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New Cataclysmic Variable in Pisces: A WZ Sge-subtype Star with Rebrightenings

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In September, 2021, we obtained $\sim$ 1100 $UBVR_cI_c$ CCD observations of the dwarf nova with coordinates RA $=23^{\rm h}11^{\rm m}10\overset{\rm s}{.}9$; Dec $= +01^\circ30'03''$ (J2000) during its outburst. Our analysis of this photometric series showed that the studied variable star had superhumps at stage "B"; two rebrightenings were detected after the end of the outburst. The mass component ratio $q = 0.06$ was estimated; color temperature variations during the outburst were studied. The variable is a typical WZ Sge star with a short superhump period, $0\overset{\rm d}{.}0516$. The detected period is close to the lower limit for the WZ Sge variables.

1 Introduction

Cataclysmic variables (CVs) are close binary systems, in which the primary component is a white dwarf (WD), and the secondary one is a red or brown dwarf of a late spectral type, filling its Roche lobe. As a result, matter from the secondary component passes through the inner Lagrange point L1, is accreted onto the WD, and forms an accretion stream. Due to the fast orbital motion, this stream does not fall directly on the WD, but swirls in the direction of orbital motion, and an accretion disk arises around the WD. As a rule, the disk and bright formations on it make the greatest contribution to the optical radiation coming from the system. Flares, humps appear on the light curve, and rapid brightness variations (flickering), depressions and other peculiarities can be observed; see, for example, Warner (1995), Osaki (1996, 2005), Cherepashchuk et al. (1996), Hellier (2001), Giovannelli (2008), Kato (2015) and other papers.

One of the CV types is SU UMa-type stars (UGSU) and their subtypes: ER UMa and WZ Sge stars.

For SU UMa stars, we observe two types of outbursts: normal ones and superoutbursts. The normal outburst durations are only several days, with amplitudes up to $3^{\rm m} - 4^{\rm m}$; a superoutburst lasts for two weeks or more. The amplitude of a superoutburst is also larger than that of the ordinary one by $1^{\rm m} - 3^{\rm m}$ (Kato et al., 2009a). The average time interval between subsequent superoutbursts is called a "supercycle". Normal (ordinary) outbursts occur between superoutbursts. Stars of the WZ Sge subtype do not exhibit ordinary outbursts.

CVs of the ER UMa subtype have the shortest supercycles, tens of days, between which usual outbursts are also observed. The amplitude of all types of outbursts in stars of this subtype is the smallest for SU UMa type stars and amounts to several magnitudes, see

