Polarimetry of the Semiregular Variable Star V CVn with the Diffraction-Limited Resolution

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Abstract. Differential speckle polarimetry is a method aimed at study of polarized flux distribution in astrophysical objects at diffraction limited resolution. The method is based on the processing of a large number of short exposure images of the object obtained in two orthogonal polarizations simultaneously. We constructed a specialized instrument — SPeckle Polarimeter — implementing the method at 2.5-m telescope of SAI MSU. Using SPP we detected in visual wavelength range for the first time polarized envelopes with size of $0.05 - 0.15''$ around a number of semiregular variable stars. A significant fraction of these envelopes show variability of morphology associated with photometric variability of the central star. In the circumstellar envelope of V CVn we detected two regions changing the brightness with the same period as the star, but with significant and different phase delays. These data allows to suspect that pulsations of V CVn are significantly non–radial.

Keywords: techniques: interferometric; techniques: polarimetric; circumstellar matter

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1 Introduction

An immense variety of protoplanetary nebulae shapes hints us that the mass loss of evolved stars is neither centrally symmetrical nor stable in time. Several processes favour such inhomogeneity, among them are: stellar/planetary companion influence, convection and pulsations. To discern between these processes it is important to have a full picture of dusty wind, down to distances from the star comparable to the stellar radius — where the wind acquires the momentum required to leave the stellar atmosphere.

The studies of the base of dusty wind benefit a lot from the progress in methods of high angular resolution observations during past 20 years: extreme adaptive optics (Beuzit et al. 2019), infrared and optical interferometry (Norris et al. 2019; Montargès et al. 2018), mm-wave radiointerferometry (Homan et al. 2018). Most of works in this field are based on one or few observational epochs. On the other hand, non–stationary nature of the atmospheres of cool evolved stars makes highly desirable a dense monitoring to study their temporal evolution (Höfner & Olofsson 2018).

Polarimetric interferometry is one of the methods which proved to be useful for studies of wind bases of evolved stars (Norris et al. 2012). The principal observable of polarimetric interferometry is the ratio $\mathcal{R}$ of visibilities in two orthogonal polarizations. We demonstrated how to measure this quantity without adaptive optics correction, using an instrument combining speckle interferometry and two–beam polarimetry: speckle polarimeter (Safonov et al. 2019a). The speckle polarimeter is a facility instrument of 2.5-m telescope of Sternberg Astronomical Institute and operates at wavelength range from 0.4 μm to 1.1 μm, thus having a resolution of 50 mas. The instrument suits well for the monitoring of polarized dusty envelopes of young and evolved stars.

In the case of Betelgeuse we were able to follow the changes in illumination pattern of the lowest part of the stellar wind, in 14 epochs throughout the deep minimum of 2019–2020 (Safonov et al. 2020). In this work we focus on another semiregular variable star V CVn. This object is quite common specimen of its kind from photometrical point of view: it demonstrates rather regular variations of brightness due the pulsations with the period of 196^d and amplitude of 1.5^m in V–band. However its polarimetric features are quite peculiar for semiregular variable. The fraction of polarization of V CVn rises up to several percent when the object at minimum, the angle of polarization, on the other hand, is quite stable throughout the observational history (more than 50 years) (Neilson et al. 2014).

In our previous work (Safonov et al. 2019b) on the basis of 20 epochs we demonstrated that the polarization is generated by scattering envelope with very unusual properties. Here we substantially increase the total number of collected epochs. New data were obtained during a period of more chaotic photometric behaviour of the star. It allows us to follow the temporal evolution of reflection nebula more clearly and infer some additional conclusions.

