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PHOTOMETRIC AND SPECTROSCOPIC ANALYSIS OF THE ECLIPSING BINARY DQ VELORUM

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Abstract. In order to obtain the main stellar and orbital parameters of the Double Periodic Variable DQ Velorum, we have carried out a series of spectroscopic and photometric observations covering several orbital cycles. We disentangle DQ Vel composite spectra and measure radial velocities using an iterative method for double spectroscopic binaries. We obtain the spectroscopic mass ratio $q = 0.31 \pm 0.03$ from the radial velocity curves. We compare our single-lined spectra with a grid of synthetic spectra and estimate the temperature of the stars. We also model the V-band light curve using a fitting method based on the simplex algorithm including an accretion disc.

We find that DQ Vel is a semi-detached system consisting on a B3V gainer ($T_g = 18500 \pm 500\mathcal{K}$) and an A1III donor star ($T_d = 9400 \pm 100\mathcal{K}$) plus an extended accretion disc around the gainer. We compare the stellar and disc parameters of DQ Vel with the DPV V393 Sco to investigate the nature and evolution of these two similar DPV systems.

Key words: eclipsing binaries - DPVs - fundamental parameters - early-type

1. Introduction

DQ Vel is a Galactic eclipsing binary of Algol-type discovered by Hoffmeister (1949). This system shows an orbital period of 6.08337 days (van Houten, 1950) and also a long-term photometric variability of 188.9 days discovered by Michalska *et al.* (2010). DQ Vel belongs to the group of variable stars called *Double Periodic Variables* (hereafter DPVs). This group of interacting binaries is characterised by two photometric variabilities linked one to each other with a period ratio around 33 (Mennickent *et al.*, 2003; Mennickent and Kołaczkowski, 2010). The short-term variability corresponds to the orbital motion of the binary while the long-term variability still has an uncertain origin. DPVs have been interpreted as semi-detached binaries showing cycles of mass loss into the interstellar medium (Mennickent *et al.*, 2008; 2012b).

In order to increase the amount of well studied DPVs we have carried out an observational campaign of DQ Vel since 2008. We collected a series of high-resolution optical spectra between 2008-2011. Most of the spectra were obtained from the CORALIE echelle spectrograph located in the Swiss telescope at La Silla Observatory. We also have photometric data including a V-band light curve obtained from the public ASAS database (www.astrouw.edu.pl/asas/) as well as 1051 frames in V-I bands and 345 frames in J-K bands obtained with the REM 0.6m telescope at La Silla.

2. Data Analysis and Results

2.1. Spectroscopic analysis

A first inspection of the composite spectra of DQ Vel shows strong absorption Balmer lines togheter with HeI and some metal lines. To check if DQ Vel is a double spectroscopic binary we select known absorption lines and compute their corresponding Doppler shifts. We did not consider the intense and broader Balmer lines which seem to contain several components and selected the stronger and unblended lines: HeI 4387.929 Å, MgII 4481.126 Å, FeI 4957.596 Å, HeI 5875.614 Å, the silicon doblet SiII 6347.103 Å/6371.359 Å and HeI 6678.151 Å. We find that all selected HeI lines seem to belong to the more massive star (hereafter gainer) while the metal lines appear to belong to the less massive star (hereafter donor). In order to disentangle the composite spectra we use an iterative method originally proposed by Marchenko *et al.* (1998). This method uses the Doppler shifts observed on the spectral lines to move all spectra to the donor rest-frame and combine these to create a first guess spectral template for the donor star. This procedure attenuates the spectral features of the remaining component (gainer). Subtracting this donor template from all spectra and shifting the resulting spectra to the gainer rest-frame we combine the data again in order to obtain a template for the gainer star. We repeat this procedure until the residuals of one component contribution disappear from the template spectra of the other one. No more than 5-7 iterations are necessary considering that with each iteration the residuals are reduced by a factor $1/n$, where n is the number of observed spectra (González and Levato, 2006). Using our previous calculated donor and gainer templates we apply a 1-D Fourier cross correlation (CCR) process to measure RVs for both stellar components. Using the donor template, we calculate RVs independently in the spectral ranges 4500-4800 Å and 4900-5600 Å where we find more spectral lines coming from the donor star. A third measurement was done using both spectral ranges simultaneously. Final RVs are obtained by taking the mean between these three measurements. We apply the same procedure using the gainer template in the 4350-4750 Å and 4900-5300 Å ranges. Figure 1 show our final RV measurements togheter with the best sinus function used to fit the RV curves. In Table I we show the circular orbit solutions obtained from the best sinus fits. We can obtain the spectroscopic mass ratio of the components which is independent of the orbital inclination i of the system (Hilditch, 2001):

