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PR Her – a WZ Sge-type cataclysmic variable

S. Shugarov[1,2], N. Katysheva[2] and N. Gladilina[3]

[1] *Astronomical Institute of the Slovak Academy of Sciences 059 60 Tatranská Lomnica, The Slovak Republic,*

[2] *Sternberg Astronomical Institute, Moscow State University, 119991 Universitetskij avenue, 13, Moscow, Russia,*

[3] *Institute of Astronomy, Russian Academy of Sciences, 119017 Pyatnitskaya Str., 48, Moscow, Russia*

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Abstract. Analysis of the photometric behavior of the WZ Sge-type object PR Herculis during the 2011 outburst was carried out. The periods of "early" ($0^d.05424$) and "ordinary" ($0^d.054990$) superhumps were determined. The value of $P_{\rm dot} = 4.7 \cdot 10^{-5}$, showing the rate of change of the period of "ordinary" superhumps during the superoutburst, was found.

Key words: dwarf novae – photometry, suberoutburst, superhumps

1. WZ Sge-type dwarf novae

The WZ Sge-type objects are the most extreme subgroup of SU UMa-type dwarf novae (DNe) with a long (several years) superoutburst recurrence time. Their orbital periods are the shortest among the SU UMa-type stars. Some of them exhibit a complex post-superoutburst rise(s) of brightness called rebrightening(s), rarely seen in other SU UMa-type DNe (see, for example, Kato et al., 2009a; Chochol et al., 2010). One of the most remarkable signatures of WZ Sge-type objects is the presence of "early" superhumps during the beginning of superoutbursts. The period of "early" superhumps is extremely close to the orbital period and commonly shows a double-humped profile, in contrast to one-humped "ordinary" superhumps of SU UMa-type DNe (Kato et al., 2009).

Osaki and Meyer (2002) suggested that a double peaked profile of "early" superhumps was manifestation of the tidal 2:1 resonance in accretion disks of binary systems with extremely low mass ratios. These superhumps can be explained by a two–armed spiral pattern of tidal dissipation generated by the 2:1 resonance. According to Kato (2002), the expansion beyond the 3:1 resonance radius can be responsible for the appearance of "early" superhumps.

The common, or "ordinary" superhumps with a single peak profile appear during the plateau of a superoutburst of the WZ Sge-type stars. Their periods are a few percent longer than the orbital ones. The "ordinary" superhumps can be explained by the thermal tidal instability model of an accretion disk (Osaki, 1989; Whitehurst, 1988). The presence of the tidal 3:1 resonance in the disk (with the radius smaller than the 2:1 resonance radius) results in the formation of an eccentric outer ring undergoing apsidal precession with a period considerably longer than the orbital one. The periodic variations, identified as superhumps, are the result of the beating of the orbital and precessional periods. This model was supported by numerical simulations (Bisikalo et al., 2005).

"Early" superhumps have not been detected in other dNe (see Kato et al., 2009, 2010).

The most complete review of the WZ Sge stars was recently made by Kato (2015).

Our paper continues a series of publications about the outburst behaviour of the WZ Sge-type systems (see Chochol et al., 2009, 2010, 2012; Pavlenko et al., 2000, 2010, 2012, 2014; Katysheva et al., 2009, 2013, 2014; Golysheva & Shugarov, 2014; Kato et al., 2015a; Uemura et al., 2008; Soejima et al., 2009; Zemko et al., 2013, 2014; Pavlov & Shugarov, 1985; Ohshima et al., 2014; the "Pdot"-series of papers by Kato et al., 2009, 2010, 2012, 2013, 2014, 2014a, 2015 and many others.)

2. The CCD observations of PR Her

PR Her is a very poorly studied cataclysmic variable. At first PR Her was discovered as a dwarf nova S 4247 by Hoffmeister (1949, 1951) with a photographic range of 14.0 – >17.5 mag. He estimated 166 photo plates from 1939 to 1946 and discovered one outburst on the negative obtained on 20 – 24 September 1941. The star was not visible on other plates.

