

OT J075418.7+381225 and OT J230425.8+062546: Promising candidates for the period bouncer

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Abstract

We report on photometric observations of two dwarf novae, OT J075418.7+381225 and OT J230425.8+062546, which showed superoutbursts in 2013 (OT J075418) and in 2011 (OT J230425). Their mean periods of the superhump were 0.0722403(26) d (OT J075418) and 0.067317(35) d (OT J230425). These objects showed a very long growth stage of the superhump (stage A) and a large period decrease in the stage A–B transition. The long stage A suggests slow evolution of the superhump due to the very small mass ratio of these objects. The declining rates during the plateau phase in the superoutburst of these objects were lower than those of SU UMa-type dwarf novae (DNe) with a similar

superhump period. These properties were similar to those of SSS J122221.7–311523, the most likely candidate for the period bouncer. Therefore, these two DNe are regarded as likely candidates for the period bouncer. We estimated the number density of period bouncers roughly from our observations for the last five years. There is a possibility that these WZ Sge-type DNe with unusual outburst properties might account for the missing population of the period bouncer suggested by the evolutionary scenario.

Key words: accretion, accretion disks — novae, cataclysmic variables — stars: dwarf novae — stars: individual (OT J075418.7+381225, OT J230425.8+062546)

1 Introduction

Cataclysmic variables (CVs) are binary star systems composed of a primary (white dwarf) and a secondary which is a typical late-type main sequence star. The secondary fills its Roche lobe and its matter spills over into the primary from the inner Lagrangian point (L_1 point).

Dwarf novae (DNe) are a subtype of CV. DNe show recurring outbursts. The outburst lasts days or weeks, for which their brightness increases by 2 to 5 mag. The outburst results from a release of gravitational energy which is caused by a sudden increase of the mass accretion rate by the thermal instability in the disk.

SUUMa-type dwarf novae are a subtype of DN. They have a relatively short orbital period (1–2 hr, near to the period minimum) and occasional “superoutbursts” that are brighter and have a longer duration than normal outbursts. The superhump is believed to result from the tidal instability that is triggered when the disk radius reaches the critical radius for the 3:1 resonance (Osaki 1989). WZ Sge-type DNe are a subgroup of SUUMa-type DN. They have a particularly short orbital period and show infrequent large-amplitude superoutbursts (for general properties of WZ Sge-type DN, see, e.g., Bailey 1979; Downes 1990; Kato et al. 2001). During the superoutburst, superhumps, periodic light variations whose periods are a few percent shorter than the orbital period, are seen. The superhump periods vary through a course of three stages: the first is stage A with a longer superhump period, the middle is stage B with a systematically varying period, and the final is stage C with a shorter superhump period (Kato et al. 2009).

According to the standard evolutionary theory of CV, the mass transfer from the secondary starts when the secondary fills its Roche lobe. The orbital period, P_{orb} , is longer when a CV is formed, and the system develops with P_{orb} becoming shorter. Once its P_{orb} reaches the period minimum, the secondary becomes oversized for its mass as a result of deviation from thermal equilibrium or becomes a brown dwarf which cannot exist in hydrogen burning. After this point, the system evolves into a longer period

and it is usually called a “period bouncer” (see, e.g., Knigge et al. 2011 and references therein, for the standard evolutionary theory of CV).

The study about the period bouncer ought to play a vital role in resolving the problems about the terminal evolution of CVs, since Kolb (1993) is said to have estimated that 70% of CVs should have passed the period bounce. The candidates for the period bouncer, however, have hardly been discovered. One of the reasons is that CVs become much fainter as they approach the period minimum (Patterson 2011). Littlefair et al. (2006) also made a great impact on the problem about the missing population in the CV. They confirmed that the secondary in the eclipsing short-period CV Sloan Digital Sky Survey (SDSS) 103533.03+055158.4 was a brown dwarf, which suggests that the system is a period bouncer. Recently, Littlefair et al. (2008) discovered three more systems which have a brown dwarf secondary with high-speed three-color photometry. Through photometric research in the period bouncer, until recently, WZ Sge-type DNe with multiple rebrightenings such as EG Cnc have been considered to be likely candidates for the period bouncer (Patterson et al. 1998). Recently, Kato and Osaki (2013) succeeded in interpreting the variation of the superhump period around stage A and developed a new dynamical method of estimating the binary’s mass ratio ($q \equiv M_2/M_1$) from the stage A superhump observations and the orbital period only. By using this new method, it became evident that many of WZ Sge-type DNe with multiple rebrightenings are not likely to have such a low mass ratio as was estimated in EG Cnc (Nakata et al. 2013). After this suggestion, a new candidate for the period bouncer was discovered; Kato et al. (2013b) reported that SSS J122221.7–311523 (hereafter SSS J122221), a transient discovered by Catalina Real-time Transient Survey (CRTS: Drake et al. 2009) Siding Spring Survey (SSS), had a very small mass ratio $q = 0.045$ and a long orbital period [a possible period of 0.075879(1) d]. They also revealed a characteristic property of SSS J122221 that stage A superhumps lasted a long time.

In this paper, we present the two DNe which are similar in property to SSS J122221. OT J075418.7+381225

Table 1. Log of observations of OT J075418.

Start*	End*	Mag [†]	Error [‡]	N [§]	Obs	Sys [#]
25.2913	25.4934	15.947	0.003	229	deM	C
26.2986	26.6882	16.191	0.010	489	deM	C
27.2431	27.6752	15.120	0.003	433	MEV	C
27.2980	27.6668	14.983	0.003	460	deM	C
27.6840	27.9237	14.944	0.003	286	GFB	C
28.2990	28.6527	14.923	0.001	441	deM	C
28.5383	28.7812	14.988	0.002	290	DKS	C
28.7016	28.9420	14.884	0.001	585	SWI	V
29.2968	29.6605	14.969	0.001	514	deM	C
29.6677	29.8488	15.019	0.002	200	GFB	C
29.7057	29.9564	14.881	0.001	609	SWI	V
30.2980	30.6371	15.005	0.001	500	deM	C
30.7285	30.9638	14.909	0.001	572	SWI	V
31.3028	31.6423	15.050	0.001	502	deM	C
31.7016	31.9142	14.968	0.001	364	SWI	V
32.3015	32.6886	15.105	0.001	608	deM	C
32.3054	32.6595	15.138	0.001	355	MEV	C
33.3011	33.6583	15.175	0.001	354	MEV	C
36.5681	36.5681	15.180	—	1	MUY	C
36.6996	36.9058	1.169	0.001	353	SWI	C
36.6996	36.9058	15.198	0.001	353	SWI	V
37.6966	37.8978	1.166	0.001	345	SWI	C
38.3036	38.6830	15.270	0.001	468	CDZ	C
39.3021	39.5805	15.299	0.002	308	CDZ	C
39.3564	39.6420	15.347	0.001	256	MEV	C
40.3004	40.6396	15.386	0.002	251	MEV	C
40.3940	40.6534	15.346	0.002	293	CDZ	C
46.3199	46.4654	15.350	0.003	148	MEV	C
47.4372	47.6331	15.362	0.002	207	deM	C
48.4312	48.6151	15.415	0.002	232	deM	C
49.4269	49.6170	15.449	0.003	212	deM	C
50.4413	50.5910	15.499	0.002	182	deM	C
52.2781	52.5203	2.233	0.005	281	DPV	C
53.3085	53.5875	15.658	0.002	354	deM	C
54.2581	54.4964	2.554	0.003	300	DPV	C
54.3650	54.6011	15.740	0.002	184	MEV	C
56.2530	56.5597	2.655	0.002	386	DPV	C
57.2314	57.5306	2.781	0.002	360	DPV	C

*BJD–2456300.0.