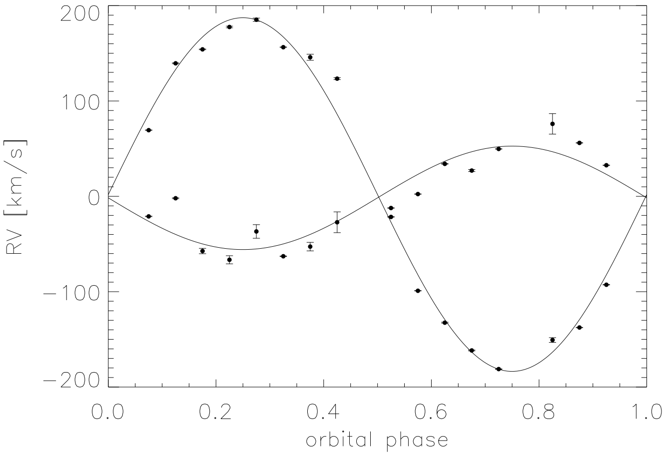

Figure 1: RV curves and best sinus fit for DQ Vel components. Each RV was measured taking the mean value in orbital phase bins of 0.05

$$\frac{m_d}{m_g} = \frac{K_g}{K_d} = q = 0.31 \pm 0.03 \tag{1}$$

where m_d and m_g are the donor and gainer masses measured in *solar masses* ($M_\odot$) and K_d and K_g are the semiamplitudes of the RV curves expressed in kms^{-1}. To get some insights on the donor star temperature, we compare our

Table I: Circular-orbit solutions obtained for the best sinus fits. K is the semiamplitude of RV curves and γ is the systemic velocity.

Parameter	Donor-star	Gainer-star
K (kms^{-1})	185.44 ± 4.96	-57.56 ± 5.54
γ (kms^{-1})	1.86 ± 3.71	-8.74 ± 4.07
r.m.s (kms^{-1})	14.8	14.07

donor template with a grid of synthetic spectra in the region 5200-5350 Å deprived of hydrogen and helium lines but with several metal lines. To determine the grid of synthetic fluxes we use atmospheric models computed with the line-blanketed LTE ATLAS9 code (Kurucz, 1993). The synthetic spectra were computed for temperatures from 6000 to 10000 K, surface gravities from 2.0 to 4.5 dex, solar and 0.5 dex higher metallicities and five different rotation velocities, $v_r sin\, i$ = 0, 25, 50, 75 and 100 kms^{-1}. After subtracting the donor template from every grid spectrum and analysing the residuals, our best fit is obtained for an A-type star with T_d = 9400 K, $\log g_d = 3.1$, $v_r sin\, i = 75$ kms^{-1} and solar metallicity.
If we consider that the donor star fills its Roche lobe and transfers mass to the gainer star via a gas stream, then the analysis of the gainer template requieres more attention in order to check the presence of circumstellar material around the gainer star. To study the spectral orbital behaviour of the gainer we remove from the original spectra the donor light contribution for each orbital phase. To do this, we calculate a donor factor contribution to the total light using the individual light contributions obtained for the best photometric model in the V-band light curve (see Figure 2). We observe on the resulting donor-subtracted spectra very interesting features: Hα and Hβ profiles are composed of a central absorption surrounded by weak blue/red asymmetric wings whose velocities reach up to about $\sim$ 350 kms^{-1} and are phased with the gainer's RVs. Similar behaviour was found in Hγ profiles. We detected a weakness of central absorption during the orbital phases $\phi_o = 0.1-0.2$ and $\phi_o = 0.6-0.7$ also observed with the Helium lines and probably related to a filling emission coming from a higher local temperature interaction regions as a hot or bright spot, visible during those orbital phases supporting our scenario of circumstellar matter around the gainer star. So, the estimation of the gainer temperature should be done in

a more independent way.