In 1999 Henden (vsnet-chat 1800) identified the object with a blue star of $\sim 21^m$.

To date we have little information about PR Her except for what is described by Kato et al. (2013), where only one paragraph was dedicated to this system. They noted that PR Her was observed in quiescence by amateurs, but it was to faint for small telescopes. So, it is very difficult to monitor this star.

PR Herculis bursted on November 21, 2011, reached $V = 12^m.84$ and was classified as a new WZ Sge-type system (Kato et al., 2013).

Our observations of PR Her were obtained at the South astronomical station of Moscow State University (MSU) with the CCD-camera Apogee-47a attached to the 0.6m Zeiss-reflector and at the Stara Lesna observatory of the Astronomical institute of SAV (a CCD-camera ST-10 mounted on the 0.5m reflector). We got ~1350 $UBVR_cI_c$ CCD frames from November 24 to December 10, 2011. In this paper we analyze the longest time series obtained in the B-, V- and R_c-bands of the Johnson-Cousins photometric system. Due to unfavorable sky location the observations of the total superoutburst were not carried out.

The star TYC 3102-02201 (R.A.=$18^h08^m08.4^s$; Dec.=$+38^o44'47''$, 2000.0) was used as the main standard for which we determined the following stellar magnitudes: $U = 12.^m95(2)$, $B = 11.^m996(8)$, $V = 10.^m687(4)$, $R_c =$

Table 1. Journal of observations in 2011.

Data	JD 24.....	Loc	U	B	V	R	I	exp, sec
Nov.24	55890	SL	4	48	52	50	13	45
Nov.24	55890	Na	62	24	24	51	12	10-15
Nov.25	55891	Na	19	25	52	72	22	12-15
Nov.26	55892	Na	4	4	4	4	4	25-40
Nov.27	55893	SL	7	18	73	21	2	75-90
Nov.28	55894	SL	5	28	105	42	3	60
Nov.29	55895	SL	1	3	15	3	1	90-120
Dec.03	55899	Na	6	3	53	65	6	45
Dec.04	55900	Na	13	6	71	38	4	45
Dec.09	55905	Na	12	5	74	57	3	45-60
Dec.10	55906	Na	-	-	30	32	-	60

"Loc" means a place of the observations: "Na" – observations in Nauchny; "SL" - observations in Stara Lesna, $UBVR_cI_c$ - the number of frames in each band. "exp, sec" gives mean exposure time in seconds for passbands V and R. On average, in the $B, I-$ passband the length of exposure is 1.5 – 2 times greater, and in the $U-$ passband it is 2 – 3 times greater than in the V, R passband.

$10.^m08(2)$, $I_c = 9.^m59(4)$. The $UBV-$ magnitudes of this star were obtained by I. Volkov using the method described in part by Kornilov et al.(1991), Volkov & Volkova (2009) and Volkov et al. (2010). We took eight stars in the frame-field as the check stars.

Journal of observations is given in Table 1.

3. Light curve analysis of PR Her

We present average per night magnitudes from our and AAVSO (American Association of Variable Stars Observers) observations in Fig. 1, where the B, V, R_c light curves (LCs) and color-indices $V - B$ and $V - R_c$ during the superoutburst (Nov 24 – Dec 10, 2011) are shown. This plot mainly illustrates, a general form of the light curve after the outburst – the plateau and the decline of brightness. Therefore, we did not share our and AAVSO data. But AAVSO outburst data were shifted so that the discrepancy between our data was minimal (close to $+0.^m1$ in the $V-$ passband). We suppose that such procedure is allowed and so we did not make any distinction between the two sets of data.

