Infrared photometry of the dwarf nova V2051 Ophiuchi: I - The mass donor star and the distance

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ABSTRACT

We report the analysis of time-series of infrared JHK_s photometry of the dwarf nova V2051 Oph in quiescence. We modelled the ellipsoidal variations caused by the distorted mass-donor star to infer its JHK_s fluxes. From its infrared colors we estimate a spectral type of M(8.0 ± 1.5) and an equivalent blackbody temperature of \( T_{BB} = (2700 ± 270) \, K \). We used the Barnes & Evans relation to infer a photometric parallax distance of \( d_{PH} = (102 ± 16) \, pc \) to the binary. At this short distance, the corresponding accretion disc temperatures in outburst are too low to be explained by the disc-instability model for dwarf nova outbursts, underscoring a previous suggestion that the outbursts of this binary are powered by mass-transfer bursts.

Key words: binaries:close – stars: individual: V2051 Ophiuchi – dwarf novae, cataclysmic variables

1 INTRODUCTION

Dwarf novae are short period interacting binaries in which an evolved, late type star overfills its Roche lobe and transfers matter to a companion white dwarf via an accretion disc. These systems show recurrent outbursts in which the disc progressively raising its surface density and gas temperature is fed at a roughly constant rate to a low viscosity disc, progressing to an outburst. DIM assumes matter is transferred from the mass-donor star. DIM interprets the outburst as the response of a high viscosity disc (\( \alpha \sim 0.1 - 1.0 \)) to a burst of enhanced mass transfer from the mass-donor star. DIM assumes matter is fed at a roughly constant rate to a low viscosity disc, progressively raising its surface density and gas temperature until it surpasses a critical limit, \( T_{crit1} \geq 6000K \), where a thermal-viscous instability sets in, greatly enhancing the local viscosity parameter (\( \alpha_{init} = 10 \alpha_{cool} \approx 0.1 \)). The instability propagates as a heating wave, bringing the whole disc into a high-viscosity regime which enables the fast accretion of the accumulated gas (e.g., Lasota 2001). A disc annulus switches back to quiescence (and to the low viscosity regime) when its temperature falls below \( T_{crit2} = (10000 - 7000) \, K \).

This limit-cycle scheme implies that the disc temperatures must be \( T < T_{crit1} \) in quiescence and \( T > T_{crit2} \) during outbursts. Therefore, the comparison of observed outburst disc temperatures with \( T_{crit1}, T_{crit2} \) provides a key test for DIM.

V2051 Oph is an ultra short-period eclipsing dwarf nova (orbital period \( P_{orb} = 90 \) min) discovered by Sanduleak (1972), Warner & Cropper (1983) and Cook & Brunt (1983) reported optical light curves showing large-amplitude (\( \gtrsim 30\% \)) flickering (random brightness variations of \( 0.1 - 1 \) mag), deep eclipses (\( \Delta M_B \sim 2.5 \) mag) and a plethora of different eclipse profiles. Superoutbursts were observed and superhumps were detected by Kiyota & Kato (1998) and Vrielmann & Offutt (2003), implying that V2051 Oph is an SU UMa type dwarf nova. Baptista et al. (1998) used HST and ground-based observations to constrain the binary parameters finding a mass ratio of \( q = 0.19 ± 0.03 \), an inclination of \( i = 83.3° ± 1.4° \), star masses and radii of \( M_1 = (0.78 ± 0.06) \, M_\odot \), \( M_2 = (0.15 ± 0.03) \, M_\odot \), \( R_1 = (0.0103 ± 0.0007) \, R_\odot \) and \( R_2 = (0.16 ± 0.01) \, R_\odot \). Saito & Baptista (2006) modelled the extracted UV-optical white dwarf spectrum to find a distance estimate of \( 9230 ± 35 \) pc. Baptista et al. (2007) found that if V2051 Oph is closer than \( 120 \) pc, its outbursting disc is cooler than \( T_{crit2} \) everywhere, therefore excluding DIM as a viable explanation for its outbursts.

Here we model the ellipsoidal modulation seen in infrared light curves of V2051 Oph to extract the fluxes of its mass-donor star and to infer a photometric parallax distance to the binary. This paper is organized as follows. Sect. 2 describes the data reduction procedures, while Sect. 3 presents
the data analysis and the results. The results are discussed in Sect. 4 and summarized in Sect. 5.