[†]Mean magnitude.[‡]1 σ of the mean magnitude.[§]Number of observations.^{||}Observer's code: deM (E. de Miguel), MEV (E. Morelle), GFB (W. N. Goff), DKS (S. Dvorak), SWI (W. Stein), MUY (E. Muylleert), CDZ (AAVSO data), and DPV (P. A. Dubovsky).[#]Filter. "V" means V filter and "C" means no filter (clear).**Table 2.** Log of observations of OT J230425.

Start*	End*	Mag [†]	Error [‡]	N [§]	Obs	Sys [#]
63.9532	64.0147	13.775	0.005	130	Siz	C
65.8770	65.9577	14.149	0.004	146	Mhh	C
65.8827	65.9319	13.683	0.005	107	Ioh	C
65.8902	66.0023	13.783	0.002	224	Siz	C
67.8853	68.0198	13.871	0.005	264	Siz	C
68.8860	69.0162	13.876	0.004	259	Siz	C
68.9449	69.0041	13.887	0.008	132	Ioh	C
68.9769	68.9841	14.259	0.019	16	Mhh	C
69.8702	70.0000	13.879	0.006	280	Ioh	C
69.8802	69.9934	14.217	0.004	424	Mhh	C
69.8892	70.0194	13.918	0.007	231	Siz	C
70.8707	71.0046	13.908	0.007	268	Ioh	C
71.8613	71.9994	13.851	0.005	292	Ioh	C
71.8624	72.0124	13.848	0.006	299	Siz	C
72.1643	72.2480	14.044	0.022	29	CRI	C
73.1712	73.2678	13.813	0.008	47	CRI	C
73.9053	73.9859	14.018	0.016	132	Ioh	C
73.9302	74.0088	14.028	0.016	120	Siz	C
74.8823	74.9998	13.951	0.009	236	Siz	C
75.1832	75.2627	13.920	0.012	26	CRI	C
75.8838	75.9353	14.272	0.009	182	Mhh	C
75.9042	75.9720	13.962	0.006	134	Siz	C
78.8920	78.9520	14.094	0.007	122	Siz	C
78.9242	78.9722	14.508	0.008	182	Mhh	C
79.9057	79.9786	14.275	0.015	120	Siz	C
80.8940	80.9777	14.449	0.022	166	Siz	C
80.9083	80.9452	14.588	0.009	136	Mhh	C
83.8728	83.9645	14.549	0.016	158	Ioh	C
86.9111	86.9111	17.401	—	1	Siz	C

*BJD–2455500.0.

[†]Mean magnitude.[‡]1 σ of the mean magnitude.[§]Number of observations.^{||}Observer's code: Siz (K. Shiokawa), Mhh (H. Maehara), Ioh (H. Itoh), and CRI (Crimean Astrophys. Obs.).[#]Filter. "C" means no filter (clear).

(hereafter OTJ075418) was detected by CRTS to be CSS 130131:075419+381225 on 2013 January 31. The quiescent counterpart was $g=22.8$ mag SDSS J075418.72+381225.2. The observed superhumps with a period of 0.07 d suggested an SUUMa-type dwarf nova (vsnet-alert 15355). OT J230425.8+062546 (hereafter OTJ230425) was originally reported that it

was discovered to be a possible nova by H. Nishimura on 2010 December 29 at 13.7 mag (Nakano et al. 2011). The quiescent counterpart was $g=21.1$ mag SDSS J230425.88+062545.6. After that, it was suggested that the nova was a dwarf nova on the basis of the color of the SDSS counterpart (vsnet-alert 12548). From subsequent observations the presence of superhumps with an amplitude of 0.06 mag was detected (A. Arai, vsnet-alert 12563). Although observations and analysis of OT J230425 were already reported in a summary form in Kato et al. (2012), we present a new interpretation of this object in this paper.

This paper is structured as follows. Section 2 briefly shows a log of observations and our analysis method. Sections 3 and 4 deal with the results of the observations of OT J075418 and OT J230425, respectively. In section 5 we discuss the results.

2 Observation and analysis

Tables 1 and 2 show the logs of photometric observations. All the observation times were written in barycentric Julian date (BJD). To correct zero-point of data differences between different observers, we added a constant to each observer's data.

The phase dispersion minimization (PDM) method (Stellingwerf 1978) was used for a period analysis. In subtracting the global trend of the light curve, we subtracted a

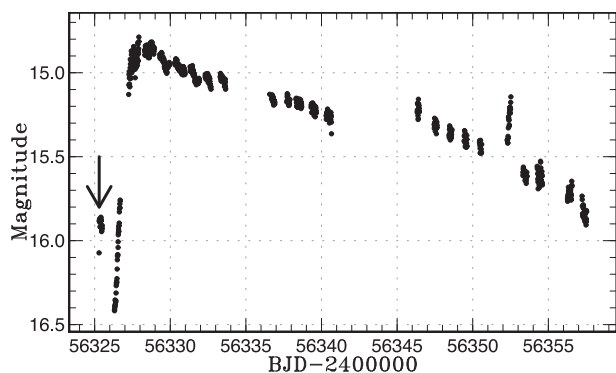


Fig. 1. Overall light curve of OT J075418. The data were binned to 0.01 d. The arrow indicates a precursor.

smoothed light curve obtained by locally weighted polynomial regression (LOWESS: Cleveland 1979) before making the PDM analysis. The 1σ error of the best estimated period by the PDM analysis was determined by the methods in Fernie (1989) and Kato et al. (2010).

A variety of bootstraps was used for estimating the robustness of the result of PDM. We analyzed about 100 samples which randomly contained 50% of observations, and performed a PDM analysis for these samples. The result of the bootstrap is shown as a form of 90% confidence intervals in the resultant θ statistics.

3 OT J075418.7+381225

3.1 Overall light curve

In figure 1 is shown the overall light curve of OT J075418. After a precursor outburst (marked with an arrow in figure 1), the superoutburst began on BJD 2456326. The early rise was well observed during BJD 2456326–2456327. The superoutburst lasted with a slow decline for at least 30 d. In the middle part of the superoutburst (BJD 2456341–2456345), there were no observations. On BJD 2456346, observations were resumed, and they showed

