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Spectroscopic and photometric variability of the intermediate polar SDSS J201116.8+600428

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In this work, an analysis of the optical variability of the intermediate polar SDSS J201116.8+600428 is presented. We have carried out simultaneous optical and infrared observations of the object in V, i, z and K passbands and obtained the light curves that show notable similarities, but each curve exhibits variability, which is weakly repetitive from one orbital cycle to another. The spectroscopic data confirm that the object belongs to the class of cataclysmic variables and includes a magnetic white dwarf. The radial velocities of the hydrogen and helium emission lines do not indicate the orbital motion in the system.

Keywords: Stars: cataclysmic variables

1 Introduction

Cataclysmic variables (CVs; see Warner 1995 for more review) are close binaries composed of a white dwarf (primary) and a low-mass main-sequence star or a subdwarf (secondary). The secondary fills its Roche lobe and loses matter through the inner Lagrangian point of the system, L_1. The mass is transferred to the white dwarf and formed into an accretion disk around the primary. The disk accretion is present in most CVs. However if the white dwarf has a strong magnetic field ($B \sim 10^7$–10^8 G), it completely prevents the formation of the accretion disk, so the accreting matter becomes a stream channelled by the magnetic field of the primary and transferred to one or both of its magnetic poles, such CVs are called polars. Some CVs include the

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white dwarf with a lower magnetic field ($B \sim 10^5$–10^7 G). In such systems the outer part of the accretion disk is preserved, but its inner part is truncated by the magnetic field, leading to the mass being channelled magnetically only in the regions close to the white dwarf.

SDSS J201116.8+600428 (Romanov V48; hereafter SDSS J2011) is a recently discovered CV. Kato & Romanov (2022) and Szkody et al. (2024) performed a periodogram analysis of its optical variability based on photometric data from the ZTF and TESS surveys, respectively. Three periods of the system have been determined: the most significant ≈60-min period is supposed to be a spin period of the white dwarf; the ≈147-min period may correspond to the CV's orbital motion; the ≈103-min period is a beat period of the two previously mentioned. The existence of these photometric periods suggests that the CV belongs to the class of intermediate polars (IPs). Additionally, Szkody et al. (2024) assumed that the IP exhibits two poles accretion according to the changing form of the TESS light curves for different beat phases.

The orbital period makes the object a member of the period gap (the period range between ≈2–3 h, where there is the observed dearth of CVs). The ratio of its spin to orbital period is ≈0.4, which is a suprisingly high value among the IPs. Also, Kato & Romanov (2022) mentioned its excess infrared emission based on the 2MASS and WISE surveys data. Finally, the object has been observed as an X-ray emission source several times, e.g. according to Pavlinsky et al. (2022), it was detected by ART-XC telescope on board of the SRG observatory in the 4–12 keV energy band, and it is possibly a CV based on its X-ray and optical photometric properties. The last two observational facts confirm the magnetic nature of the system and the possible presence of its cyclotron emission source.

2 Photometric data

Some CVs show sufficient brightness changes on a long-term time scale indicating the changes in accretion rates in the systems. So our photometric research of the SDSS J2011 has started with an analysis of its long-term variability. The data were obtained from the All-Sky Automated Survey for Supernovae (ASAS-SN; Shappee et al. (2014a), Kochanek et al. (2017)) and the Zwicky Transient Facility (ZTF; Masci et al. (2018)) photometric surveys. The light curves are presented in Figs 1 and 2. They show long-term variability with the magnitude amplitude $\sim 0.5^m$, but the magnitude remains on the same level on average. It indicates that the object has remained in almost a stable state for the last ≈ 11 years.

It was mentioned before that the object has an infrared excess, which may be a result of the presence of a cyclotron source. Its behavior may be better understood through more detailed research into its infrared variability.