A form of all LCs is a smooth decreasing of the brightness of about 2 magnitudes in 16 days (a rate of decreasing 0.125 mag per day) with a small jump between JD 2455897 and ...900. These days "ordinary" superhumps replaced "early" superhumps (see the next paragraph). As noted above, it was impossible to observe the end of the superoutburst because of an unfavorable star location in the sky and bad weather. The color-index $V - R_c$ was practically constant, but the index $B - V$ increased slightly to $\sim 0^m.1$.

To estimate the duration of the outburst we added the values of brightness in two nights from the AAVSO database, when the star was not visible on the CCD frames (with a limit of about 17.3 mag). In the insert plot of Fig. 1 the LCs with these two points (triangles) are present. Using these two measurements we define the possible duration of the outburst as 20–30 days. This value is typical for superoutburts of WZ Sge-systems.

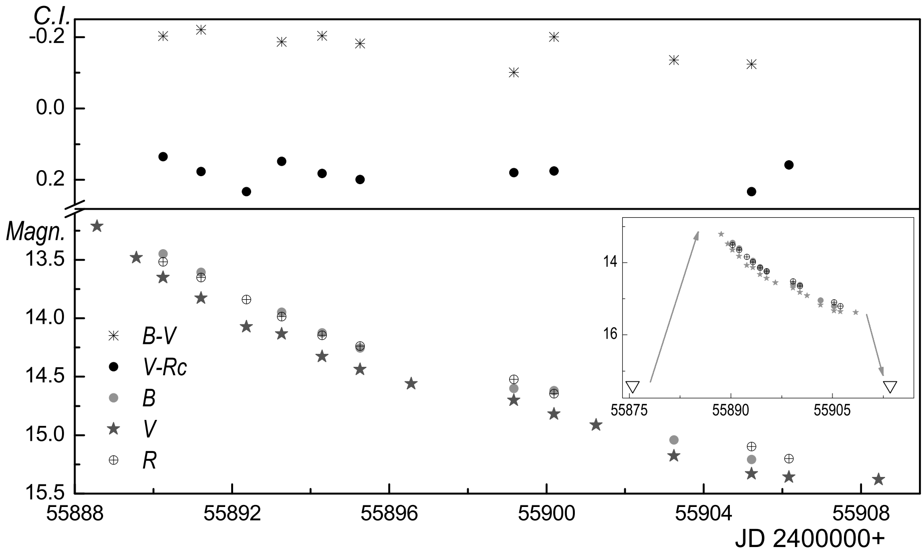

Figure 1. Bottom: The average per night B, V, R_c- magnitudes from AAVSO and our data. Triangles show the upper limit of magnitudes when the object was not registered. Top: Color-indices $B - V$ and $V - R_c$ during the superoutburst. Before JD 2455897 "early" superhump take place, later – "ordinary" superhumps. See also Fig. 2

4. The periodogram analysis

We used both our and AAVSO V, R_c data after removal of the declining trend to refine the photometric period. As a result, the average nightly magnitude varies around zero and the maxima of brightness confidently differed from the minima. At other bands (U, B, I_c) the time series were sparse, not so accurate, and for this reason were not used for the periodicity analysis.

"Early" superhumps with a small amplitude and the period close to the orbital one can be observed immediately after the beginning of the supeoutburst of WZ Sge-type stars (see, Kato, 2015 and paragraph 1 of our paper) and they are the trademark of these systems. Unfortunatelly, "early superhumps" are