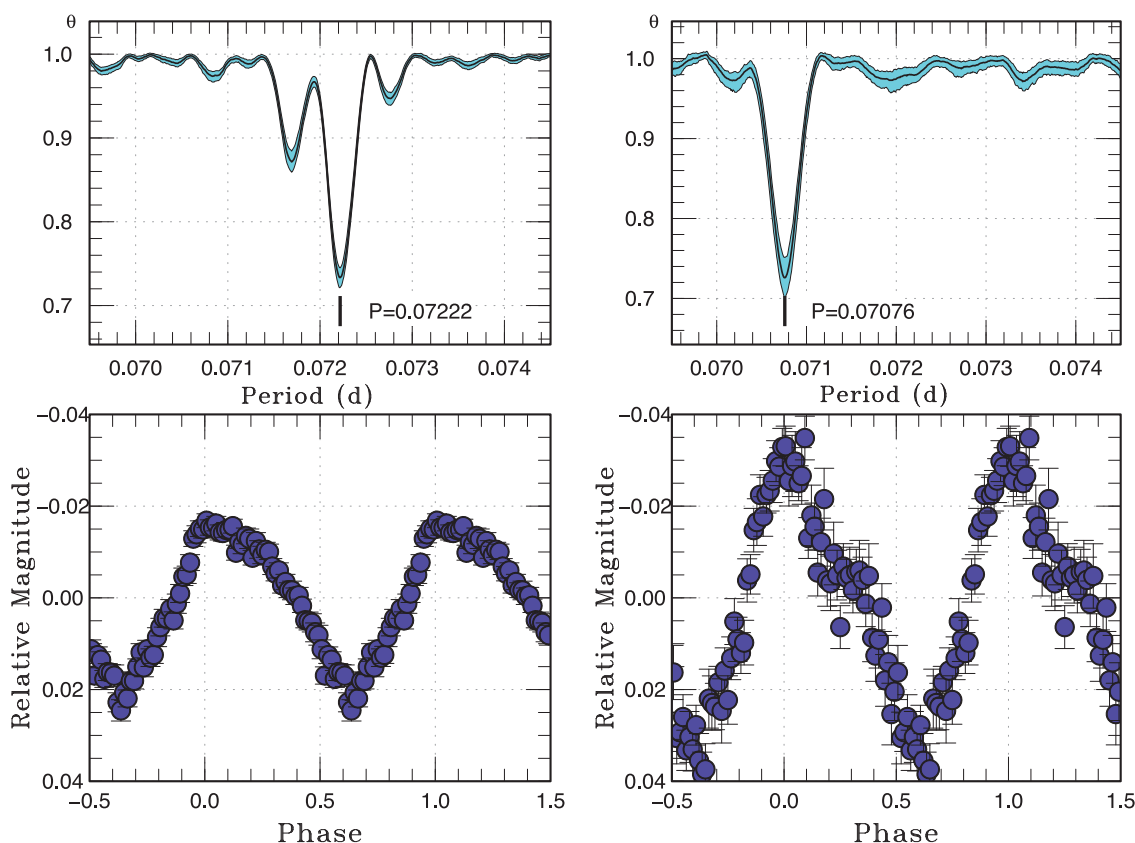


Fig. 2. Superhumps in OT J075418 (BJD 2456328–2456358). Left-hand upper: θ diagram of our PDM analysis of stage A superhumps (BJD 2456328–2456341). Left-hand lower: Phase-averaged profile of stage A superhumps. Right-hand upper: θ diagram of our PDM analysis of stage B superhumps (BJD 2456345–2456355). Right-hand lower: Phase-averaged profile of stage B superhumps. (Color online)

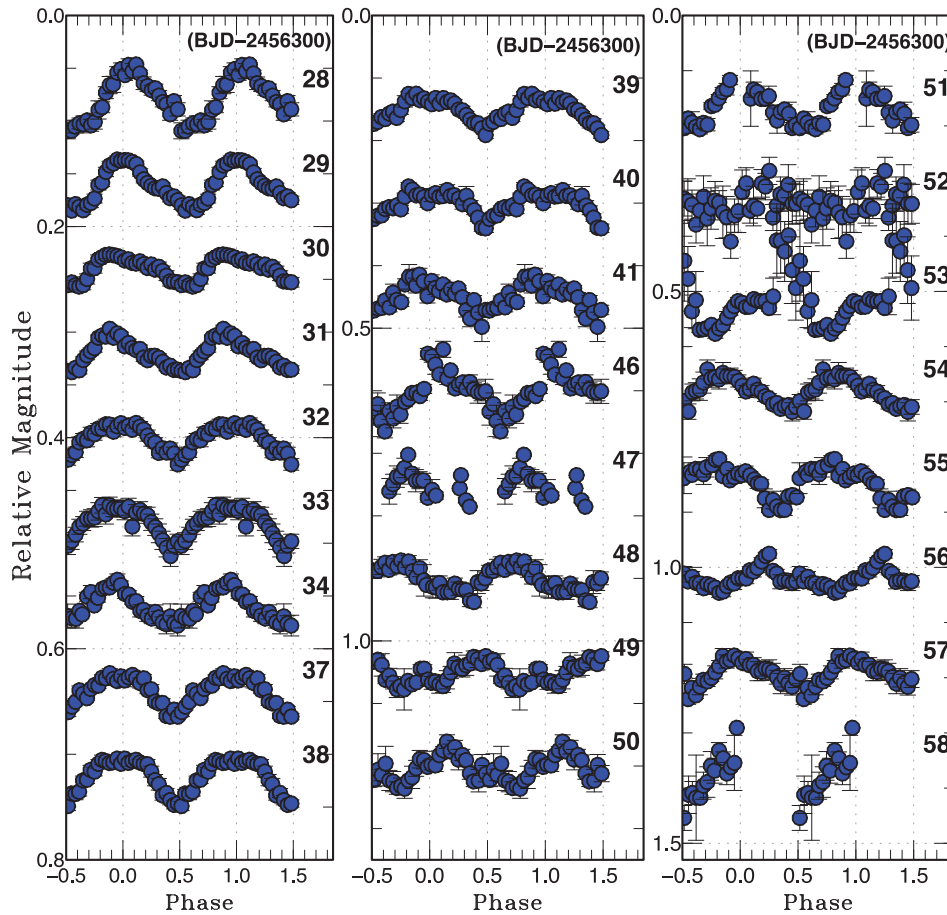


Fig. 3. Nightly variation of the profile of superhumps in OT J075418. (Color online)

a small rise in brightness. On BJD 2456352, there was a rapid brightening. This phenomenon was confirmed by using different comparison stars. It may have been the interesting phenomenon that we could not explain theoretically. However, it may have been an artifact, because the observing condition was very bad due to clouds and the Moon.

3.2 Superhumps

In figure 2, a period analysis by using the Phase Dispersion Minimization method (PDM: Stellingwerf 1978) indicated the presence of periods of 0.072218(3) d during stage A (BJD 2456328–2456341) and 0.070758(6) d during stage B (BJD 2456345–2456355). The mean profiles of stage A and stage B superhumps are also shown in the lower panels of figure 2. The amplitude of the superhumps during stage B is larger than that during stage A.

In figure 3 is shown the nightly variation of the profile of superhumps. The amplitude of superhumps was 0.03–0.06 mag, smaller than those in typical SUUMa-type DNe.

We determined the times of maxima of ordinary superhumps in the same way as in Kato et al. (2009). The resultant times are listed in table 3.

The O–C curve of OT J075418 is shown in figure 4. The very long stage A ($30 \leq E \leq 220$) and stage B ($E \geq 280$) are seen. Although the data when the stage A–B transition took place cannot be estimated precisely because of lack of observations, it occurred between BJD 2456342 and 2456346. In stage A, superhumps with a mean period of $P_{\text{sh}} = 0.0722179(32)$ d and the time derivative of the superhump period $P_{\text{dot}} (= \dot{P}/P) = +3.6(0.7) \times 10^{-5} \text{ s s}^{-1}$ were recorded. In stage B, superhumps with a mean period of 0.0707581(58) d and P_{dot} of $-2.4(0.5) \times 10^{-5} \text{ s s}^{-1}$ were recorded.

3.3 Two-dimensional Lasso analysis

The least absolute shrinkage and selection operator (Lasso) method was introduced by Kato and Uemura (2012). This method has been proven very effective in separating closely spaced periods and has been extended

Table 3. Times of superhump maxima in OT J075418.