2 OBSERVATIONS AND DATA REDUCTION

We used the OSIRIS Infrared Imager and Spectrograph attached to the 4.1 m SOAR Telescope at Cerro Pachón, Chile, to collect time-series of \( JHK_s \) photometry of V2051 Oph in 2013 June 20th, while the star was in quiescence. The observations are summarized in Table 1. The fourth column gives the number of exposures in each passband, while the fifth column lists the binary cycles (E) covered by each run. We adopted a single exposure time of 10\( s \) for all runs and employed a 2\( \times \)3 dithering pattern with an offset of 10\( ^{\prime} \) between positions. We observed two full orbital cycles in the \( K_s \) band and about 1.5 orbital cycles in the \( H \) and \( J \) bands. The images were obtained with clear, photometric skies and the full moon near the field, with seeing ranging 1\( ^{\prime\prime} \) − 1.8\( ^{\prime\prime} \).

The data were reduced with the IRAF package. Exposures were corrected from non-linearity effects of the instrument using the third-order polynomial of Pogge et al. (1999). Differences in pixel-to-pixel sensitivity were compensated for dividing each corrected exposure by a normalized out-of-eclipse average flux. The light curves were phase-folded according to the linear ephemeris of Eq. (1).

\[
T_{\text{mid}}(BJJD) = 2443245.97752(3) + 0.0624278634(3) \times E
\]  

The images were obtained with clear, photometric skies and the full moon near the field, with seeing ranging 1\( ^{\prime\prime} \) − 1.8\( ^{\prime\prime} \).

\[
\Delta \text{BB} = \frac{A \Delta \text{BB}}{d}
\]

where \( \Delta \text{BB} \) is the white dwarf mid-time eclipse and \( E \) is the binary cycle. V2051 Oph shows cyclical period modulations (Baptista et al. 2003). The difference between the predicted eclipse timings for the linear and sinusoidal ephemeris amounts to \( \Delta t_{\text{BB}} = -0.00210 \) for the epoch of our observations. Combining all these time corrections leads to a net phase shift of \( \Delta \phi = 0.0217 \), which centers the eclipse at phase zero.

During the observing night, a small \( -0.1 \) mag brightening was observed along the \( H \) band run followed by a \( -0.1 \) mag decline during the \( J \) band run. A cubic spline was fitted to the uneclipsed parts of these light curves to level the out-of-eclipse average flux.

3 DATA ANALYSIS AND RESULTS

We modelled the ellipsoidal modulation caused by the changes in phase of the projected area of the distorted mass-donor star with a computer code, described in Ribeiro et al. (2007). We assumed a mass ratio of \( q = (0.19 \pm 0.03) \), an inclination \( i = 83.3^\circ \pm 1.4^\circ \) (Baptista et al. 1998), and that the mass-donor star has a uniform surface brightness. We adopted a gravity darkening coefficient of \( \beta = 0.05 \) (Sarna 1989), and the non-linear square-root limb-darkening law of Diaz-Cordoves & Gimenez (1992).

\[
I_v = I_0 \left[ 1 - a_v (1 - \cos \gamma) \right] - b_v \left[ 1 - \sqrt{\cos \gamma} \right]
\]

where the \( a_v \) and \( b_v \) coefficients are \( a_J = -0.465, b_J = 1.199 \), \( a_H = -0.454, b_H = 1.173, a_K = -0.448 \) and \( b_K = 1.066 \) (Claret 1998). \( I_0 \) is the undarkened intensity and \( \gamma \) is the angle between the normal to the surface element and the line of sight. The primary \(-0.1 \) to \(+0.1 \) and secondary \(+0.4 \) to \(-0.4 \) eclipse phases are removed from the light curve and the remaining curve is input to the fitting code, which returns the best-fit orbital contribution of the mass-donor star (represented by its flux at phase zero, \( f_2 \)) plus a constant flux level (attributed to the accretion disc, \( f_1 \)). The results of this fit are shown in Fig. 1 and listed in Table 2.