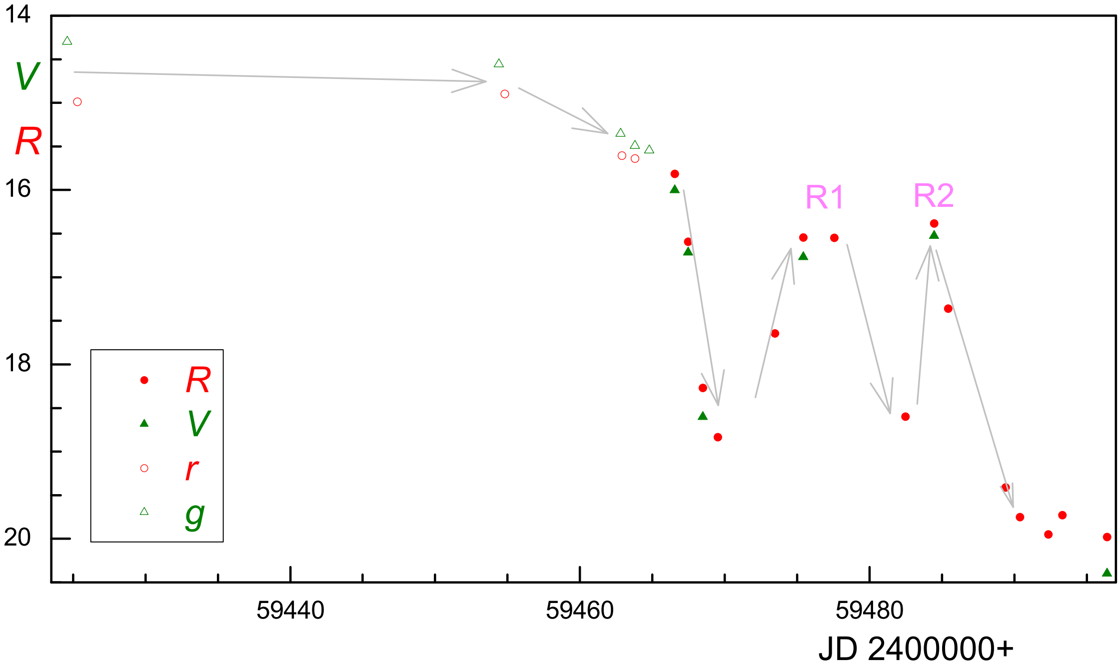

Figure 1. Light curve of the OT J231110.9+013003 in the V (green triangles) and R_c (red circles) passbands. The filled symbols are our observations. The open symbols are data from various sources in the literature. Two rebrightening are marked “R1” and “R2”.

Patterson et al. (2013), Zemko et al. (2014), Ohshima et al. (2014), Kato et al. (2016b), Shugarov et al. (2018).

WZ Sge-subtype stars have the largest outburst amplitudes, up to $8^{\rm m} - 9^{\rm m}$ (Kato, 2015). Hereafter, we designate such stars as “SUWZ”.

In some cases, the photometric behavior of SUWZ stars can be similar to light variations of classical novae. However, outbursts with amplitudes as large as $19^{\rm m}$, like that observed for the classic nova V1500 Cyg (see Honda et al., 1975; Harevich et al., 1975; Young et al., 1976) were never observed for SUWZ stars.

During superoutbursts, all mentioned objects show sinusoidal brightness variations called superhumps. Their periods are not strictly constant, they can vary by several percent; the amplitudes can also change, their average value being $0\overset{\rm m}{.}2\pm0\overset{\rm m}{.}1$. Superhumps have three stages (Kato et al., 2009a). Stage “A” is early evolution, during which the superhump amplitude increases. During the stage “B”, a prolonged “plateau” is observed; at this time, the brightness of the star slowly decreases, and the superhumps are most pronounced. At the final stage of the superoutbursts, “C”, they are less distinct and their amplitude usually decreases.

Most of such stars have superhump periods longer than their orbital period, and the observed brightness variations are called “positive superhumps”. If the period of the superhumps is slightly less than the orbital period, such brightness variations are called “negative superhumps”.

In some CVs of the SUWZ type, repeating echo outbursts, or rebrightenings, with a shorter duration and smaller amplitudes are observed after the main superoutburst. For example, 11 rebrightenings were observed for EZ Lyn (Kato et al., 2009b; Pavlenko et al., 2007) and for TCPJ18154219+3515598 (Zubareva et al., 2018). For ASASSN-15po (Namekata et al., 2017), 10 rebrightenings were detected. EG Cnc (Kimura et al., 2021), ASASSN-18fk (Pavlenko et al., 2019), and V1006 Cyg (Kato et al., 2016a; Pavlenko et al.,