<i>E</i>	Max*	Error	$O - C^\dagger$	$N^\ddagger$
0	56325.4119	0.0040	-0.0295	65
13	56326.3502	0.0065	-0.0224	72
14	56326.4264	0.0018	-0.0179	73
15	56326.4975	0.0013	-0.0184	71
16	56326.5656	0.0019	-0.0219	72
17	56326.6432	0.0020	-0.0160	74
26	56327.2791	0.0005	-0.0249	64
27	56327.3527	0.0005	-0.0229	136
28	56327.4234	0.0004	-0.0238	138
29	56327.4965	0.0008	-0.0224	125
30	56327.5678	0.0004	-0.0227	106
31	56327.6370	0.0005	-0.0251	139
32	56327.7092	0.0004	-0.0246	62
33	56327.7832	0.0010	-0.0222	64
34	56327.8537	0.0007	-0.0233	71
35	56327.9219	0.0023	-0.0268	44
41	56328.3564	0.0007	-0.0221	73
42	56328.4308	0.0007	-0.0193	73
43	56328.4955	0.0009	-0.0263	71
44	56328.5700	0.0008	-0.0234	138
45	56328.6443	0.0011	-0.0208	123
46	56328.7130	0.0010	-0.0236	157
47	56328.7840	0.0005	-0.0243	178
48	56328.8524	0.0006	-0.0275	141
49	56328.9284	0.0010	-0.0232	115
55	56329.3637	0.0029	-0.0177	87
56	56329.4315	0.0012	-0.0216	83
57	56329.5031	0.0023	-0.0215	82
58	56329.5719	0.0013	-0.0244	83
59	56329.6463	0.0016	-0.0216	61
60	56329.7189	0.0007	-0.0207	158
61	56329.7986	0.0014	-0.0126	198
62	56329.8692	0.0013	-0.0137	157
63	56329.9355	0.0017	-0.0190	133
69	56330.3692	0.0015	-0.0151	85
70	56330.4385	0.0011	-0.0174	84
71	56330.5183	0.0014	-0.0092	86
72	56330.5836	0.0010	-0.0156	89
74	56330.7380	0.0024	-0.0045	78
75	56330.8028	0.0009	-0.0113	140
76	56330.8767	0.0007	-0.0091	141
77	56330.9376	0.0011	-0.0198	141
83	56331.3822	0.0019	-0.0050	80
84	56331.4572	0.0011	-0.0017	77
85	56331.5234	0.0014	-0.0071	95
86	56331.5895	0.0028	-0.0126	94
88	56331.7528	0.0020	0.0074	99
89	56331.8094	0.0018	-0.0077	99
90	56331.8869	0.0022	-0.0018	99
97	56332.4002	0.0027	0.0100	158
97	56332.4002	0.0027	0.0100	158
98	56332.4612	0.0018	-0.0006	145
99	56332.5408	0.0021	0.0074	154
100	56332.6046	0.0018	-0.0004	152

Table 3. (Continued)

<i>E</i>	Max*	Error	$O - C^\dagger$	$N^\ddagger$
101	56332.6660	0.0058	-0.0107	127
110	56333.3244	0.0012	0.0030	45
111	56333.3999	0.0008	0.0068	59
112	56333.4755	0.0022	0.0108	61
113	56333.5443	0.0027	0.0080	54
114	56333.6192	0.0008	0.0112	61
157	56336.7342	0.0008	0.0459	188
158	56336.7965	0.0006	0.0365	198
159	56336.8676	0.0013	0.0359	196
171	56337.7416	0.0011	0.0504	99
172	56337.8029	0.0012	0.0400	99
179	56338.3237	0.0015	0.0593	51
180	56338.3865	0.0013	0.0505	71
181	56338.4648	0.0013	0.0572	70
182	56338.5365	0.0010	0.0572	71
183	56338.6070	0.0018	0.0561	72
193	56339.3314	0.0025	0.0641	74
194	56339.4109	0.0011	0.0720	73
195	56339.4686	0.0017	0.0580	131
196	56339.5543	0.0045	0.0721	136
197	56339.6130	0.0009	0.0592	69
207	56340.3481	0.0020	0.0779	55
208	56340.4063	0.0029	0.0645	91
209	56340.4856	0.0013	0.0722	123
210	56340.5570	0.0020	0.0719	89
211	56340.6249	0.0013	0.0681	91
291	56346.3452	0.0008	0.0575	47
292	56346.4170	0.0007	0.0576	56
307	56347.4816	0.0011	0.0478	50
308	56347.5504	0.0015	0.0449	61
309	56347.6214	0.0020	0.0442	49
321	56348.4747	0.0011	0.0379	71
322	56348.5453	0.0018	0.0368	70
335	56349.4669	0.0012	0.0272	70
336	56349.5385	0.0013	0.0272	46
337	56349.6049	0.0017	0.0220	59
376	56352.3683	0.0014	-0.0085	70
390	56353.3551	0.0011	-0.0246	72
391	56353.4255	0.0011	-0.0258	70
392	56353.4981	0.0012	-0.0249	72
393	56353.5691	0.0010	-0.0256	63
404	56354.3470	0.0012	-0.0357	74
405	56354.4204	0.0021	-0.0339	99
406	56354.4874	0.0009	-0.0385	105
407	56354.5571	0.0010	-0.0404	55
432	56356.3251	0.0020	-0.0633	71
433	56356.3984	0.0031	-0.0617	72
434	56356.4674	0.0014	-0.0643	70
435	56356.5428	0.0012	-0.0606	61
446	56357.3150	0.0016	-0.0764	67
447	56357.3838	0.0018	-0.0793	67
448	56357.4591	0.0013	-0.0756	70

*BJD-2400000.0.

 $^\dagger C = 2456325.4414 + 0.0716368 E$. ‡ Number of points used for determining the maximum.

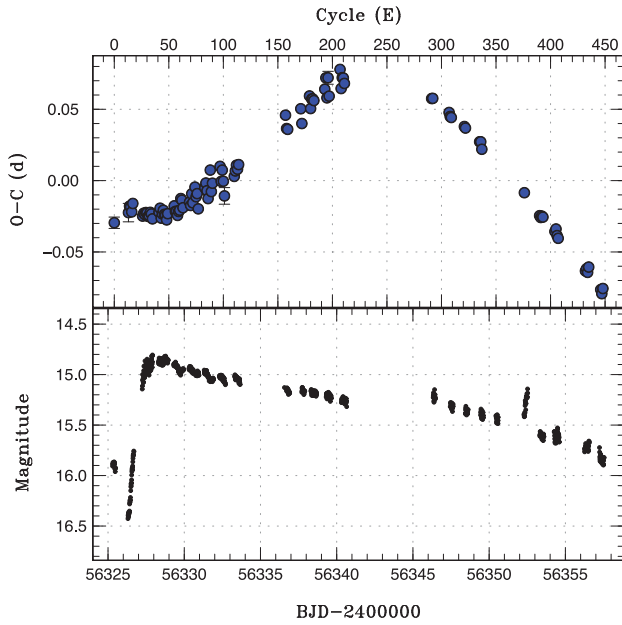


Fig. 4. Upper: The $O-C$ curve of OT J075418. An ephemeris of $\text{BJD } 2456325.4414 + 0.0716368E$ was used for drawing this figure. Lower: Overall light curve, the same as figure 1. The horizontal axis in units of BJD and cycle number is common to both of upper and lower panels. (Color online)

to two-dimensional power spectra (Osaki & Kato 2013; Kato & Maehara 2013).

A two-dimensional Lasso analysis of OT J075418 data is shown in figure 5. A major change in frequency from ~ 13.85 cycles/day (c/d) to ~ 14.1 c/d can be seen between BJD 2456341 and 2456345. It suggests that the change took place with good timing when the stage A–B transition occurred. During stage A (BJD 2456328–2456341), the frequency becomes lower. In contrast, it shows a tendency to become higher in stage B (BJD 2456345–2456355).