The amplitude of the modulation, the depth of the secondary eclipse (at phase \( \pm 0.5 \)) and the contribution of the mass-donor star increase with wavelength, indicating that it has a very late-type spectrum. On the other hand, the primary eclipse depth and the disc flux \( f_1 \) decrease with increasing wavelength, telling us that the accretion disc is bluer than the mass-donor star. A blackbody fit to the mass-donor star fluxes yields a temperature of \( T_{BB} = 2700 \pm 270 \) K and a preliminary distance estimate of \( d_{BB} = 107 \pm 17 \) pc. The inferred \( JHK_s \) fluxes of the mass-donor star and the best-fit blackbody to these fluxes are shown in Fig. 2. The predicted optical flux of the mass-donor star (\( \lesssim 0.1 \) mJy) is
consistent with the remaining flux at mid-eclipse observed by Baptista et al. (1998).

The extracted $JHK_s$ fluxes were converted to magnitudes in order to infer the infrared colours of the mass-donor star (Table 3). The inferred colours allow us to estimate both the spectral type and the distance to the system by the method of Bailey (1981) using the empirical Barnes-Evans relations for the infrared provided by Beuermann (2006). Since the measured colours are consistent with those of late $M$ type stars, we adopted the lower main sequence ($M_6.5 \leq SpT \leq L8$) empirical relation of Beuermann (2006) to obtain the $K$ band surface brightness of a star as a function of its spectral type,

$$S_K = 9.651 - 0.88541X + 0.068535X^2 - 0.00211177X^3$$  \hspace{1cm} (3)

where the parameter $X$ for $M$ stars is given by $SpT = M(20 - X)$, $11 \leq X \leq 20$. Once $S_K$ is known, the distance can be estimated from the Barnes-Evans relation (Barnes et al. 1978),

$$S_K = m_K + 5 \log (R/R_\circ) - 5 \log (d/10 \text{ pc}) \, .$$  \hspace{1cm} (4)

In order to estimate the spectral type of the mass-donor star, we applied the equations of Elias et al. (1983) to transform the measured magnitude and colours from the 2MASS to the CIT photometric system and matched the resulting magnitude and colours to the sample of cool late type dwarfs of Cruz et al. (2003), taking into account the larger size of the mass-donor star with respect to isolated stars of same mass, to find $SpT = M(8.0 \pm 1.5)$. We then performed Monte Carlo simulations, applying random gaussian noise to the spectral type, the $K$ band magnitude, and the radius of the mass-donor star ($R_2 = 0.16 \pm 0.01 \text{ R}_\odot$, Baptista et al. 1998) to Eqs. (3) and (4) to obtain $S_K = (5.24 \pm 0.21)$ and a photometric parallax distance estimate of $d_{BE} = (102 \pm 16 \text{ pc})$.

According to Luhman et al. (2003), a typical $M8$ star has $T_{eff} = 2710 K$, in good agreement with our estimate. Our result is also consistent with the spectral type $SpT = M(7 \pm 1)$ obtained by Hamilton et al. (2011), and the $T_{eff} = 2600 K$ and $SpT = M7$ expected for a dwarf nova with $P_{orb} = 90 \text{ min}$ (Knigge 2006). The scaled spectrum of the $M8$ star LP~412-31 (Testi 2009) is shown in Fig. 2 for illustration purposes.

The distance estimates to V2051 Oph obtained independently from the fit to the white dwarf UV-optical spectrum ($d = 92^{+30}_{-35} \text{ pc}$, Saito & Baptista 2006) and from the ellipsoidal modulation of the mass-donor star in the infrared ($d_{BE} = 102 \pm 16 \text{ pc}$) are consistent with each other at the 1-$\sigma$ confidence level.

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**Table 3. Magnitudes and colours of the mass-donor star**

| Band  | Colour (mag) |
|-------|--------------|
| $J$   | 15.42 ± 0.10 |
| $H$   | 14.79 ± 0.05 |
| $K_S$ | 14.25 ± 0.05 |

**Figure 1.** Phase-folded orbital $JHK_s$ light curves of V2051 Oph (dots), the modelled mass-donor star contribution (solid curve) and the ellipsoidal curve plus the constant disc flux $f_i$ (dashed curve).

