use the linear approximation, with limb-darkening coefficient $u = 2/3$. Both of these approximations produced a very similar but significant effect in the light-curve synthesis.

The solution of the light-curve analysis, based on this model of V448 Cygni, is given in Table 1. The parameters are given in the first column, whereas the values derived from photometry in the *UBV* filters are given in the second, third and fourth columns, respectively. The last column gives the mean values obtained from all three filters, with their formal errors. These errors were estimated by combining the individual *UBV* solutions and the results of numerous numerical tests obtained by means of the simplex algorithm initialized with different input parameters.

The first three rows of Table 1 present the number of *UBV* observations (n), the final sum of the squares of the residuals between observed (LCO) and synthetic (LCC) light curves $\sum(\mathrm{O-C})^2$ and the rms of the residuals $\sigma_{\rm rms}$, respectively.

Table 1. Results of the analysis of V448 Cygni light curves obtained by solving the inverse problem for the Roche model with an accretion disc around the more massive (hotter) component.

Quantity	*U* filter	*B* filter	*V* filter	Mean
n	543	544	541	
Σ(O-C)^2	1.3820	0.4833	0.5626	
$\sigma_{\rm rms}$	0.0502	0.0298	0.0322	
i (°)	87.9	88.0	87.8	87.9 ± 0.5
F_d	0.97	0.97	0.97	0.97 ± 0.02
T_d(K)	26 320	23 700	24 150	24 700 ± 1600
$d_e(a_{\rm orb})$	0.086	0.085	0.085	0.085 ± 0.009
$d_c(a_{\rm orb})$	0.06	0.06	0.06	0.06 ± 0.02
a_T	1.84	1.81	1.82	1.8 ± 0.2
F_h	0.384	0.385	0.385	0.385 ± 0.008
T_c(K)	20 350	20 410	20 260	20 340 ± 150
$A_{\rm HS} = T_{\rm HS}/T_d$	1.20	1.12	1.14	1.15 ± 0.08
$\theta_{\rm HS}$(°)	18.7	19.3	18.1	18.7 ± 0.9
$\lambda_{\rm HS}$(°)	327.5	327.8	327.3	327.5 ± 2.1
$\theta_{\rm rad}$(°)	−24.8	−22.8	−19.3	−22.3 ± 5.7
$A_{\rm BS} = T_{\rm BS}/T_d$	1.32	1.30	1.32	1.31 ± 0.06
$\theta_{\rm BS}$(°)	45.6	43.7	45.9	45.1 ± 3.0
$\lambda_{\rm BS}$(°)	112.2	109.9	105.8	109.3 ± 4.5
Ω_h	6.96	6.95	6.95	6.95 ± 0.03
Ω_c	2.98	2.98	2.98	2.98 ± 0.02
$\mathcal{M}_h(\mathcal{M}_\odot)$	24.7	24.7	24.7	24.7 ± 0.7
$\mathcal{M}_c(\mathcal{M}_\odot)$	13.7	13.7	13.7	13.7 ± 0.7
$\mathcal{R}_h$(R$_\odot$)	7.7	7.8	7.8	7.8 ± 0.2
$\mathcal{R}_c$(R$_\odot$)	16.3	16.3	16.3	16.3 ± 0.3
$\log g_h$	4.05	4.05	4.05	4.05 ± 0.03
$\log g_c$	3.15	3.15	3.15	3.15 ± 0.03
$M_{\rm bol}^{h}$	−6.88	−6.89	−6.88	−6.88 ± 0.08
$M_{\rm bol}^{c}$	−6.74	−6.75	−6.72	−6.74 ± 0.08
$a_{\rm orb}$(R$_\odot$)	49.5	49.5	49.5	49.5 ± 0.6
$\mathcal{R}_d$(R$_\odot$)	20.6	20.6	20.7	20.6 ± 0.5
d_e(R$_\odot$)	4.22	4.22	4.23	4.2 ± 0.3
d_c(R$_\odot$)	3.10	3.13	3.11	3.1 ± 0.3

Fixed parameters: $q = \mathcal{M}_c/\mathcal{M}_h = 0.555$ – mass ratio of the components; $T_h = 30\,490$ K – temperature of the more massive (hotter) star; $F_c = 1.0$ – filling factor for the critical Roche lobe of the cooler (less massive) star; $f_h = f_c = 1.00$ – non-synchronous rotation coefficients of the components; $\beta_{h,c} = 0.25$ – gravity-darkening coefficients of the components and $A_{h,c} = 1.0$ – albedo coefficients of the components.