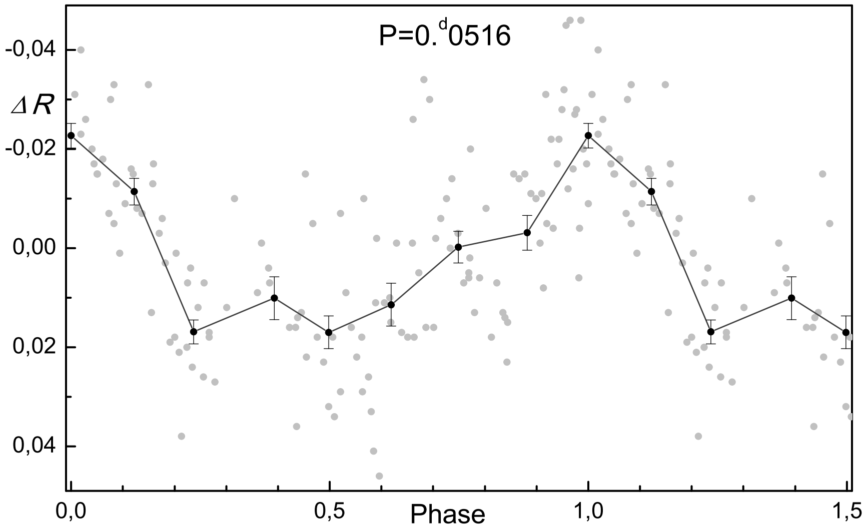

Figure 2. Phase light curve, folded with the superhump period found from our data in the JD 2459465–469 time interval.

2018) had 6 rebrightenings. MASTER OT J203749.39+552210.3 showed 4 rebrightenings; MASTER OT J211258.65+242145.4 exhibited 8 rebrightenings (Nakata et al., 2013). A possible explanation for this phenomenon is given by Meyer & Meyer-Hofmeister (2015).

2 Physical processes occurring during superoutbursts

During a superoutburst, due to large energetics, the disk shape is distorted to elliptical, and precession rotation begins. Y. Osaki showed that such behavior in a CV system can be explained by simultaneous action of the tidal-instability and thermal-instability mechanisms (Osaki, 1989, 1996, 2005; Whitehurst, 1988) and can cause the appearance of superhumps.

In this model, for a system with a low mass ratio ($q = M_2/M_1 \leq 0.25$), the radius of the disk can reach the size at which the ratio of the orbital period of the system and the orbital period of a physical point on the disk becomes 3:1. Because of such ratio of the periods, resonant rotation sets in the accretion disk. At this time, eccentric instability becomes most pronounced, the turbulence, as well as mass exchange rate, increases, a superoutbursts starts, and superhumps appear on the light curves; see Kato et al. (2009a), Kato (2015), Hirose & Osaki (1990), Whitehurst (1988), Osaki (1989, 1996), Ringwald et al. (2012), Udalski (1988).

As a result, the same configuration of the elliptical precessing disk, the hot formation on it, and the orbital phase repeat at a time interval equal to the superhump period:

$$1/P_{sh} = 1/P_{orb} - 1/P_{prec}.$$

“Negative superhumps” can be explained with the accretion disk being inclined to the orbital plane and with the simultaneous nutational motion of it. An explanation of this phenomenon can be found in Udalski (1988), Harvey et al. (1995), Wood & Burke (2007), Ohshima et al. (2014).

CVs with negative superhumps are rare compared to those with positive superhumps, so their study is of special interest; see Patterson (2002), Ohshima et al. (2014), Sosnovskij et al. (2017), Sklyanov et al. (2020), Pavlenko et al. (2021), Ringwald et al. (2012).