Our near-infrared photometry of SDSS J2011 was carried out on the 2.5-m telescope of the Caucasian Mountain Observatory of the Sternberg Astronomical Institute (CMO SAI) with the ASTRONIRCAM camera (see Nadjip et al. (2017)) on the night of August 16/17, 2024. We employed the broadband photometric filter K and the dithering observing mode when acquiring frames, shifting the telescope by $3''$ between exposures. The procedure of primary frame reduction is described in

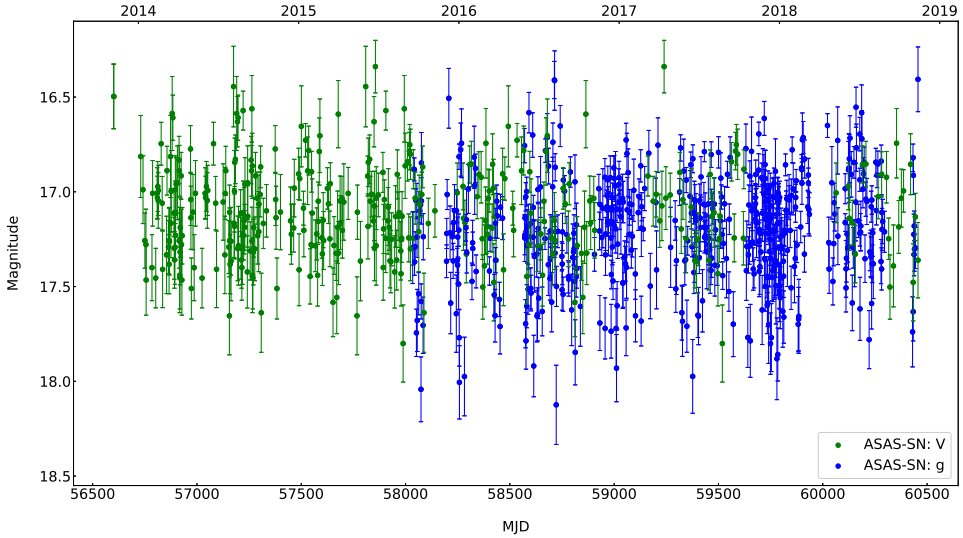


Figure 1 ASAS-SN long-term light curve of SDSS J2011 in V and g passbands.

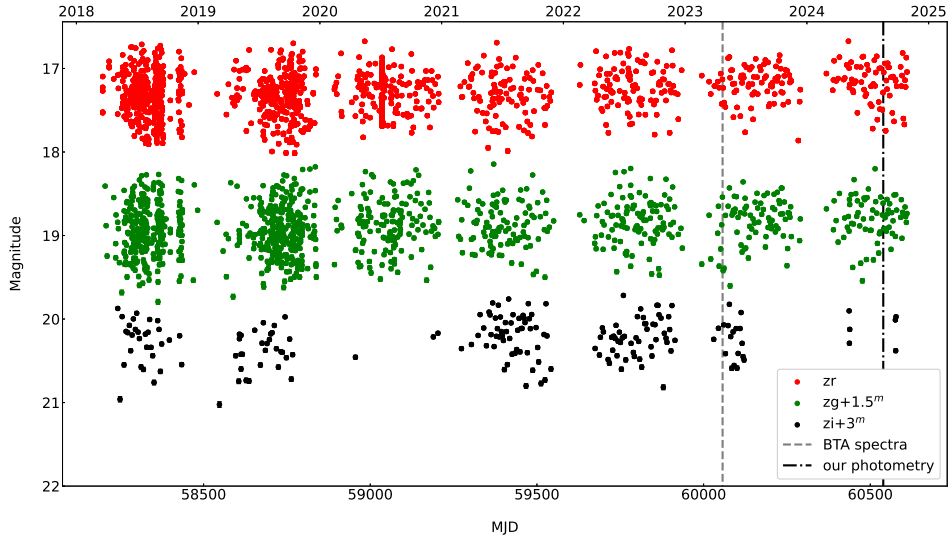


Figure 2 ZTF long-term light curve of SDSS J2011 in zg, zr and zi passbands (the curves are shifted for clarity). The moments of our photometric and spectroscopic observations are identified.