Note. n – number of observations; Σ (O-C)^2 – final sum of squares of residuals between observed (LCO) and synthetic (LCC) light curves; $\sigma_{\rm rms}$ – rms of the residuals; i – orbit inclination (in arc degrees); $F_d = R_d/R_{yc}$ – disc dimension factor (ratio of the disc radius to the critical Roche lobe radius along y-axis); T_d – disc edge temperature; d_e, d_c, – disc thicknesses (at the edge and at the centre of the disc, respectively) in the units of the distance between the components; a_T – disc temperature distribution coefficient; $F_h = R_h/R_{zc}$ – filling factor for the critical Roche lobe of the hotter, more massive star (ratio of the stellar polar radius to the critical Roche lobe radius along z-axis); T_c – temperature of the less massive cooler star; $A_{\rm HS,BS} = T_{\rm HS,BS}/T_d$ – hot and BSs' temperature coefficients; $\theta_{\rm HS,BS}$ and $\lambda_{\rm HS,BS}$ – spots' angular dimensions and longitudes (in arc degrees); $\theta_{\rm rad}$ – angle between the line perpendicular to the local disc edge surface and the direction of the HS maximum radiation; $\Omega_{h,c}$ – dimensionless surface potentials of the hotter gainer and cooler donor; $\mathcal{M}_{h,c}(\mathcal{M}_\odot)$, $\mathcal{R}_{h,c}$(R$_\odot$) – stellar masses and mean radii of stars in solar units; $\log g_{h,c}$ – logarithm (base 10) of the system components effective gravity; $M_{\rm bol}^{h,c}$ – absolute stellar bolometric magnitudes; $a_{\rm orb}$(R$_\odot$), $\mathcal{R}_d$(R$_\odot$), d_e(R$_\odot$), d_c(R$_\odot$) – orbital semimajor axis, disc radius and disc thicknesses at its edge and centre, respectively, given in the solar radius units.

By combining our photometric solutions with spectroscopic data (Harries et al. 1997), we estimated the basic elements of the system. These elements are listed in the bottom 12 rows of Table 1.

The gainer (surrounded by the accretion disc) is eclipsed by the donor at the deeper (primary) minimum of the light curves. The analysis shows that the accretion disc is very large. The disc radius ($R_d = 20.6\ R_\odot$) amounts to about 97 per cent of the corresponding Roche lobe radius. The outer disc edge thickness is $d_e = 4.2\ R_\odot$ and the central one is $d_c = 3.1\ R_\odot$. Hence, the disc has slightly concave shape. The disc temperature increases from the edge ($T_d \sim$ 24 700 K) to the centre according to equation (1). The disc temperature profile parameter is estimated to be $a_T \sim 1.8$. Consequently, the disc effective temperature is significantly higher than the edge temperature. The inclination of the orbit was estimated to be $i \sim 88^\circ$, thus the observer can see the radiation originating mainly from the disc's edge whereas the radiation from other (inner) parts of the disc is practically negligible. Note that in the case when the disc is oriented nearly edge-on, the sensitivity of the inverse-problem solutions to the parameter a_T is relatively weak and its error may be larger than the formal, tabulated one. Due to the high inclination, the disc eclipses a significant part of the radiation coming from the gainer.

The light-curve asymmetry could be simulated by the presence of two active bright regions (spots) on the disc edge, located at nearly opposite longitudes. The table gives the characteristics of these active regions. The HS is located at longitude $\lambda_{HS} \sim 327^\circ$, at the place where the gas stream falls on to the disc. The angular dimension of the HS is $\sim 19^\circ$. Its temperature is approximately 15 per cent higher than the disc edge temperature. The direction of its maximum radiation is shifted by $\theta_{rad} \sim 22^\circ$ with respect to the line perpendicular to the local disc edge surface. The larger BS is placed at the longitude $\lambda_{BS} \sim 109^\circ$. The angular dimension of BS is $\sim 45^\circ$, more than two times larger than the HS. Its temperature is about 30 per cent higher than the disc edge temperature, contributing decidedly to the light-curve asymmetry.