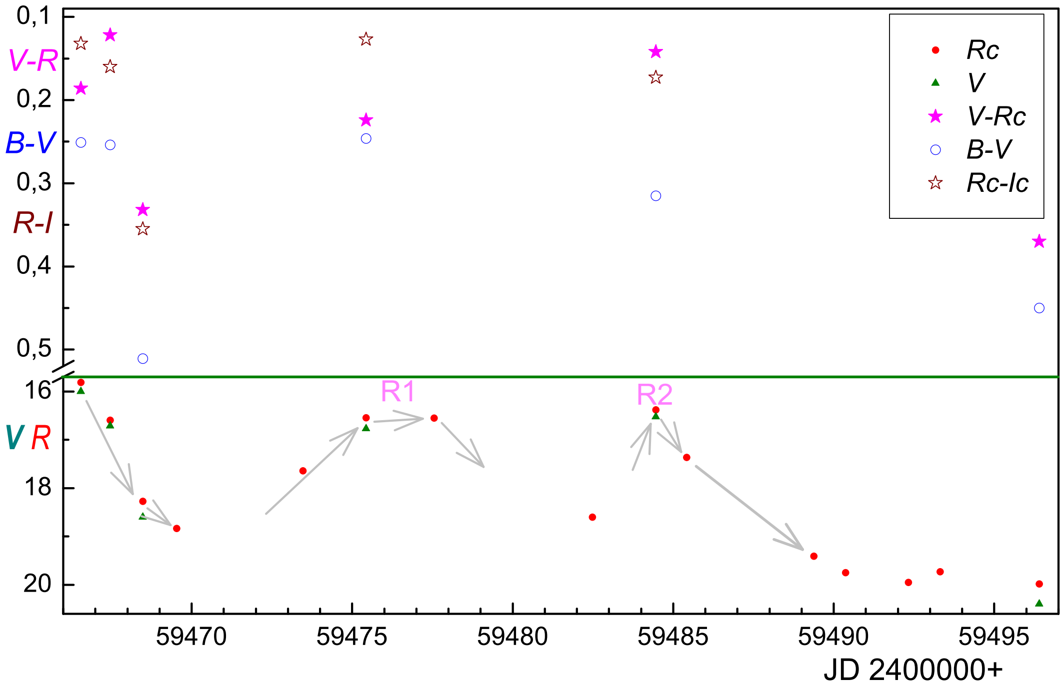

Figure 3. Light curve (bottom) and color indices (top) according to our data. Reddening of the variable's color indices is seen during depressions. See also the caption to Fig. 1.

Soon after a superoutburst, "early superhumps" may appear in SUWZ stars. At this time, the system shows a small amplitude, about a few hundredths of a magnitude, the optical modulation having the shape of a double wave and repeating with the same period as the orbital one. Kato (2015) explains this behavior by the fact that, for a low mass ratio of the components, the accretion disk can reach the size at which the 1:2 resonance can occur in the system. This resonance is stronger than the 3:1 resonance described above. In this case, two-arm waves appear on the disk, and a two-peaked wave must appear on the light curves. Note that this phenomenon is not observed for SU UMa stars.

3 A brief history of studies of the the program object

The previous superoutburst of USNO-B1.0 0915-0569037 = OT J231110.9+013003 (hereafter J2311) was discovered by Koichi Itagaki and observed in November, 2007 (see the AAVSO database); however, a detailed light curve was not recorded. According to data from the SDSS, the color indices of J2311 are small (the object is clearly white or blue); the star was included by Kato et al. (2012) in the CV candidate list. In the AAVSO VSX Index, the object has the name AAVSO UID 000-BCY-485, where also the brightness variation limits $15^{\rm m}_{.}7$ V – $20^{\rm m}_{.}6$ B and the variability type UG are given.

Yutaka Maeda (see vsnet-alert No. 27671) detected a new outburst of the object outburst to $14^{\rm m}_{.}2$ on August 27, 2021. This outburst was partially restored from the ZTF database (Masci et al., 2019). During these observations, the star was at the "plateau" stage after the outburst.

4 Observations

On September 8, 2021, immediately after the announcement of the new outburst (vsnet alert No. 27671), we began to observe the star using the 60-cm telescope of the Slovak Academy of Sciences (Stará Lesná) equipped the FLI ML3041 CCD camera. Since the star at this time was already at 15^{m}, most of the observations were carried out without a filter, in integral light. However, whenever possible, we obtained $UBVR_cI_c$ measurements in order to analyze color variations of J2311 during the outburst. In addition to our observations, Alexey Sosnovskij obtained an R_c estimate with the 2.6-m ZTSh telescope of the Crimean Observatory on JD 2459493, and Natalya Ikonnikova carried out BVR_c measurements with a 60-cm reflector at the Caucasian Mountain Observatory of the Sternberg Astronomical Institute (Moscow University) on JD 2459496.