4 OT J230425.8+062546

4.1 Overall light curve

In figure 6 is shown the overall light curve of OT J230425. This object was discovered on 2010 December 29 (JD 2455559) with a recordable possible maximum brightness of $V = 13.72$. The early rise was missed. The superoutburst lasted ~ 25 d. The light curve showed a slow decline until BJD 2455575. After BJD 2455578, it declined faster.

4.2 Superhumps

During BJD 2455563–2455585, superhumps with an amplitude of 0.03–0.07 mag were present. A period analysis by using all the data indicated that the mean superhump period was 0.067317(35) d. The PDM analysis of all superhumps was described in Kato et al. (2012).

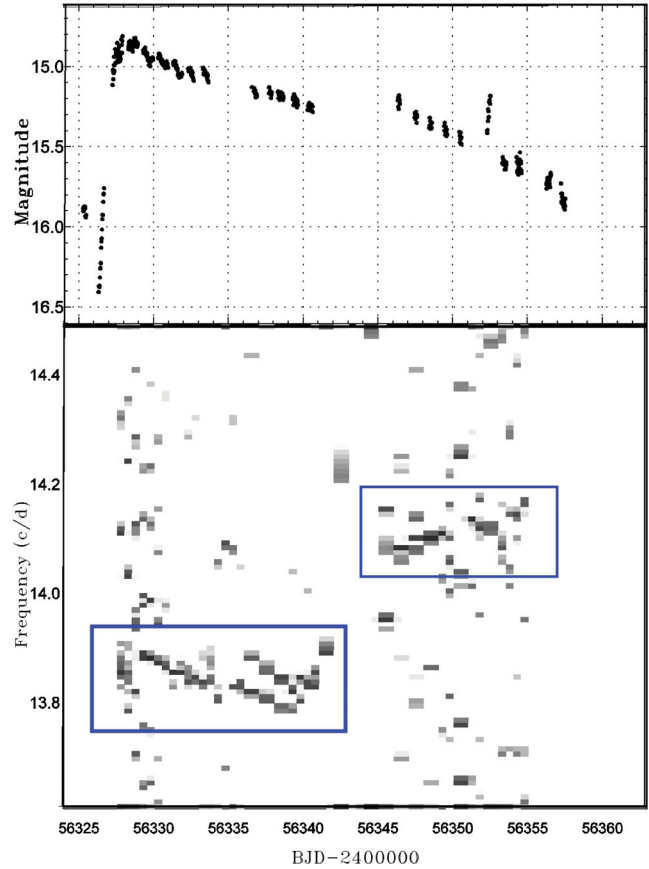


Fig. 5. Two-dimensional Lasso period analysis of OT J075418. Upper: Overall light curve binned to 0.01 d, the same as figure 1. Lower: Result of two-dimensional Lasso analysis (5 d window, 0.5 d shift, and $\log \lambda = -8.5$). The appearances of the stage A and stage B frequencies are boxed. (Color online)

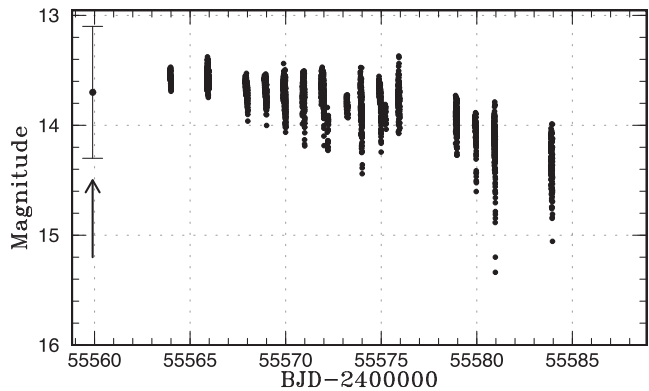


Fig. 6. Overall light curve of OT J230425. The data were binned to 0.01 d. The arrow indicates the discovery of the superoutburst (Nakano et al. 2011).

A period analysis indicated a change in period from 0.067245(17) d during stage A (BJD 2455563–2455572) to 0.066351(12) d during stage B (BJD 2455571–2455585) (figure 7). The mean profiles of stage A and stage B superhumps are also shown in the lower panels of figure 7. In

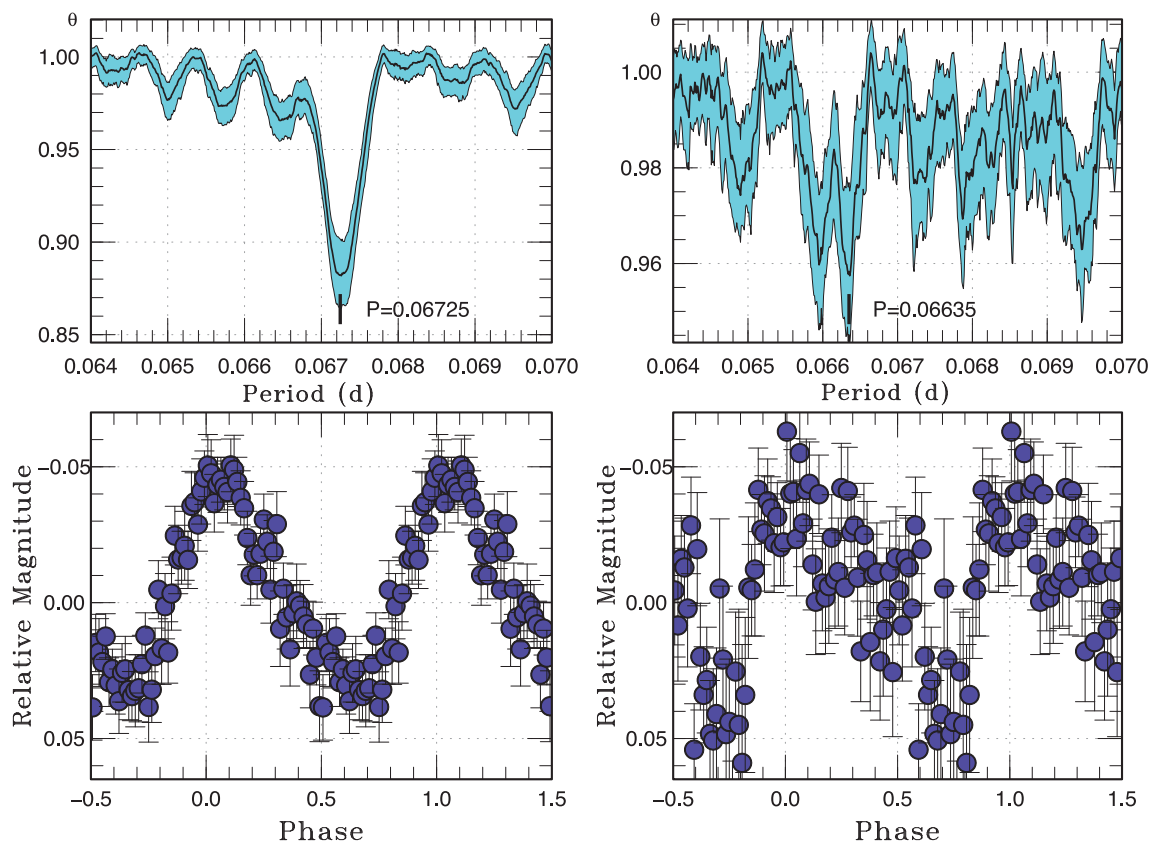


Fig. 7. Superhumps in OT J230425 (BJD 2455563–2455585). Left-hand upper: θ diagram of our PDM analysis of stage A superhumps (BJD 2455563–2455572). Left-hand lower: Phase-averaged profile of stage A superhumps. Right-hand upper: θ diagram of our PDM analysis of stage B superhumps (BJD 2455571–2455585). Right-hand lower: Phase-averaged profile of stage B superhumps. (Color online)

figure 8 is shown the nightly variation of the profile of superhumps. The maximum amplitude of superhumps was seen around BJD 2455571.