**Figure 2.** Mass-donor star $JHK_s$ fluxes (dots with error bars), best-fit $T_{BB} = 2700 K$ blackbody model (dot-dashed line), and scaled spectrum of an M8 star (dashed line) from Testi (2009).
4 DISCUSSION

We investigated whether our results could be affected by interstellar extinction or by irradiation effects on the mass-donor star from a hot white dwarf or accretion disc.

The signature of irradiation is the presence of an orbital hump centred at phase ±0.5, when the irradiated face of the mass-donor star is seen face-on. Saito & Baptista (2006) measured a white dwarf temperature of $T_{WD} = 9500^{+2900}_{-1900}$ K. At such low white dwarf temperature, there are not enough UV photons to produce detectable irradiation effects. Furthermore, at a distance of about 100 pc, even in outburst the accretion disc of V2051 Oph is everywhere cooler than ~10 000 K and cannot lead to significant irradiation effects. We confirmed that expectation by modifying the ellipsoidal variation code to allow modelling of an additional bright spot on the inner face of the mass-donor star caused by possible irradiation effects. The resulting intensity of this additional spot is negligible in all bands, in agreement with the lack of evidence for any orbital hump at phase ±0.5.

Spectroscopy of V2051 Oph shows no evidence of the 2200 Å absorption feature (Watts et al. 1986; Baptista et al. 1998) or the NaI D5890,5896 absorption doublet (Steeghs et al. 2001), suggesting that interstellar extinction effects are also negligible. Indeed, from Schlafly & Finkbeiner (2011) we estimate $E(B − V) ≤ 0.42$ mag kpc$^{-1}$ towards the direction of V2051 Oph, which leads to reddening corrections of $ΔK_s ≤ 0.013$ mag and $Δ(J − K_s) ≤ 0.025$ mag for a distance of 102 pc, small in comparison to the uncertainties in the derived magnitude and colours.

The error in the inferred photometric parallax distance estimate is largely dominated by the uncertainties in the measured IR magnitude and colours and by the uncertainties in the spectral classification of very late-type stars (e.g., Testi 2009), with non significant influence from irradiation or interstellar extinction effects.

The distance to the binary is a key factor to distinguish which of the two available models is responsible for the outbursts of V2051 Oph. Because the DIM thermal limit-cycle relies on the partial ionization of hydrogen, disc temperatures are strongly constrained in the DIM framework, with quiescent discs bound to $T < T_{crit} ≈ 6000$ K and hotter outbursting discs with $T > T_{crit} = (10000 − 7000)$ K for $R ≈ (0.02 − 0.5)$ R$_D$. There are no temperature restrictions for discs in the MTIM. Disc surface brightness derived via eclipse mapping techniques can be transformed to brightness temperatures (under the assumption of optically thick disc emission) if the distance to the binary is known (Baptista 2016). For a given surface brightness map, shorter distances imply fainter and cooler discs. Baptista et al. (2007) found that, during outbursts, the V2051 Oph disc brightness temperatures remain everywhere below $T_{CR2}$ if the distance is lower than 120 pc. Our photometric parallax distance estimate indicates it is not possible to explain the outbursts of this dwarf nova within the DIM framework, which leaves MTIM as the only current alternative explanation for the outbursts of V2051 Oph.

5 SUMMARY

We modelled the ellipsoidal modulation caused by the distorted mass-donor star to infer its fluxes in the $IHK_s$ bands and used those fluxes to obtain its magnitudes and colours. The derived colours matches those of a typical lower main-sequence star of spectral type M(8.0 ± 1.5), with temperatures in the $T_{eff} = 2700$ K range, in good agreement with the spectral type inferred by Hamilton et al. (2011) and that expected for a dwarf nova with similar orbital period (Knigge 2006).

The infrared surface brightness and colours imply a photometric parallax distance estimate of $d_{PG} = (102 ± 16)$ pc for V2051 Oph, consistent at the 1-$σ$ confidence level with the independent estimate by Saito & Baptista (2006). At this short distance, the outbursts of V2051 Oph occur at disc temperatures everywhere below the minimum outburst temperature required by the thermal-viscous disc instability model and is, therefore, incompatible with this dwarf nova outburst model. This underscores the previous suggestion that the outbursts of this dwarf nova are powered by bursts of mass transfer from its donor star.

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