As a result, we obtained more than 1100 CCD brightness measurements in the $UBVR_cI_c$ passbands and in integral light during 15 nights (See Table 1).

Table 1. Observations. The Julian Date, average night magnitude in the $UBVR_cI_c$ passbands, and the number of frames N for each magnitude are indicated.

JD 24...	U	N_U	B	N_B	V	N_V	R	N_R	I	N_I
59466.55	15.546	3	16.252	3	16.00	3	15.815	102	15.683	3
59467.46	16.097	1	16.971	2	16.717	1	16.595	107	16.435	2
59468.48	–	–	19.11	3	18.60	3	18.27	65	17.916	3
59469.53	–	–	–	–	–	–	18.84	201	–	–
59473.47	–	–	–	–	–	–	17.644	202	–	–
59475.43	–	–	17.015	4	16.769	3	16.545	63	16.418	4
59477.55	–	–	–	–	–	–	16.55	15	–	–
59482.48	–	–	–	–	–	–	18.6	8	–	–
59484.46	–	–	16.840	7	16.525	5	16.383	235	16.21	5
59485.42	–	–	–	–	–	–	17.362	36	–	–
59489.38	–	–	–	–	–	–	19.41	2	–	–
59490.37	–	–	–	–	–	–	19.75	6	–	–
59492.33	–	–	–	–	–	–	19.95	11	–	–
59493.31	–	–	–	–	–	–	19.73	9	–	–
59496.41	–	–	20.8	3	20.35	3	19.98	3	–	–

We used the star of the horizontal branch of our Galaxy 2MASS J23105687+0132563 (= HE 2308+0116, see Christlieb et al., 2005) as the main standard. The following magnitudes of this star have been found using the standard stars located near AG Peg (Henden & Munari, 2006) for calibration:

$$V = 15.^{\mathrm{m}}43;\ U - B = -0.^{\mathrm{m}}12;\ B - V = 0.^{\mathrm{m}}40;\ V - R_c = 0.^{\mathrm{m}}19;\ R_c - I_c = 0.^{\mathrm{m}}01.$$

We estimate the measurement uncertainty for this star as a few hundredths of a magnitude; for $U - B$, the error can be about $0.^{\mathrm{m}}1$. Additionally, we also measured 6 stars around the variable.

Comparison of quasi-simultaneous observations of the variable with respect to this standard in integral light and in the R_c passband showed that the discrepancy usually did not exceed $0.^{\mathrm{m}}1$, and we accepted that the magnitude in integral light was the same

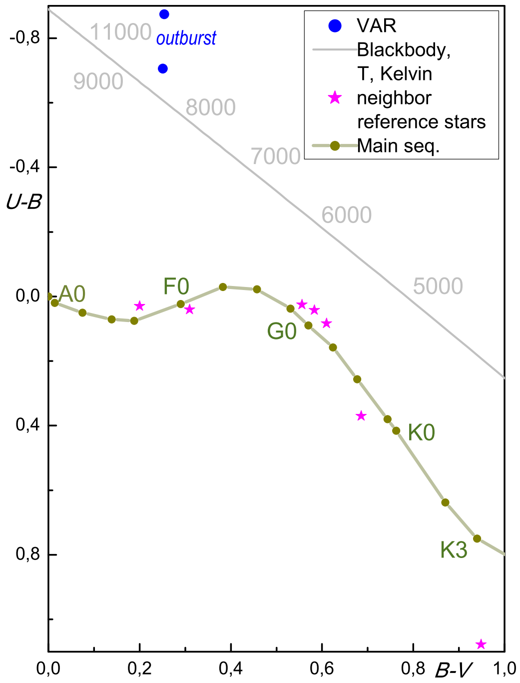

Figure 4. Position of the star in the two-color diagram during the outburst. The main sequence and blackbody lines are also drawn.

as R_c. Our V, R_c data, as well as earlier observations from the ZTF and other sources (open circles), are plotted in Fig. 1.