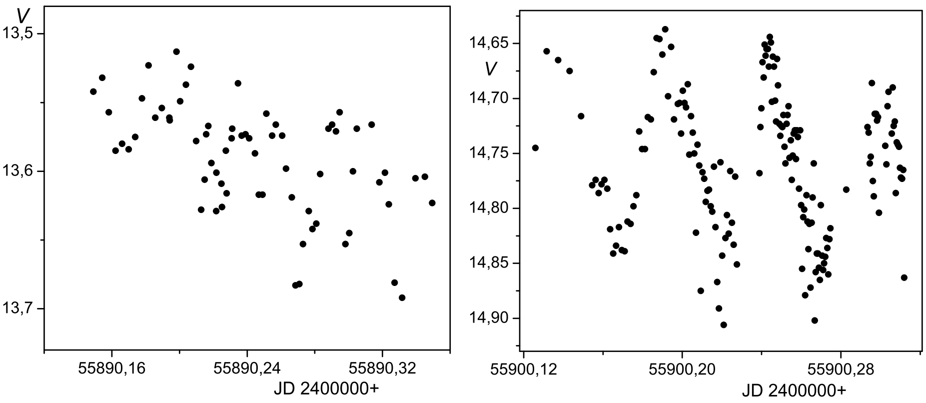

Figure 2. Fragments of individual LCs from our observations: "early" superhump (left) and "ordinary" superhumps (right).

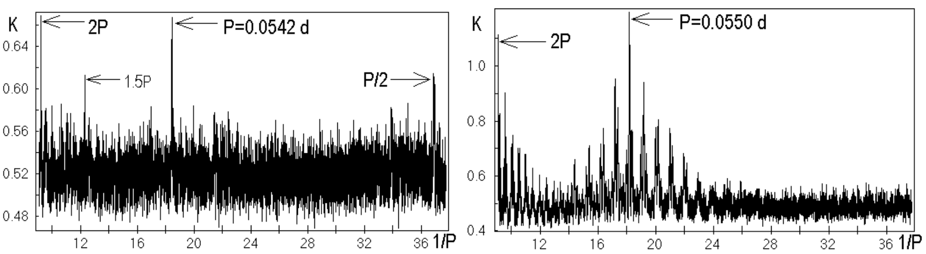

Figure 3. *Left* : Periodogram for the "early" superhump stage, JD 2455888–897. *Right* : The periodograms for the "ordinary" superhump stage, JD 2455899–906. The ordinate "K" is the inverse of the parameter θ, calculated by the Lafler-Kinman method (Lafler & Kinman, 1965). The periods of superhumps and some harmonics are marked by arrows.

not always observed due to a short time of their occurrence. Further, "ordinary superhumps" with a larger amplitude and period replace "early superhumps".

In Fig. 2 the light curves for JD 2455888 (left, "early" superhumps) and JD 2455899 (right, "ordinary" superhumps) are shown.

Because of a different character of variability (Kato, 2009, 2015 and Fig. 2) observed during the "early" and "ordinary" superhump stage, we divided out the data into two intervals and searched for the periods for each interval independently. The search for periodicities was made by the Lafler-Kinman method (1965). Periodograms are shown in Fig. 3 for the JD 2455888–897 (left) and JD 245899–908 (right) time intervals.

Note that "ordinary" superhumps appeared only on the $\sim 12^{th}$ day after the

Table 2. The $O - C$ residuals constructed with the help of eq. (2)

JD max	error	O-C, day	N	Data
55899.1482	0.0005	0.0000	0	OUR
55900.1370	0.0010	-0.0010	18	OUR
55900.1925	0.0010	-0.0005	19	OUR
55900.2438	0.0007	-0.0042	20	OUR+AAVSO
55900.2456	0.0006	-0.0024	20	Kato
55900.3020	0.0015	-0.0010	21	AAVSO
55900.3034	0.0006	+0.0004	21	Kato
55900.8507	0.0015	-0.0022	31	Kato
55900.9020	0.0021	-0.0059	32	Kato
55901.2905	0.0005	-0.0023	39	Kato
55901.2910	0.0015	-0.0018	39	AAVSO
55902.2771	0.0008	-0.0055	57	Kato
55905.1390	0.0020	-0.0031	109	OUR
55905.1940	0.0019	-0.0031	110	OUR
55905.2512	0.0004	-0.0009	111	Kato
55905.2515	0.0010	-0.0006	111	OUR+AAVSO
55905.3094	0.0011	+0.0023	112	Kato

"OUR" – our observations; "AAVSO" - observations from the AAVSO database; Kato - see Kato et.al. (2013); N is a cycle number.

outburst. This is unusual because normally the "early" superhump stage is very short and very often this stage cannot be caught by observers. However, there is known a WZ Sge-star whose "ordinary" superhumps began on the 30th day after the beginning of the superoutburst (PNV J18422792 + 4837425, Katysheva et al., 2013).