2.2. Photometric analysis

Using the Fourier decomposition technique we disentangled multiperiodic V, I, J and K light curves finding two main periodicities. The first one is related to the orbital variability of the binary with a period of 6.083299 days. The second periodicity is associated with a period of 188.7 days and represented by a smooth variability whose amplitude is $\sim 2\%$ of the total luminosity. The following ephemerides were found for the orbital and long-term variability respectively:

$$HJD_{min,orb} = 2453407.60(2) + 6.083299(7) * E \tag{2}$$

$$HJD_{max,long} = 2453437.2(16) + 188.7(2) * E \tag{3}$$

In order to obtain the physical stellar parameters we carried out a V-band light curve fitting using the inverse-problem solving method based on the simplex algorithm. Main binary elements used in the model as well as light curve fitting procedure are well described in Djurašević (1992, 1996). We used a semi-detached configuration with the donor filling its Roche Lobe. After unsuccessful tries to model the system without a disc we finally adopt a configuration including an optically thick accretion disc around the gainer star. The disc is characterised by its temperature $T_{disc}(r)$ radially dependent, its radius R_{disc}, its thickness at edge d_e and at centre d_c and assuming it is in physical and thermal contact with the gainer.

The model also includes two active regions *hot spot* (hs) and *bright spot* (bs) with a higher local temperatures and located at the edge of the disc. The inclusion of these regions significantly improves the fit. They are represented by their temperatures ($T_{hs,bs}$), angular dimensions ($\theta_{hs,bs}$) and longitudes ($\lambda_{hs,bs}$) which are free parameters in the model. To restrict the number of free parameteres we fixed the donor temperature $T_d = 9400$ K and mass ratio $q = 0.31$ whose values were derived from our previous spectroscopic analysis. Gravity darkening and albedos coefficients for the stellar components were also fixed to the values $\beta_{d,g} = 0.25$ and $A_{d,g} = 1.0$ respectively according to the von Zeipel's law for radiative shells (von Zeipel, 1924). We assume the donor star is rotating synchronously with a rotation coefficient $f_d = 1.0$. We modeled the light curve with the gainer star in synchronous rotation regime ($f_g = 1.0$) and also under a critical rotation scenario with a non-synchronous rotation coefficient $f_g = 12.8$. We do not observe a significant difference of both fitting results revealing a minor effect of the gainer rotational velocity on the system parameters. The best fit model and final parameters of the fitting are shown in Figure 2 and Table II respectively. The physical parameters for the gainer suggest a B3V type star (Schmidt-Kaler, 1982; Castelli and Kurucz, 2004). From the model we observe that the disc has a concave shape with higher thickness at its edge than at its centre and also is extended filling $(89 \pm 3)\%$ of the critical gainer Roche Lobe. The hot spot is located at longitude $329.1° \pm 7.0°$ and has a temperature of $T_{hs} = 9500 \pm 750\,\mathrm{K}$ which is close to the donor temperature. This is probably the main reason why we do not observe emission from the hot spot on the composite spectra. As the disc is extended the distance

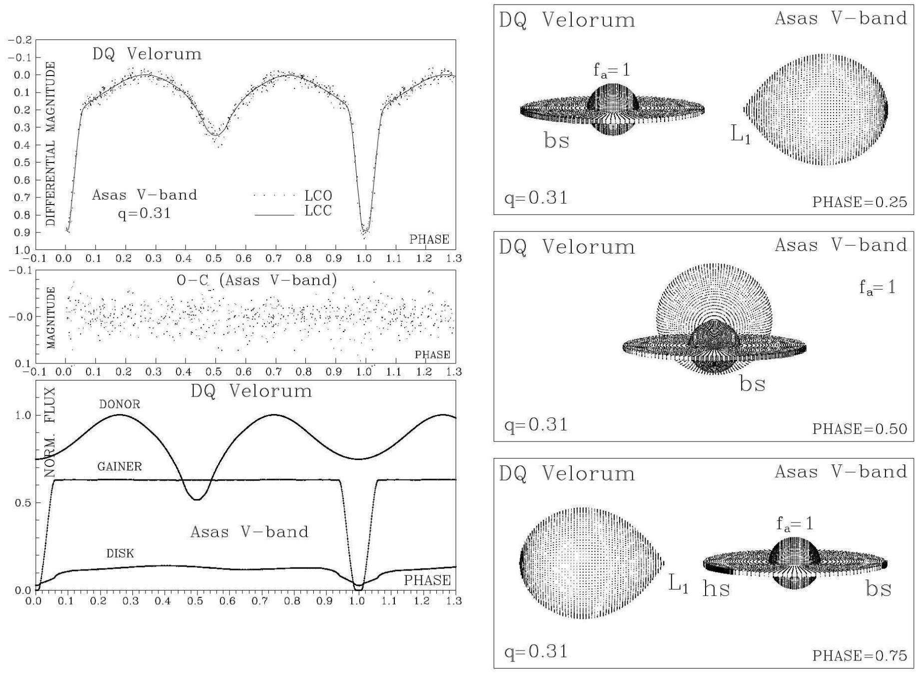

Figure 2: Observed (LCO) and synthetic (LCC) light-curves of DQ Vel obtained by analysing photometric observations; final O-C residuals between the observed and optimum synthetic light curves; fluxes of donor, gainer and of the accretion disc, normalised to the donor flux at phase 0.25.