5 Analysis of the light curve

It appears from Fig. 1 that we began to observe the star on the last day of the plateau stage; thereafter, the brightness of J2311 began to decrease rapidly. Frequency analysis of the data using the Fourier method showed the presence of a periodic component with a period of $0\overset{d}{.}05161$ (see Fig. 2). This period was seen during the brightness decrease (JD 2459466–469). However, note that alternative periods, $0\overset{d}{.}049$ and $0\overset{d}{.}053$, which correspond to the closest daily aliases to our period, can also be true.

We see in Fig. 1 that, after a short-term brightness decrease to almost 19^{m}, two rebrightenings took place, during which the brightness increased by 2^{m}. The second rebrightening was shorter than the first one, and it was the last one in this series of outbursts. However, the fact of this phenomenon proves that the star belongs to the SUWZ subclass, since no rebrightenings are observed for SU UMa-type stars. Also note that we did not find periodic processes in J2311 during these rebrightenings.

Thus, our object belongs to a relatively rare type of SUWZ stars with rebrightenings. Later, the star reached the level of 20^{m}, which is brighter than before the outburst. According to various sources, the brightness at quiescence is $20\overset{\mathrm{m}}{.}5 - 21^{\mathrm{m}}$, and the total outburst amplitude was $6^{\mathrm{m}} - 7^{\mathrm{m}}$, typical of such stars.

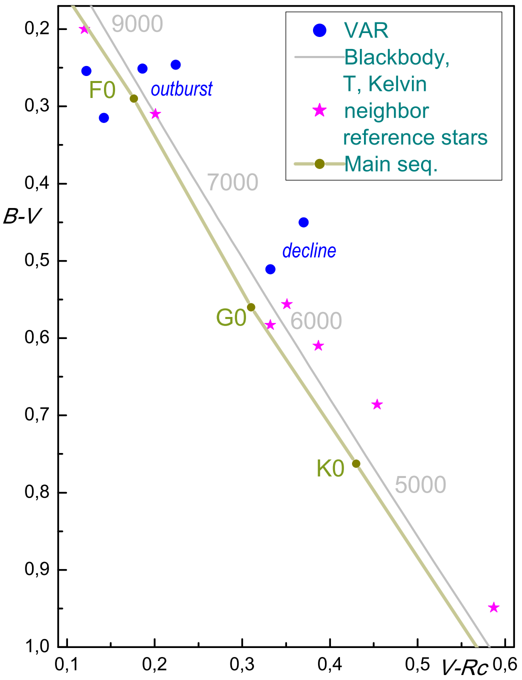

Figure 5. The $B-V/V-R_c$ diagram. A decrease of color temperature from outburst to decline is visible. See the caption to Fig. 4.

6 Color variations

Figure 3 shows the light curves in the V and R_c passbands (bottom part of the figure) according to our data and (top) changes of the color indices $B-V$, $V-R_c$, and R_c-I_c. The average overnight measurements from Table 1 are plotted here.

Only two multicolor measurements were obtained during the brightness decline, but it is clearly seen that all three color indices increased, i.e. the variable became red compared to the outburst stage. During the fading, the main contribution to the object's light still comes from the accretion disk, but its temperature obviously decreased after the end of the outburst.

Note that such color behavior is typical of most CVs, cf. Šimon et al. (2001), Pavlenko et al. (2002ab, 2005, 2008), Katysheva et al. (2013), Neustroev et al. (2017).

Temperature variations can be evaluated more accurately using two-color diagrams. We present three diagrams for different photometric passbands, i.e. for different ranges of the spectrum covered with the $UBVR_cI_c$ photometric system.