2 Observations using Differential Speckle Polarimetry

The object was observed 42 times in period from March 2017 to September 2020 at three filters centered at 550 nm, 625 nm, 880 nm, with the FWHM of 50, 50 and 80 nm, respectively. Thus we covered 7 pulsation cycles. Each observation produced the estimation of differential polarimetric visibility $\mathcal{R}$. This quantity

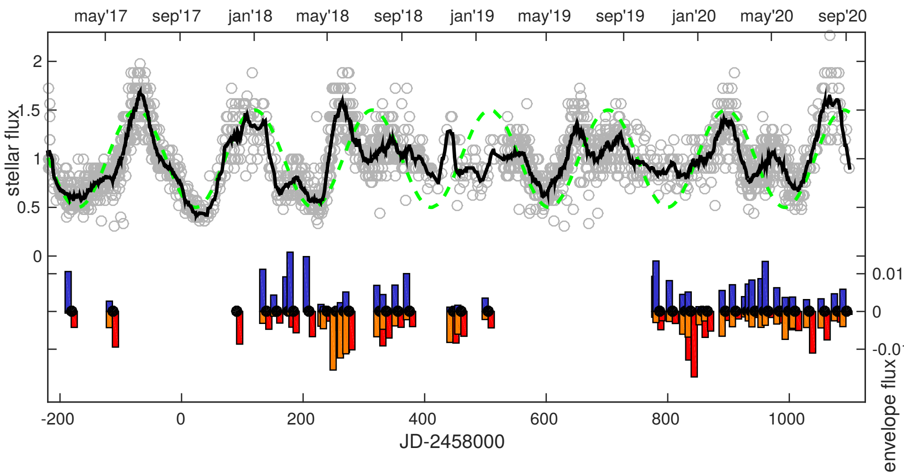

Fig. 1. Grey circles and thick black line: AAVSO visual lightcurve of V CVn converted to flux in arbitrary units (the scale to the left). Green dashed line: cosine with the period of 196^d highlighting the periodic component of the photometric variability. Colored bars in the lower part of the plot indicate the polarized brightnesses of the envelope regions. Blue is for Northern region, orange and red — for Southern region. Polarized brightnesses are expressed in the same units as was used for the star (see the scale to the right).

carries information about distribution of polarized flux in the envelope of the star. In our work (Safonov et al. 2019a) we demonstrated how $\mathcal{R}$ can be used to recover the image of polarized flux of the object at diffraction limited resolution.

For the purposes of the current work the measurements of $\mathcal{R}$ were approximated using the model of three scattering arcs, each subtending 45°, see for details (Safonov et al. 2019b). The radii of the arcs are the same and were determined from our observations: 39 mas. The arcs are displaced to the NNE, SSE, and SSW from the star. Each observation was represented by the polarized brightnesses of the arcs, the results are displayed in Fig. 1, under the light curve of the star.

3 Results and Discussion

The first thing one can note in Fig. 1 is that the arcs systematically change their brightness in sync with the star. Specifically, the Northern arc is brighter when the star is fading and the Southern arcs are brighter when the star is brightening. To more clearly see this dependence we plotted a cosine wave with the period of star's pulsations: 196^d in the same figure. In our work (Safonov et al. 2019b) we considered several hypotheses which could explain such behaviour and demonstrated that the model of strongly non–radial pulsation of the star is the most likely one.

In this model different points of the stellar photosphere pulsate with the same period, but with different phase shifts. In this case, parts of the nebula, scattering radiation of the different parts of the star, will have significant phase shifts relative to the star as well.

Since the second half of 2018 the photometric variability of the star became more chaotic: the amplitude reduced 2-3 times and the periodicity is not so prominent anymore. From the lightcurve of AAVSO it follows that the star enters such state each 18-20 years. The reason for this is unknown. We recorded the behaviour of the circumstellar envelope during chaotic state in 2018-2020 and found that it is as systematic as it was in 2017–2018, during more stable total flux variations. We come to a qualitative conclusion that the irregularity in the variations of the visual flux is introduced by a perturber localized on the line of sight towards the observer. The perturber does not affect the visibility of the star from the point of view of circumstellar envelope as much, therefore their photometric behaviour is more stable.

V CVn is a unique object allowing us to study high amplitude non–radial pulsation from the different line of sights. It definitely deserves further monitoring with high angular resolution methods.

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