Table II: Results of the analysis of DQ Vel V-filter light-curve obtained using the Roche model with an accretion disc around the gainer in synchronous rotation regime.

Parameter	Value	Parameter	Value
n	583	$\mathcal{M}_{\rm g}[\mathcal{M}_\odot]$	7.3 ± 0.3
$\Sigma(\rm O - C)^2$	0.3984	$\mathcal{M}_{\rm d}[\mathcal{M}_\odot]$	2.2 ± 0.2
$\sigma_{\rm rms}$	0.0258	$\mathcal{R}_{\rm g}[\rm R_\odot]$	3.6 ± 0.2
$i[^\circ]$	82.5 ± 0.2	$\mathcal{R}_{\rm d}[\rm R_\odot]$	8.4 ± 0.2
$\rm F_{disc}$	0.89 ± 0.03	$\log g_{\rm g}$	4.2 ± 0.1
$\rm T_{disc}[K]$	6580 ± 300	$\log g_{\rm d}$	2.9 ± 0.1
$\rm d_e[\mathit{a}_{orb}]$	0.019 ± 0.005	$M^{\rm g}_{\rm bol}$	-3.1 ± 0.2
$\rm d_c[\mathit{a}_{orb}]$	0.011 ± 0.005	$M^{\rm d}_{\rm bol}$	-1.9 ± 0.1
$\rm a_T$	4.5 ± 0.3	$a_{\rm orb}[\rm R_\odot]$	29.7 ± 0.3
$\rm f_g$	1.00	$\mathcal{R}_{\rm disc}[\rm R_\odot]$	12.9 ± 0.3
$\rm F_g$	0.271 ± 0.005	$\rm d_e[R_\odot]$	0.6 ± 0.1
$\rm T_g[K]$	18500 ± 500	$\rm d_c[R_\odot]$	0.3 ± 0.1
$\rm A_{hs} = T_{hs}/T_{disc}$	1.45 ± 0.1	$\Omega_{\rm g}$	8.45 ± 0.02
$\theta_{\rm hs}[^\circ]$	16.0 ± 2.0	$\Omega_{\rm d}$	2.49 ± 0.02
$\lambda_{\rm hs}[^\circ]$	329.1 ± 7.0	$\rm A_{bs} = T_{bs}/T_{disc}$	1.39 ± 0.1
$\theta_{\rm rad}[^\circ]$	-19.7 ± 5.0	$\theta_{\rm bs}[^\circ]$	50.1 ± 5.0
		$\lambda_{\rm bs}[^\circ]$	142.7 ± 9.0

Note: n - number of observations, $\Sigma(\rm O - C)^2$ - final sum of squares of residuals between observed (LCO) and synthetic (LCC) light-curves, $\sigma_{\rm rms}$ - root-mean-square of the residuals, i - orbit inclination, $\rm F_{disc} = R_{disc}/R_{yc}$ - disc dimension factor (the ratio of the disc radius to the critical Roche lobe radius along y-axis), $\rm T_{disc}$ - disc-edge temperature, $\rm d_e$, $\rm d_c$, - disc thicknesses (at the edge and at the centre of the disc, respectively) in the units of the distance between the components, $a_{\rm T}$ - disc temperature distribution coefficient, $\rm F_g = R_g/R_{zc}$ - filling factor for the critical Roche lobe of the gainer (ratio of the stellar polar radius to the critical Roche lobe radius along z-axis for a star in synchronous rotation regime), $\rm T_g$ - temperature of the gainer, $\rm A_{hs,bs} = T_{hs,bs}/T_{disc}$ - hot and bright spots' 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 hot-spot maximum radiation, $\Omega_{\rm g,d}$ - dimensionless surface potentials of the gainer and donor, $\mathcal{M}_{\rm g,d}[\mathcal{M}_\odot]$, $\mathcal{R}_{\rm g,d}[\rm R_\odot]$ - stellar masses and mean radii of stars in solar units, $\log g_{\rm g,d}$ - logarithm (base 10) of the system components effective gravity, $M^{\rm g,d}_{\rm bol}$ - absolute stellar bolometric magnitudes, $a_{\rm orb}$ $[\rm R_\odot]$, $\mathcal{R}_{\rm disc}[\rm R_\odot]$, $\rm d_e[R_\odot]$, $\rm d_c[R_\odot]$ - orbital semi-major axis, disc radius and disc thicknesses at its edge and centre, respectively, given in solar units.

between $L1$ and the outer radius of the disc is short and not sufficient to produce a substantial acceleration of the gas stream and thus reach a higher temperature at this region.