From the $U-B/B-V$ diagram (Fig. 4), it can be seen that the average color temperature reached about 10,000 K during the outburst. We notice from the same figure that all 7 comparison stars are located near the main sequence. Their galactic latitudes are about $-52°$, and we conclude that the interstellar reddening in the direction to the program star is low. Note that, on average, color temperatures of such stars are higher, they can reach 12000–15000 K.

The other two-color diagrams, based on the redder passbands of the spectrum ($B-V$, R_c-I_c, Figs. 5 and 6), show a slightly lower color temperature. At these wavelengths, the total radiation comes from the cooler outer zones of the accretion disk. The color temperature changes from 9000 K during the outburst to 6000 K during the brightness decline; obviously, the color temperature in the disk decreases after the outburst.

For comparison, we remind that color temperature varied within similar limits for other

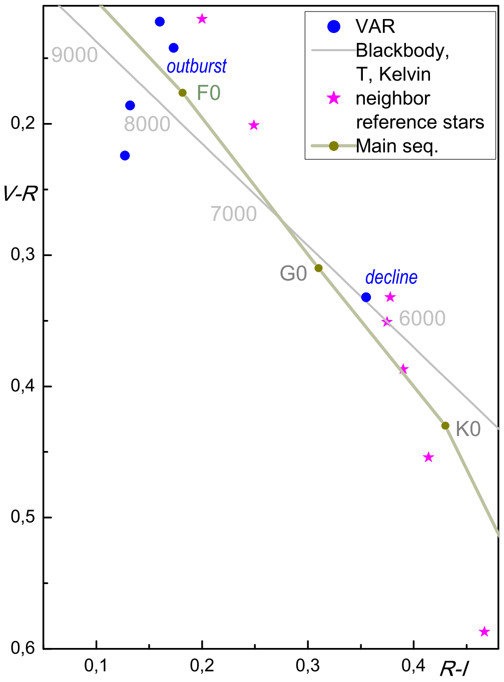

Figure 6. The $V-R_c/R_c-I_c$ diagram. See the caption to Fig. 5.

stars of the SUWZ type, see Shugarov et al. (2018), Golysheva et al. (2012), Chochol et al. (2010, 2015), Golysheva & Shugarov (2014), Golysheva et al. (2017). However, on average, as can be seen from the cited papers, other CVs have temperatures higher than that of J2311. At quiescence, the color temperature may increase again, due to the main contribution to the flux coming from the hot WD at that stage. Unfortunately, we are currently able to obtain only observations without a filter, in integral light, and have no possibility to estimate the temperature.

Figure 7 shows the track of J2311 on the color–magnitude diagram (actually, the Hertzsprung–Russell diagram). It can be seen how the star's light declined after the outburst. However, at the end of our observations, the luminosity of the object remains significantly higher than the luminosity of a standard WD; obviously, the contribution from the accretion disk is still significant. The fraction of radiation from the red component at this time is negligible, since the $B-V$ color index remains blue.

7 Physical characteristics of J2311

Unfortunately, we data we obtained is not sufficient to accurately calculate parameters of the cataclysmic system. However, some preliminary conclusions can be presented.

According to the relation from Patterson (2011, eq. 3), we find the absolute magnitude at outburst maximum for J2311: $M_V = +5\overset{\mathrm{m}}{.}3$. Thus, the distance modulus is $14\overset{\mathrm{m}}{.}3 - 5\overset{\mathrm{m}}{.}3 = 9^{\mathrm{m}}$, corresponds to the system's distance about 630 pc (if we neglect the interstellar absorption of light).

The orbital period is unknown, but the period of superhumps at stage "B" is known. For approximate calculations, we can use this superhump period instead of the orbital period, since the difference between these periods is usually no more than 5%.