As shown in the right-hand upper panel of figure 7, there was a possible period which is shorter than the indicated period 0.066351(12)d. It was suggested that the period was a possible orbital period of 0.06589(1)d. Assuming 0.06589(1)d to be the orbital period, the new method of estimating the binary's mass ratio, q , by using stage A superhumps (Kato & Osaki 2013) implies $q = 0.053(1)$. It suggests that OT J230425 is a likely candidate for the period bouncer.

In figure 9 is described an O – C curve of OT J230425 (filled circles), compared with O – C curve of OT J075418 exhibited in figure 4 (filled squares). The resultant times of OT J230425 are listed in table 4. The O – C curve of OT J230425 is very similar to that of OT J075418. The very long stage A ($E \leq 123$) and the subsequent stage B ($E \geq 118$) are seen. The stage A–B transition occurred around BJD 2455572. The periods of superhumps in stage A and stage B were 0.067194(30)d and 0.066281(63)d, respectively. The P_{dot} in stage B was $-3.9(2.4) \times 10^{-5} \text{ s s}^{-1}$.

5 Discussion

5.1 Decrease of superhump period between stage A and stage B

The O – C curves of OT J075418 and OT J230425 (figures 4 and 9) suggest a very long stage of increasing O – C values (or a long period) and a certain stage transition in the middle of the superoutbursts. Kato et al. (2009) argued that the superhump period usually decreases by 1.0%–1.5% at the stage A–B transition and by $\sim 0.5\%$ at the stage B–C transition. The fractional period decreases at the transition were $\sim 2.0\%$ in OT J075418 and $\sim 1.4\%$ in OT J230425. Such a large variation in frequency of OT J075418 can be clearly seen in figure 5. Since they were too large for a stage B–C transition, we regard this transition as a stage A–B transition.

The disk precession results mainly from direct axisymmetric tidal potential of the secondary, secondarily from the gas pressure in the eccentric mode and resonant wave stress (Lubow 1992). Although the tidal potential produces a net prograde precession, the gas pressure effect makes a retrograde contribution and decreases the precession rate. Murray (2000) gave the hydrodynamical precession ω in

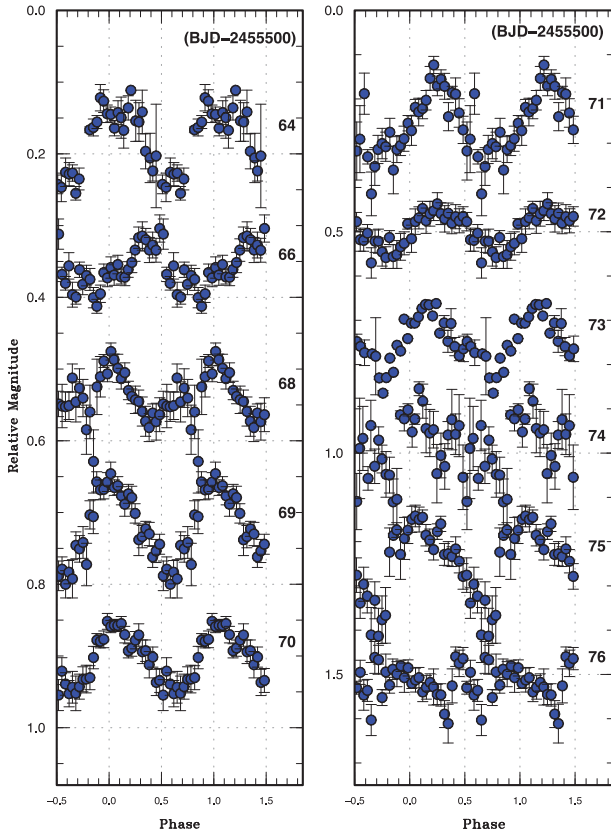


Fig. 8. Nightly variations of the profile of superhumps in OT J230425. (Color online)

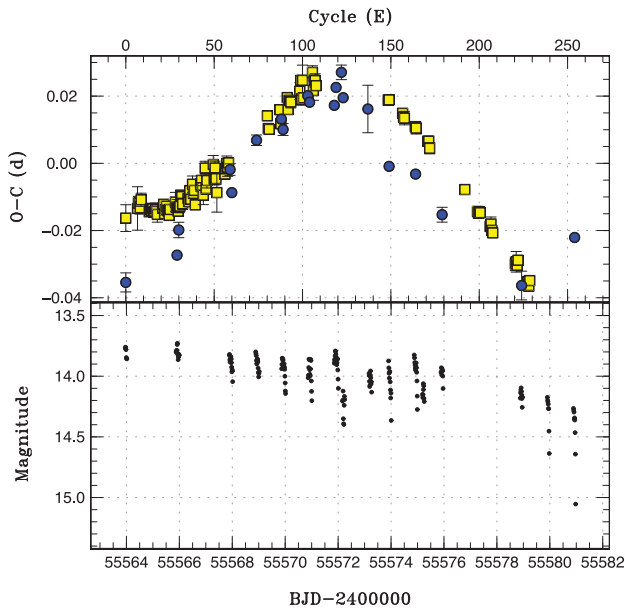


Fig. 9. Upper: $O-C$ curve of OT J230425, compared with that of OT J075418. Filled circles and filled squares represent $O-C$ diagrams of OT J230425 and OT J075418, respectively. The $O-C$ diagram of OT J075418 was shifted to fit it to that of OT J230425. An ephemeris of $\text{BJD } 2455565.925 + 0.06695E$ was used for drawing this figure. Lower: Light curve of OT J230425, the same as figure 6 except its leftmost part. (Color online)

Table 4. Times of superhump maxima in OT J230425.

E	Max*	Error	$O - C^\dagger$	$N^\ddagger$
0	55563.9791	0.0028	-0.0354	108
29	55565.9214	0.0011	-0.0273	274
30	55565.9956	0.0023	-0.0198	64
59	55567.9479	0.0017	-0.0019	104
60	55568.0077	0.0015	-0.0087	70
74	55568.9571	0.0016	0.0069	215
88	55569.8972	0.0014	0.0132	347
89	55569.9608	0.0018	0.0101	427
103	55570.9046	0.0013	0.0201	116
104	55570.9694	0.0011	0.0182	107
118	55571.9022	0.0009	0.0172	217
119	55571.9743	0.0014	0.0226	211
122	55572.1788	0.0022	0.0271	15
123	55572.2380	0.0014	0.0195	12
137	55573.1684	0.0071	0.0162	16
149	55573.9517	0.0014	-0.0009	148
164	55574.9499	0.0013	-0.0032	107
179	55575.9383	0.0022	-0.0153	150
224	55578.9187	0.0043	-0.0364	237
254	55580.9340	0.0014	-0.0221	192

*BJD-2400000.0.

$^\dagger C = 2455565.925 + 0.06695E$.

‡ Number of points used for determining the maximum.

terms of the dynamic precession (ω_{dyn}) and the pressure contribution to the precession (ω_{pres}):

$$\omega = \omega_{\text{dyn}} + \omega_{\text{pres}}. \quad (1)$$

Note that ω_{pres} is a negative value according to its retrograde contribution. The ratio $\omega_{\text{pres}}/\omega_{\text{orb}}$ corresponds to the fractional decrease of the superhump period in transition between stage A and stage B, where ω_{orb} is the orbital frequency. Therefore, it is possible that the large decrease in superhump period between stage A and stage B indicates a large pressure contribution.