We found that the period of "early" superhumps is close to $0^d.0542$ (JD 2455888–55897) and that of "ordinary" superhumps – $0^d.0550$ (JD 2455899–55908). For a more precise determination of the periods of superhumps we constructed the graph $O - C$, using our moments of maximum brightness and supplemented them by additional maximums from of the AAVSO database. For the analysis the $O - C$ values taken from Kato et al. (2013) were also added. The calculated $O - C$ residuals are given in Table 2 and Fig. 4.

As a result, we got the following heliocentric ephemeris for "early" and "ordinary" superhumps, respectively:

$$JD_{max,ear} = 2455888.5778 + 0.05424(8) \cdot E, \quad (1)$$

$$JD_{max,ord} = 2455899.1482 + 0.054990(5) \cdot E. \quad (2)$$

On the $O - C$ diagram (see Fig. 4) we can see the linear increasing period of "ordinary" superhumps (a parabolic form of the $O - C$ curve). Using this diagram it is possible to either update the superhump period or find a time

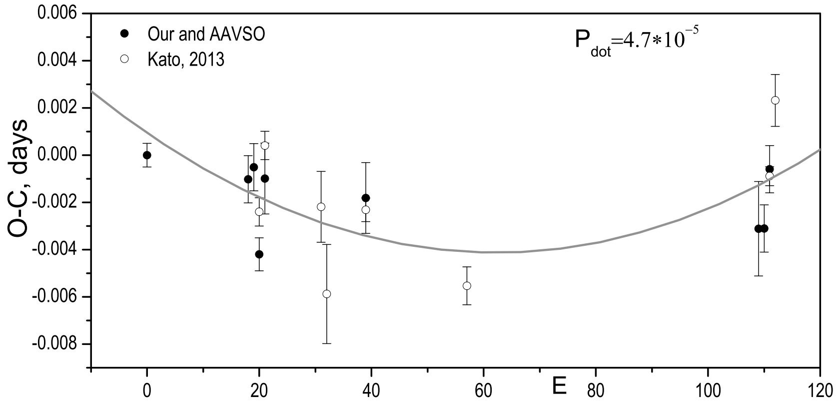

Figure 4. The $O-C$ graph. Filled circles – a combination of our and AAVSO observations; open circles – the data from Kato, 2013. The $O-C$ diagram was constructed employing eq. (2), as in Table 2.

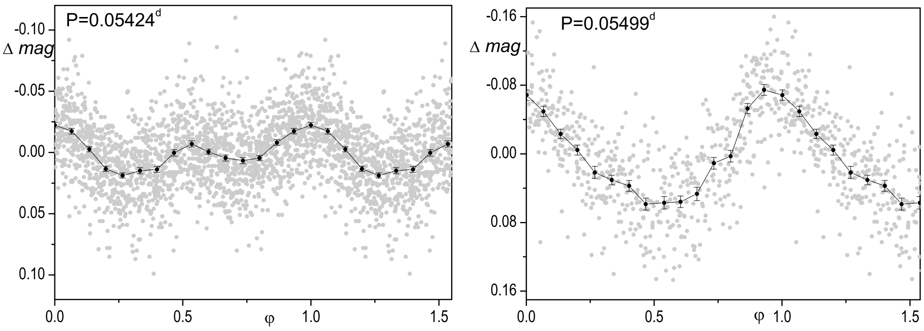

Figure 5. The light curves of PR Her, folded with the "early" (*left*) and "ordinary" (*right*) superhump periods. The scale of magnitudes is a combination of V and R_c observations, as described in the first paragraph of section 4. The gray circles are the individual observations, black ones – the average point and the value of errors.

dependence of the period. During superoutbursts of SU UMa- and WZ Sge-type stars superhump periods in many cases increase, but sometimes then decrease (see, Kato et al. 2009 ..... 2015). So, it is desirable to find the following value $P_{\rm dot} = \dot{P}/P$ which is very important for the study of SU UMa-stars. Kato et al. (2009) wrote "Since the superhump period, or its variation, is related to the radius of the accretion disk, or propagation of the eccentricity wave, the period variation is expected to provide diagnostics of the dynamics in the outbursting accretion disk".