Fig. 1 (left-hand panels) presents the optimal fit of the observed light curves (LCO) by the synthetic ones (LCC) following from the inverse-problem solutions for individual *UBV* light curves. The light curves are normalized to the system brightness at the orbital phase 0.25. The right-hand panels in Fig. 1 show the individual *UBV* synthetic fluxes of the components (DONOR, GAINER, disc), normalized to the total synthetic flux of the system at orbital phase 0.25. It is evident that the main flux contribution comes from the donor (approximately 50–60 per cent at the light-curve maxima) and that the contribution of the gainer is slightly less than 20 per cent. This is due to the fact that the central star is partially obscured by the accretion disc. In *B* and *V* filters, the disc contribution to the total flux of the system is about 25 per cent, but the increase of the disc flux is evident in *U* filter. Moreover, the flux contribution of the donor, on the one hand, and that of the gainer with its surrounding accretion disc, on the other hand, are approximately equal.

Fig. 1 (bottom-left panels) shows the *UBV* observations and the corresponding variations $\Delta(U - B)$ and $\Delta(B - V)$ of the colour indices with orbital phase. The $U - B$ colour index shows significant change in the vicinity of the primary minimum. At the same time, the $B - V$ colour index does not change considerably with orbital phase. The *U*-band excess and the variation of the $U - B$ colour with phase could be an important indicator of the disc presence around the gainer. According to our results, the disc flux is significantly higher in *U* band.

Two views of V448 Cygni's optimal model at orbital phases 0.25 and 0.75, chosen so that its basic constituents are visible, are shown in the bottom-right panels of the same figure.

4 DISCUSSION AND CONCLUSION

In this paper, we modelled the *UBV* light curves of the eclipsing binary star V448 Cygni (Kumsiashvili & Kochiashvili 2003) by using our improved code for the systems with accretion disc (Djurašević et al. 2008). The light-curve analysis shows that the model with an optically and geometrically thick accretion disc fits the observations very well. The main advantage of our disc model is in its capability to naturally explain the photometric behaviour of V448 Cygni. To fit the light-curve asymmetry, the disc model requires the two active bright regions, the presence and location of which on the disc can be explained by the gas dynamics in the system (see e.g. Heemskerk 1994; Bisikalo et al. 1998, 2000; Harmanec et al. 2002; Nazarenko & Glazunova 2003, 2006a,b; Bisikalo et al. 2005). The HS in our photometric model is a rough approximation of the hot line, which forms at the edge of the gas stream flowing from the donor. The BS related to the spiral shock due to radiative cooling forms at the outer boundary of the disc at orbital phase around 0.25.

Our solution shows that disc fills the Roche lobe almost completely (97 per cent). In this case, the donor is close to the edge of the disc and tidal forces on the disc are large. It is known from hydrodynamical calculations that a spiral-shaped tidal shock can be produced in a disc in this way (see e.g. Heemskerk 1994). The tidal shock waves generated by the massive donor can produce one or two extended spiral arms in the outer parts of accretion disc. The first arm is in the region of the HS in which we have interaction of the gas stream and the disc. The second spiral arm, we modelled as a larger BS on the disc edge, is at the opposite side of the disc. The BS can also be interpreted as a zone in which, in addition to the effect described above, the disc significantly deviates from the circular shape. Note that Zhao et al. (2008) found evidence for an asymmetric disc in β Lyrae.