5.2 Slow evolution of superhumps

The duration of stage A reflects the growth time of the 3:1 resonance. As described in subsections 3.2 and 4.2, it took ~ 190 superhump cycles (OT J075418) and ~ 120 (OT J230425) to fully develop into the 3:1 resonance. Considering the absence of observations immediately after the discovery of OT J230425, the growth time of the 3:1 resonance may be even longer in OT J230425. This long duration of stage A suggests very small mass ratios q of these objects because the growth time of the 3:1 resonance is expected to be inversely proportional to q^2 (Lubow 1991). The duration of stage A of

these objects was 4–8 times longer than those of typical SUUMa-type DNe with a short orbital period of ~ 0.06 d and a mass ratio of 0.10–0.15 (Kato et al. 2009). The mass ratio of these objects can be estimated to be 2–3 times smaller, suggesting a possible mass ratio ~ 0.05 . Despite the possible very small mass ratios, the orbital period of these objects, which are estimated to be less than 1% shorter than their superhump periods, are longer than that of a typical short-period SUUMa ($P_{\text{orb}} \sim 0.06$ d). This supports the hypothesis that these objects are candidates for the period bouncer.

5.3 Slow fading rate

During the superoutburst of SUUMa-type dwarf novae, an almost exponential, slow-declining phase exists, which is called the plateau phase. Osaki (1989) derived the time scale of this slow fading as follows:

$$t_d \simeq 8.14 R_{d,10}^{0.4} \alpha_{0.3}^{-0.7} [\text{d}], \quad (2)$$

where $R_{d,10}$ is the disk radius in units of 10^{10} cm and $\alpha_{0.3}$ is $\alpha_{\text{hot}}/0.3$ (α_{hot} represents the disk viscosity in the hot state). Kato et al. (2014a) suggested that α_{hot} in the candidate for the period bouncer that show slow fading rate is probably smaller than in higher- q systems. In addition to this, the radius of the 3:1 resonance can be formulated in terms of q :

$$r_{3:1} = 3^{(-2/3)}(1+q)^{-1/3}. \quad (3)$$

Thus a small q produces a large radius of the 3:1 resonance and a large disk radius. But the contribution by a small q is smaller than that by a small α_{hot} , since equation (2) shows the dependence of t_d on q is larger than that on α .

The fading rates of OTJ075418 and OTJ230425 were $0.0189(3) \text{ mag d}^{-1}$ and $0.0340(4) \text{ mag d}^{-1}$, respectively. In figure 10 is shown the relation between the superhump period in stage B (P_{orb}) and the fading rate of SUUMa-type DNe (filled circles), WZ Sge-type DNe (filled triangles), and possible candidates for the period bouncer including OTJ075418 and OTJ230425 (filled stars). SSSJ122221 (J122221 in figure 10) was reported as a perfect candidate for the period bouncer (Kato et al. 2013b). Kato et al. (2013b) also suggests that OTJ184228.1+483742 (J184228 in figure 10) showing a double superoutburst is a likely candidate for the period bouncer. In figure 10, the fading rates of OTJ075418 and OTJ230418 are lower than those of SUUMa-type DNe with a similar period. Furthermore, the location of these objects

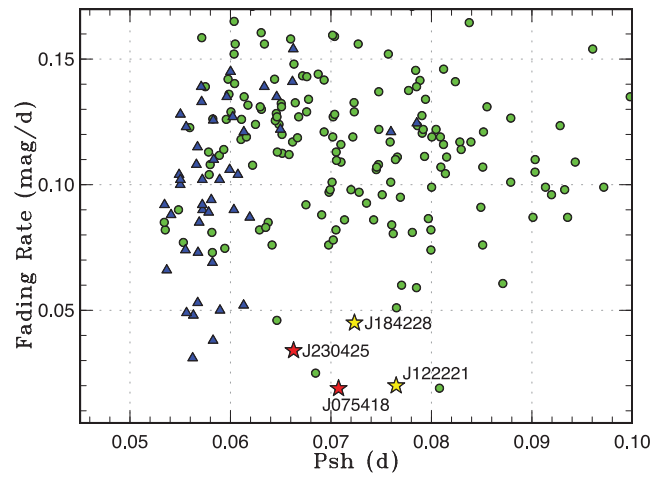


Fig. 10. Fading rate versus superhump period in stage B. The data are obtained from Kato et al. (2014a). The filled circles and the filled triangles represent SUUMa-type DNe and WZ Sge-type DNe, respectively. The filled stars represent the candidates for the period bouncer, including OTJ075418 and OTJ230425. (Color online)

is close to that of the likely candidates previously suggested for the period bouncer. This increases the possibility that these two objects are likely candidates for the period bouncer.

There are two more objects near these candidates for the period bouncer in figure 10. One of them is BC Dor, which showed a superoutburst in 2003, and another is PV Per detected in its superoutburst in 2008. Their last superoutbursts were reported in Kato et al. (2009). Since they had relatively frequent outbursts, we considered them not to be candidates for the period bouncer. They were within a range of the period bouncer including errors due to the poor-quality data in figure 10.

5.4 Absence of early superhumps

OTJ184228, a likely candidate for the period bouncer, showed a double superoutburst consisting of the first one with early superhumps and another with ordinary superhumps (Kato et al. 2013b). SSSJ122221 also showed a similar pattern to the superoutburst.

OTJ075418 and OTJ230425, however, showed no early superhumps. Early superhumps, as mentioned in section 1, arise when the disk radius reaches the 2:1 resonance radius due to its low q . And they cannot be detected in a system with a low inclination (e.g., GW Lib reported by Hiroi et al. 2009), since the origin of early superhumps is the emission of a disk surface that has a nonaxisymmetric vertical structure (Nogami et al. 1997; Kato 2002). The absence of the stage of early superhumps may indicate that the radius of the 2:1 resonance was not reached by the disk radius of these objects. Although this does not generally support their low q 's, we expect OTJ075418 and

OT J230425 to have a low q because of other strong evidence that we discussed above. Furthermore, it has been reported that a system with a low q corroborated did not show early superhumps (Kato et al. 2014b). It was considered that the superoutburst triggered by an inside-out (slowly rising) outburst made it impossible to establish the 2:1 resonance.

5.5 Existence of a precursor in OT J075418

In OT J075418, a precursor preceding its superoutburst was detected (BJD 2456325). This is rare for a WZ Sge-type DN, which hardly shows the normal outburst.

Osaki and Meyer (2003) suggested that in a superoutburst with a precursor the disk radius does not reach the tidal truncation radius, which is the maximum radius and larger than the 3:1 resonance one, while the disk radius reaches the tidal truncation radius in a superoutburst without a precursor. It is thought that the system in a precursor fades rapidly the same as in a normal outburst, since its accretion disk does not reach the tidal truncation radius and the disk permits the cooling wave to propagate inwardly. During this fading, if the disk becomes sufficiently eccentric, the tidal dissipation from the secondary brings the disk to the hot state. Then, we observe that it is a superoutburst with a precursor. As mentioned in subsection 5.3, however, OT J075418 faded very slowly. Similarly, 1RXS J053234+624755 has a very small mass ratio, 0.074(19), and showed a superoutburst with a precursor (Kapusta & Thorstensen 2006; Imada et al. 2009). Following Imada et al. (2009), we suggest that the radius of the accretion disk of OT J075418 should extend far beyond the 3:1 resonance radius, but not reach the tidal truncation radius, if a mass ratio of the system is small enough to provide a sufficient space between the 3:1 resonance and the tidal truncation radius.