2.3. DQ Vel and V393 Sco

V393 Sco is a galactic ($d = 523$ pc) bright DPV comprised of an A-type donor and a B-type gainer surrounded by a massive disc. The system has been deeply studied including photometry (VIJK bandpasses and V-ASAS light curves) and high resolution spectroscopy in the optical, near-infrared and ultraviolet (Mennickent *et al.*, 2010; 2012a; 2012b). We note strong similarities on the physical properties of V393 Sco and DQ Vel. Stellar parameters like masses, radii, temperatures, gravities and also orbital parameters (binary separation and inclination) are very similar. However, a detailed comparison shows significant differences on the optical spectral features of both systems. These differences could be associated with the physical properties of the accretion discs and thus with the mass transfer rates. Table III shows the main stellar and disc parameters for DQ Vel and V393 Sco. Strong differences can be seen on the physics and geometry of the discs: DQ Vel' s disc seems to be extended, colder and concave contrary to the modeled disc in V393 Sco which is hotter, convex and probably with most of its mass concentrated close to the gainer. We suggest that the main differences of the discs are related to different evolutionary stages. A higher mass transfer rate in V393 Sco would produce a massive accretion disc and accelerate the gainer until critical rotation. DQ Vel instead, could be in a state of lower mass transfer allowing the formation of an extended and colder disc.

3. Summary and Future Work

Our analysis of photometric data togheter with high resolution spectroscopy allowed us to estimate the physical stellar and accretion disc parameteres of the DPV system DQ Vel. Using the disentangled spectra like stellar templates we derived the RV curves through a cross correlation process to obtain the spectroscopic mass ratio of the system $q = 0.31 \pm 0.03$. The comparision of the donor template with a grid of synthetic spectra enabled us to estimate the temperature of the donor star $T_d = 9400 \pm 100$ K. Subtracting the donor light contribution to the total flux on the composite spectra we anal-

Table III: Main stellar and disc parameters for DQ Vel and V393 Sco according to photometric and spectroscopic analysis. Results for V393 Sco were taken from Model A in Mennickent *et al.* (2012a). Parameters for DQ Vel are from this work.

Parameter	DQ Vel	V393 Sco
	Stellar Components	
T_g[K]	18500 ± 500	16600 ± 500
T_d[K]	9400 ± 100	8600 ± 600
i [°]	82.5 ± 0.2	80.0 ± 0.2
$\mathcal{M}_g[\mathcal{M}_\odot]$	7.3 ± 0.3	7.8 ± 0.2
$\mathcal{M}_d[\mathcal{M}_\odot]$	2.2 ± 0.2	2.0 ± 0.2
$\mathcal{R}_g[R_\odot]$	3.6 ± 0.2	4.4 ± 0.2
$\mathcal{R}_d[R_\odot]$	8.4 ± 0.2	9.4 ± 0.3
$\log g_g$	4.2 ± 0.1	4.0 ± 0.1
$\log g_d$	2.9 ± 0.1	2.8 ± 0.1
$a_{orb}[R_\odot]$	29.7 ± 0.3	35.1 ± 0.3
	Disc	
F_{disc}	0.89 ± 0.03	0.55 ± 0.04
$\mathcal{R}_{disc}[R_\odot]$	12.9 ± 0.3	9.7 ± 0.3
$d_e[R_\odot]$	0.6 ± 0.1	1.3 ± 0.3
$d_c[R_\odot]$	0.3 ± 0.1	2.1 ± 0.4

ized the gainer spectral features showing a strong variability on the Balmer and Helium profiles along the orbital cycle which suggest the presence of circumstellar material. The photometric model of the V-band light curve with the mass ratio and the donor temperature as fixed parameters, enabled us to get the best fit for the system. The best model suggests a semi-detached binary comprised of an A1III donor and a B3V gainer with an extended accretion disc around the gainer star. We also obtain the orbital separation and the inclination angle of the system.

We observe strong similarities between the stellar parameters of DQ Vel and V393 Sco but differences on the geometrical and physical properties of both accretion discs. We suggest that they are related to different evolutionary stages. A detailed analysis of the evolutionary stage of DQ Vel remains for a close future work.

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