Fig. 5 exhibits the light curves folded with the period of "early" (left) and "ordinary" (right) superhumps, according to ephemeris (1) and (2) for combined V and R_c observations. The light curve of the "early" superhump stage shows a double-wave with $P_{\rm ear} = 0^d.05424$. The amplitude of the light variation of "ordinary" superhumps reached $0^m.25$ in several days (see Fig. 2), while the "early" superhump's amplitudes were only $0^m.05$ (see Fig. 2 and Fig. 5).

As mentioned above for WZ Sge-stars $P_{\rm orb}{\sim}P_{\rm ear}$. The period excess, $\varepsilon = 1 - P_{\rm orb}/P_{\rm sh} = 0.014$. This value is typical for the WZ Sge- and SU UMa-stars (Kato et al., 2009; Kato, 2015).

We calculated also the period derivative of superhumps $P_{\rm dot}$ ("Pdot") as:

$$P_{\rm dot} = \dot{P}/P{\sim}4.7(\pm1.8)\cdot10^{-5}. \qquad (3)$$

Kato et al. (2013) gave $P_{\rm dot}{\sim}8.8(\pm3.7){\cdot}10^{-5}$ for PR Her. We believe that our value of "Pdot" is more accurate because we used twice the number of extrema over a larger time interval. We also included data from Kato et al. (2013) for the $O-C$ analysis.

Another alternative analysis of the $O-C$ plot implies a straight line in Fig. 4, i.e., the acceptance of proposal about a constant superhump period. Such a conclusion cannot be completely excluded; however, squared residuals (SR) of the approximating curve in the case of a parabolic approximation are slightly smaller than in the case of a straight line (SR=0.0018 or SR=0.0022, respectively). Furthermore, our "Pdot" and "Pdot" from Kato et al. (2013), taking into account the measurement errors, essentially do not contradict each other. This value shows the period derivative during the "ordinary" superhump stage. For the majority of WZ Sge and SU UMa-stars the value of $P_{\rm dot}$ varies from 1 to 15×10^{-5} (See Kato, 2015, Kato, et al., 2009, 2010, 2012, 2013, 2014, 2014a, 2015). So, this parameter for PR Her is typical one.

According to Kato et al. (2009, page 37, eq. 5) we estimated the mass ratio $q = M_2/M_1 = 0.08$.

5. Positions of PR Her on the $B-V$, $V-R_c$ diagram.

The two-color diagram $B-V$, $V-R_c$ is shown in Fig. 6. The temperature markers are located along the blackbody curve and the spectral classes' markers along the main sequence curve.

The track of PR Her on this diagram is illustrated by closed black circles. The position corresponding to the beginning of our multi-color observations (JD 2454890) is marked "890", and "905" refers to our last observations (JD 2454905). The positions of surrounding stars (our standard star and check stars) are labeled by asterisks. It is obvious that nearby stars have no significant interstellar absorption and lie along the main sequence curve.