Also, the value of $P_{dot} = \dot{P}/P$ is still unknown, making it impossible to find the mass ratio of the components more accurately (see Kato et al., 2009a, 2017, 2020).

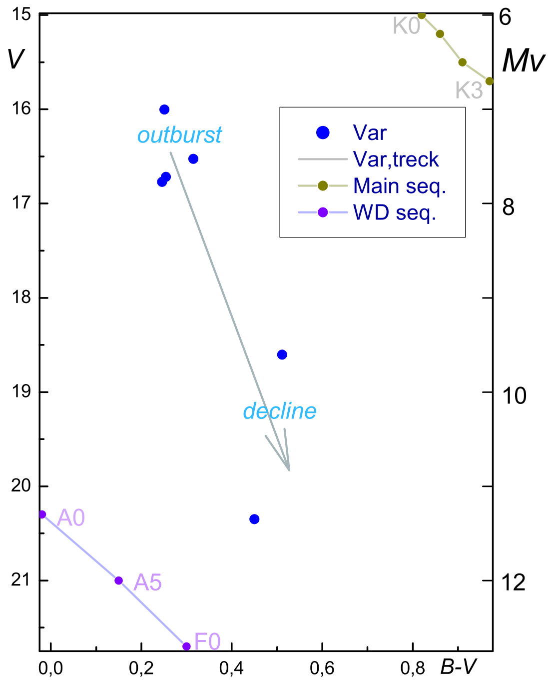

Figure 7. The color–magnitude diagram. The vertical axis on the left shows the visible magnitude and on the right, the absolute magnitude.The distance modulus is assumed to be $+9^{\mathrm{m}}$, the interstellar extinction was neglected (see explanation in the text). A schematic track of J2311 is shown. The main sequence and the sequence of white dwarfs are also plotted.

The approximate mass ratio as a function of the orbital period is given by Patterson (1998, Fig. 6; 2011, Fig. 8). We find that $q = 0.08 \pm 0.02$. The mass of the donor star can be taken, using the orbital period of $0\overset{\mathrm{d}}{.}051$, as $0.06 \pm 0.02 M_\odot$ (Knigge et al., 2011, Fig. 9). The mass of the white dwarf in our case is evaluated as $M_{WD} = (0.75 \pm 0.03) M_\odot$.

The distance between the components (semi-major axis of the orbit) is only 0.5 of the solar radius according to the Kepler–Newton law.

Note that J2311 is similar to ASASSN-15po (Namekata et al., 2017). The duration of the outburst (plateau) for both stars was about 30 days, the total amplitude was $7^{\mathrm{m}} - 8^{\mathrm{m}}$; both stars have very short periods (for stage "B"), $0\overset{\mathrm{d}}{.}05091$ for ASASSN-15po and $0\overset{\mathrm{d}}{.}05161$ for J2311, and showed rebrightenings after the main outburst (probably 9 events for ASASSN-15po and 2, for J2311). In the cited paper, its authors found the ratio of the masses of the components $q = 0.066(7)$ much more accurately than for J2311, and also described the evolutionary status of the object. Since both stars have the shortest periods among SUWZ stars, a comparison of these objects is very relevant.

For a more accurate modelling, explaining of the processes occurring in our system, and determining accurate physical parameters of the components, we need new photometric and spectral observations of J2311. However, the interval between the recent outburst and the previous one was 14 years. Therefore, the probability of a new outburst that would permit new detailed study of the star during the next several years is low.

8 Main results

We have shown that:

– the program star is a typical WZ Sge-subtype variable with an outburst amplitude

$\sim 7^{\mathrm{m}}$;

– rebrightenings of the object occurred;

– the duration of the outburst to the end of the plateau was about 30 days;

– the period of superhumps at stage "B" was $P = 0\overset{\mathrm{d}}{.}05161(20)$;

– the color temperature at the time of the outburst was about 10000 K and then decreased to 6000 K after it.

We estimated the distance to the system and the possible mass ratio of the components.

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