Tatarnikov et al. (2023). It includes correction for nonlinearity, pixels overflow, bad pixels and flat field. Then we performed aperture-based photometry. We used the field stars as standards, with their brightness values sourced from the Two Micron All Sky Survey (2MASS; Skrutskie et al. (2006)). To transform the magnitude in K of

Table 1 Details of the photometric observations of SDSS J2011.

Telescope	2.5-m, CMO	RTT-150	Zeiss-600, CAS
Filter	K	i, z (alternately)	V
Seeing, $''$	1	1	2
Begining of observations, UT	20:08:21	20:29:17	20:19:58
Duration of observations, h	3.6	3.2	4.3
Exposure, sec	30	30	180
Aperture photometry accuracy, ^{m}	0.09	0.01	0.01

the instrumental camera photometric system (which closely resembles the MKO-NIR system) into K_S of the 2MASS, we used the reduction equations from Tatarnikov & Tatarnikov (2023).

The most intuitive interpretation of the infrared light curve might be achieved by comparing it with the optical ones obtained in a shorter wavelength range. For this reason, optical photometric observations simultaneous with the infrared observations were performed with the Russian-Turkish 1.5-m telescope (RTT-150, Turkish National Observatories, the Observatory in Antalya, Turkey) equipped with the TFOSC instrument, and with the 60-cm Zeiss telescope equipped with a photometer of the Crimean Astrophysical Station of the SAI (CAS SAI). Other details about all the photometric observations are presented in Table 1. The observations were carried out in good weather conditions. We processed these data with the differential aperture photometry method as well as the infrared data. The standard stars' magnitudes were taken from the Pan-STARRS DR1 catalogue (Chambers et al. (2017)) and the

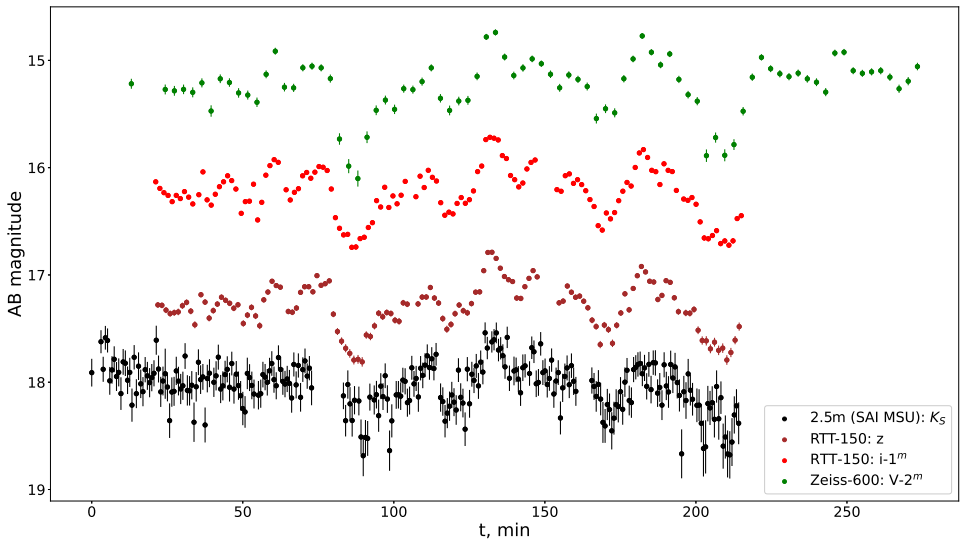


Figure 3 Optical light curves of SDSS J2011. The time on the horizontal axis is counted from the beginning of the observations at the 2.5-m telescope of CMO. The light curves in V and i bands are shifted for the ease of comparison.

AAVSO Photometric All-Sky Survey (APASS) DR9 catalogue (Henden et al. (2016)) for RTT-150 and 60-cm telescope data, respectively. The photometry accuracy in the table is estimated from the standard deviations of the magnitude of the check stars chosen in the frames with the object.