Given the galactic latitude of PR Her $b = 25^o$ we conclude that the star is far from the dust matter in the galactic plane. On these galactic latitudes and far from the center of Galaxy ($l = 65^o$) the interstellar extinction $E(B-V)$ is

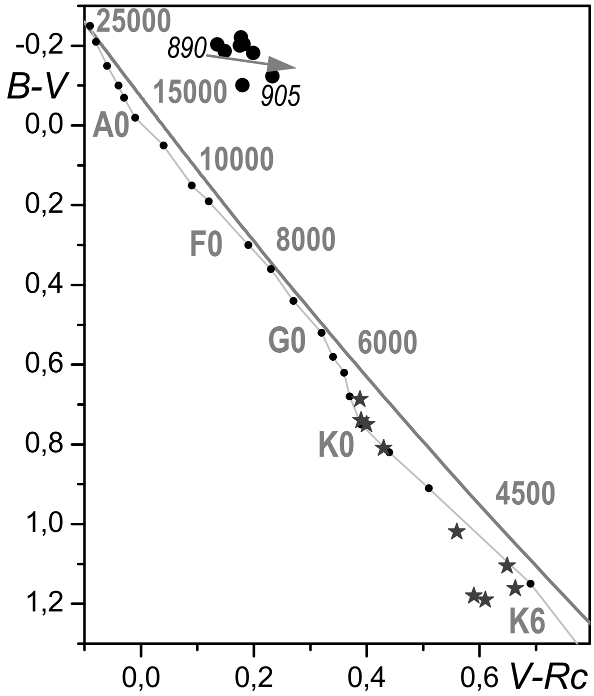

Figure 6. A two–color diagram. The main sequence and blackbody curves are shown. The position of PR Her on the diagram is illustrated by black circles. The arrow shows the direction of motion of the star position during the superoutburst.

less than $0^m.10 - 0^m.15$. So, we neglected interstellar reddening for our values of the average color temperature.

It is seen that the total color temperature of all emitting components decreases slightly during the outburst: on the $B-V, V-R$ diagram the star shifted right and down. The main sources of emission of CVs are the accretion disk and the region of collision of the stream and the disk. Total radiation is neither stellar nor blackbody (Shakura & Sunyaev, 1973). But a blackbody approximation is acceptable as an initial one.

We estimated the color temperature of PR Her to be $\sim$ 15000 K, with a "blue" excess . Similar temperatures during superoutbursts were found for PNV J19150199 + 0719471 (Golysheva & Shugarov, 2014), CSS130418: 174033.5 + 414756 in Hercules (Chochol et al., 2015), OT J213806.6 + 261957 (Chochol et al., 2012), 12000 – 13000 K for V466 And (Chochol et al., 2010) and for OT J023839.1 + 355648 (Chochol et al., 2009).

Note that the $U-B, B-V$ diagrams of twenty classical novae are given by Hachisu & Kato (2014). The positions of novae after outbursts at a stage of the expanding shell on these plots are similar to the positions of the dwarf novae, including PR Her. Warner (1995, eq. 3.8) found that there was a "color-orbital period" relationship for CVs. For these reasons, the study of two-color diagrams is very actual for the search for different relations.

6. Conclding remarks

PR Her is a poorly studied WZ Sge-type star.

We confirmed the values of the periods found by Kato et al. (2013) and refined the value of $P_{\rm dot} = 4.7(\pm1.8)\cdot10^{-5}$, determined the duration of the superoutburst (20–30 days) and the color indices. There is a "blue" excess of radiation, which is caused, as usual for outburst CVs, by the radiation from the the hot accretion disk around the white dwarf.

Duration of the outburst, its amplitude, the rate of brightness fading and the period excess ε are typical for such dNe.

The long manifestation of "early" superhumps and the absence of a clear plateau at the light curve distinguish PR Her from other WZ Sge-type stars.

Our last observations of PR Her were made on the November 5, 2015, with the 1.25-m telescopes and a VersArray-1300 CCD-camera. The brightness of the system, reduced to the photometric R_c-passband, was about $21^m \pm 0^m.4$. This is an insufficient accuracy for the analysis of light variations. So, PR Her is very weak in quiescence, and it is necessary to use large telescopes to study the star.

We believe that it is very important to search for previous outbursts on old negatives of photo archives of different observatories, to get new observations in quiescence with large telescopes.

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