As can be seen in the lightcurve, it took a relatively long time to change from the fading of a precursor outburst to the appearance of a superoutburst. It may be due to a long growth time of the 3:1 resonance because of its small mass ratio.

5.6 Number density problem of period bouncers

Now, we know four candidates for the period bouncer (OT J075418, SSS J122221, OT J230425, and OT J184228). To investigate whether our observations are capable of accounting for the missing population of period bouncers suggested by the evolutionary theory, we counted how many superoutbursts of SU UMa stars were observed. For the last five years, after the current project for observing SU UMa-type stars was undertaken the same as at

present, we have observed about 291 superoutbursts in 248 SU UMa-type stars (Kato et al. 2010, 2012, 2013a, 2014a). The number of detected superoutbursts is unknown.¹

The recurrence time of the superoutburst, T_s , is inversely proportional to mass-transfer rate $\dot{M}$ (Osaki 1995), and $\dot{M}$ is approximately proportional to q^2 in a short-period system evolved by gravitational radiation (Patterson 1998). We can estimate the parent population of the period bouncer from the statistics of recorded outbursts. Since many of SU UMa-type DNe have $T_s \sim 1$ yr, we can assume that many of them have been detected in a superoutburst for the last five years. If period bouncers have a recurrence time of $T_s(\text{PB})$, the detection probability of period bouncers can be estimated to be $f \times 5/T_s(\text{PB})$, where f stands for the fraction of time covered by surveys. If we conservatively assume $f \sim 0.1$ – 0.5 , then we can estimate the ratio of parent populations of $N(\text{PB})/N(\text{ordinary SU UMa-type})$ to be $\sim 4/248 \times 1/f \times T_s(\text{PB})/5$.

There is a large uncertainty in $T_s(\text{PB})$. We can, however, estimate $T_s(\text{PB}) > 5$ yr, since these objects were hardly detected in outbursts in the past CRTS and other surveys.² As to OT J230425, two outbursts have been detected by CRTS. One outburst was in 2006 December and the other was in 2011 January. It suggests that the recurrence time of the outbursts of OT J230425 is not as long as that of WZ Sge-type DNe. Therefore, it is possible that some candidates for the period bouncer have a higher mass-transfer rate than we expected and show outbursts more frequently than WZ Sge-type DNe. Three of the four candidates for the period bouncer, however, are WZ Sge-like stars. We assume that a majority of the candidates for the period bouncer are WZ Sge-like stars, and discuss the number density of period bouncers excluding such systems as OT J230425. We regard $N(\text{PB}) = 3$ hereafter, excluding OT J230425.

If we assume that the mass-transfer is purely driven by the gravitational wave radiation, $\dot{M}(\text{PB}) \sim 10^{-2} \dot{M}(\text{ordinary SU UMa-type})$ and $T_s(\text{PB})$ is expected to be $\sim 10^2$ yr. If we assume $T_s(\text{PB})$ is $\sim 10^1$ and $\sim 10^2$ yr and conservatively assume $f \sim 0.1$ – 0.5 , we can obtain roughly $N(\text{PB})/N(\text{SU UMa}) \sim 0.048$ – 2.4 . Considering the possibility of such period bouncers as OT J230425, the population of the period bouncer can be estimated to be larger. As mentioned in section 1, it was predicted that a majority of CVs [$\sim 70\%$ (Kolb 1993)] have passed

¹ There were systems of which superoutburst was detected but was not targets of time-series observations.

² Although a typical interval of observations in CRTS is 10 d, and there is a seasonal gap when the object is near the solar conjunction, we consider that many (fraction f) of the superoutbursts should have been recorded since WZ Sge-type DNe usually show a long-fading tail lasting several months. No previous outbursts in four systems suggest that T_s for these systems is efficiently long.

the period bouncer. On the contrary, few candidate for the period bouncer has been discovered from observations. We call the theoretically predicted population of the period bouncer the “missing population” of the period bouncer. Although the true recurrence time of candidates for the period bouncer should be confirmed by future observations, this ratio suggests a possibility that the period bouncers we have identified might account for the missing population of the period bouncer predicted by the evolutionary scenario. Thus we identify these WZ Sge-type objects with unusual outburst properties as the likely candidates for the hidden population of the terminal evolution of CVs.

Although we discussed photometric properties of the candidates for the period bouncer, Gänsicke et al. (2009) suggested their spectroscopic properties. They argued that SDSS CVs in the 80–86 min period spike showed spectra dominated by emission from the white dwarf with no spectroscopic signature from the companion star at optical wavelengths. These characteristics suggest that these systems have a very low accretion rate, and they are the most likely DNe with an extremely long recurrence time. It takes a long time to detect many candidates for the period bouncer in photometric observations on account of their long recurrence time. Spectroscopic studies of the four newly identified candidates are desired.

6 Summary

We report on photometric observations of two dwarf novae, OT J075418.7+381225 and OT J230425.8+062546, which showed superoutbursts in 2013 (OT J075418) and in 2011 (OT J230425). The results of the analysis of our data are summarized in table 5.

In OT J075418 and OT J230425, some peculiar properties that were similar to those of a likely candidate for

the period bouncer (SSS J122221.7–311523) could be seen. These two DNe are likely candidates for the period bouncer. We then propose the general properties of candidates for the period bouncer below:

- (i) They show a very long growing stage of superhumps (stage A) and a large period decrease of the stage A–B transition ($\sim 1.5\%$). The long stage A, which reflects the slow evolution of the superhump, is due to the very small mass ratio of these objects.
- (ii) The declining rates in the plateau phase in the superoutburst of these objects are lower than those of SU UMa-type DNe with a similar superhump period to these objects.

To investigate whether our observation is capable of accounting for the missing population of the period bouncer suggested by the evolutionary theory, we counted how many SU UMa stars showed superoutbursts. For the last five years, we have observed about 291 superoutbursts in 248 SU UMa-type stars, and the four likely candidates for the period bouncer have been suggested, including OT J075418 and OT J230425. Three of the four candidates were WZ Sge-like stars, and OT J230425 may have a shorter recurrence time than the others. We estimated the number density of the period bouncer from the stars excluding such systems as OT J230425. Although there is a large uncertainty in the recurrence time of period bouncers, we assumed that superoutbursts of the period bouncer were 10^1 – 10^2 times less frequent than those of ordinary SU UMa-type DNe, according to the theoretical prediction. Under this assumption, we can obtain roughly $N(\text{PB})/N(\text{SU UMa}) \sim 0.048$ – 2.4 . This ratio suggests a probability that the period bouncers we have identified might account for the missing population of the period bouncers predicted by the evolutionary scenario.

Acknowledgments

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Table 5. Results of the analysis of OT J075418 and OT J230425.

	OT J075418	OT J230425
Mean period*	0.0722403(26)	0.067317(35)
Stage A [†]	0.072218(3) (56328–56341)	0.067245(17) (55563–55572)
Stage B [‡]	0.070758(6) (56345–56355)	0.066351(12) (55571–55585)
Fading rate [§]	0.0189(3)	0.0340(4)

*Mean period of the all superhumps in units of d.

[†]Stage A superhump period in units of d. The interval used for determining the period is in parentheses. BJD–2400000.

[‡]Stage B superhump period in units of d. The interval used to determine the period in parentheses. BJD–2400000.

[§]In units of mag d^{-1} .

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