The resulting light curves in all four bands have been combined in a single graph, which is presented in Fig. 3. In general, the light curves of SDSS J2011 have similar shapes, they do not show any eclipses of the system components. The further analysis of the light curves failed to find the previously mentioned orbital and spin periods. This suggests that the variability is complex and does not consistently repeat from one orbital cycle to another.

3 Spectroscopic data

The spectoscopic data of SDSS J2011 were obtained on the night of April 22/23, 2023 at the 6-m BTA telescope of the Special Astrophysical Observatory of the Russian Academy of Sciences (SAO RAS). The telescope was equipped with the SCORPIO focal reducer, which was operated in long-slit spectroscopy mode (Afanasiev & Moiseev (2005)) with the VPHG1200G grism as the disperser (with spectral range 4000–5700 Å). The data consist of 20 spectra with 300-sec exposure, the duration of the observations was ≈105 min, which covers ≈0.7 of the SDSS J2011 orbital cycle. The standard star HZ44 was observed to perform the spectrophotometric calibration.

The average calibrated spectrum of the object is shown in Fig. 4. It features broad hydrogen Balmer lines (Hα, Hβ, Hγ, Hδ, Hϵ), neutral helium lines (HeI λ4026, λ4144, λ4388, λ4471, λ4713, λ4921, λ5015), which are typical for CVs. There is an ionised carbon line CII λ4267 and the Bowen blend CIII/NIII. The spectrum also shows

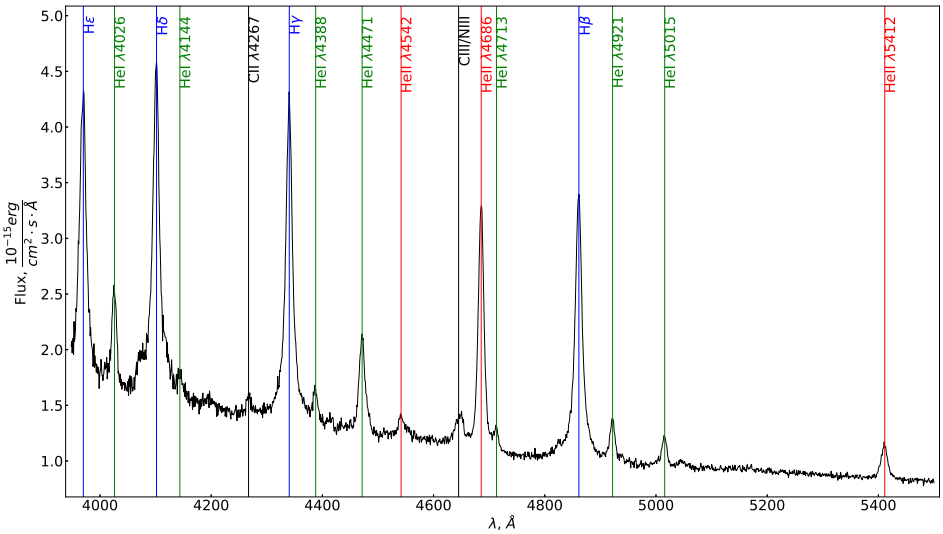


Figure 4 The average calibrated spectra of SDSS J2011 with labeled emission lines.