The accretion disc model for V448 Cygni provides a good fit of the individual *UBV* light curves, where solutions are in good mutual agreement. However, we have to point out that the contribution of the disc flux to the total flux of the system in the *U* spectral band is significantly larger than in the other two spectral bands. The $U - B$ colour index also shows a significant deepening near the primary minimum, but at the same time the $B - V$ colour index does not change considerably. Therefore, the change of the $U - B$ is caused by variation of the *U* magnitude. In our solution we formally attributed this ultraviolet (UV) flux excess to higher temperature of the disc and of the HS, but it is probably caused by other features that are not directly included in our model. For the appropriate modelling of the *U*-band light curve, a significantly higher temperature of disc edge and larger HS temperature coefficient are necessary than for the modelling of *B* and *V* light curves. Hence, to explain that anomaly, an additional source of radiation associated with the disc is required. This *U* excess could be explained, for instance, by the scattering of the gainer radiation on the electrons of corona-like structure overlying the accretion disc (Linnell 2000). Balmer continuum emission could also contribute to the excess of radiation in the *U* band. Another possible explanation of the *U* excess could be the shock waves or bipolar outflows radiation (see e.g. Nazarenko & Glazunova 2006a,b). To fully understand the origin of the *U* excess, it is necessary to collect more light curves and spectroscopic observations from UV to infrared spectral range. These observations could indicate the possible mechanism (like the Thomson scattering or bremsstrahlung radiation), producing the U excess.

The light-curve analysis of V448 Cygni, performed by means of our modified code (Djurašević et al. 2008), demonstrated that this light-curve fitting code represents a useful tool for the analysis of light curves and for modelling of any conically shaped accretion disc and any brightness feature appearing on the disc lateral side. However, caution is required when interpreting the results, since the large number of free parameters makes the determination of the unique solution difficult. To check the obtained results we reduced the number of free parameters by fixing some of them and by using a simpler accretion disc model with a constant thickness. The obtained results basically confirm the estimated parameters of the system.

Note that in our analysis we assumed the synchronous rotation of the components; the estimate of the projected rotational velocities ($210\,\mathrm{km\,s^{-1}}$ for the gainer and $145\,\mathrm{km\,s^{-1}}$ for the donor) by Stickland & Lloyd (2001) is probably consistent with this assumption for the Roche-filling mass donor, but the gainer is almost certainly spinning much faster than in synchronous rotation. Consequently, the distorted shape and gravity darkening of the gainer will be somewhat different than we assumed. To check the influence of the gainer's non-synchronicity on the light-curves shape, we performed some additional tests. We calculate the gainer's non-synchronicity factor $f_{\rm h} \sim 3.0$ from the rotational velocities and the estimated radii of components (assuming that donor rotates synchronously). Non-synchronicity factor is defined as the ratio of the gainer angular rotation rate ($\omega_{\rm h}$) to the Keplerian ($\omega_{\rm K}$) orbital rate. In the case of faster-than-synchronous rotation ($f_{\rm h} > 1$), the resulting critical lobe is smaller than the Roche lobe, and characterized by a rotationally distorted shape. The filling factor $\mu_{\rm h}$ (defined as the ratio of the gainer's polar radius to the critical non-synchronous lobe radius along z-axis) describes the stellar dimension and rotational distortion, which is significant for $\mu_{\rm h}$ close to 1. If the filling factor is decreased, the rotational distortion rapidly diminishes and the star becomes smaller and approaches a spherical form. From the light-curve analysis, we obtained $\mu_{\rm h} \sim 0.6$, so the gainer's shape is close to spherical, very similar to the one obtained for the synchronous rotation. This has a consequence that the photometric effects of the gainer's non-synchronous rotation are practically negligible.

This analysis indicates that the evolved binary V448 Cygni is in the phase of an intensive mass transfer from the Roche lobe-filling donor towards the gainer, which leads to the formation of the accretion disc around this more massive and hotter star. Our study shows that the model with an accretion disc is in agreement with the available photometric data as well as to the spectroscopic data as proposed by Glazunova et al. (1986).

Despite significant advantages of the Roche semidetached model with accretion disc around the gainer for the study of the V448 Cygni system, we are sure that problems with the complete interpretation of this system still persist. The complex nature of V448 Cygni requires more high-quality observational data than has been collected. To improve the model of V448 Cygni it is necessary to obtain high-resolution spectra with good phase coverage, which could give more information on the motion of the gas in the system. Moreover, these spectroscopic observations would make it possible to estimate the level of the disc flux contribution to the total flux of the system. The study of the orbital period changes is also very important, since it can provide the estimates of mass transfer and mass-loss ratios. Thus, further photometric observations are necessary for more realistic modelling and accurate estimates of the parameters of this active binary system.

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