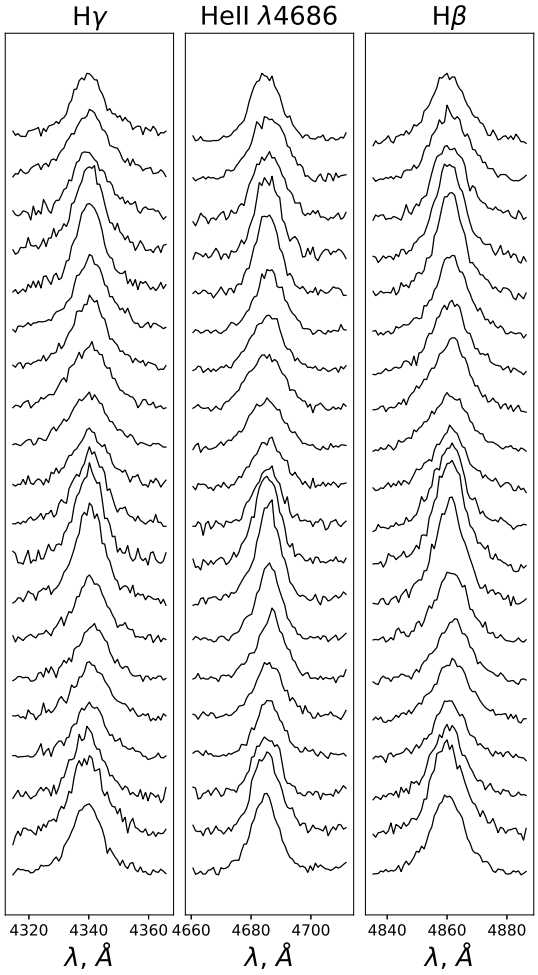


Figure 5 The profiles of Hγ, HeII λ4686 and Hβ emission lines.

ionised helium lines HeII λ4542, λ4686 and λ5412, indicating the magnetic nature of the system.

The variability of the profiles of three strong emission lines is presented in Fig. 5. They show the noticeable changes, revealing a multi-component and asymmetric structure. The fluxes and widths variability is also visible.

We have determined the radial velocities of the lines in each spectrum using the cross-correlation method, with the first spectrum serving as the reference. The examples of our resulting radial velocity curves are presented in Fig. 6. The changes of the radial velocities are visible, however they do not fit orbital sinusoidal variability in any lines of hydrogen and helium. A similar result of radial velocity determination is discussed in Szkody et al. (2024).

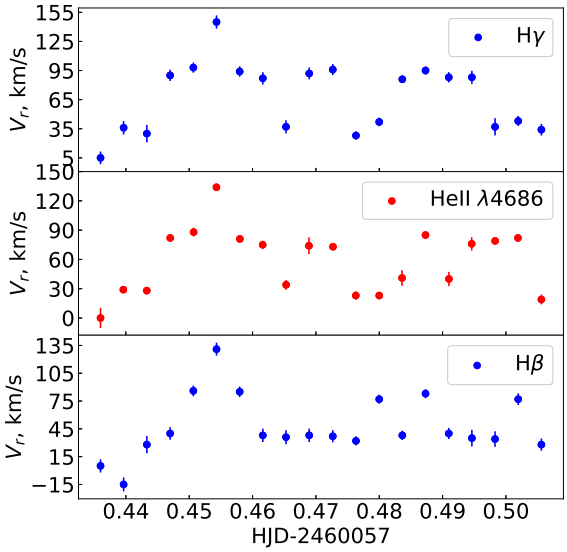


Figure 6 Radial velocity curves in the HeII λ4686, Hβ and HeI λ5015 lines.

Conclusion

In this research, we analyse the photometric and spectroscopic variability of the unusual intermediate polar SDSS J2011, which is an X-ray source and a member of the period gap with a high spin-to-orbit ratio. Based on its long-term variability from the ZTF and ASAS-SN surveys' data, no obvious state changes in the system were revealed. We obtained its simultaneous light curves in the K_S, z, i and V filters. The average K_S magnitude is $\approx 18.1^m$ and $\approx 17.2^m$ in other filters. A preliminary visual analysis indicates that the light curves are similar to each other, but the variability of the object is quite complex. The long-slit spectra of the object contain strong broad emission lines of hydrogen, neutral and ionised helium, which may result from high accretion rates in the system. According to the long-term photometric light curves, the high state has persisted for more than 11 years. The radial velocities we constructed do not reflect the orbital motion of the system. Both the photometric and spectroscopic data are planned to be analysed in more detail.

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