SSS J122221.7−311523: Double Superoutburst in a Best Candidate Period Bouncer

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Abstract

We observed the 2012–2013 superoutburst of the newly identified transient SSS J122221.7−311523 and found that this object showed successive two superoutbursts. Superhumps grew in amplitude during the second superoutburst and showed a characteristic pattern of period change reflecting the growth of the superhump. Assuming that the periods of superhumps during the growing stage [0.07721(1) d] and post-superoutburst stage [0.07673(3) d], represent the dynamical precession rates at the radius of the 3:1 resonance and the radius immediately after the superoutburst, respectively, we found that this object has a very small mass ratio \( q = M_2/M_1 < 0.05 \). The possible orbital period from quiescent data suggests \( q = 0.045 \), one of the smallest among hydrogen-rich cataclysmic variables. The long orbital period and low \( q \) make this object a perfect candidate for a period bouncer. We suggest that the peculiar pattern of double superoutburst is a result of a low \( q \) and may be characteristic to period bouncers.

Key words: accretion, accretion disks — stars: novae, cataclysmic variables — stars: dwarf novae — stars: individual (SSS J122221.7–311523)

1. Introduction

Cataclysmic variables (CVs) are close binary systems consisting of a white dwarf and a red-dwarf secondary transferring matter via the Roche-lobe overflow [for a review, see Warner (1995)]. According to the standard scenario of CV evolution, CVs with longer orbital periods \( (P_{\text{orb}}) \) evolve toward shorter \( P_{\text{orb}} \) due to angular momentum loss due to the process of magnetic braking and gravitational radiation. At a certain point (called the period minimum), the thermal time-scale of the secondary exceeds the mass-transfer time-scale and the mass-radius relation is reversed for degenerate dwarfs, \( P_{\text{orb}} \) starts to lengthen (e.g. Kolb, Baraffe 1999). These objects are usually called period bouncers. Although the theory predicts the majority of CVs have already evolved beyond the period minimum, the population appears to be smaller than expected (Gänsicke et al. 2009) and these objects are observationally still elusive (Patterson 2011). Using the new technique based on the dynamical precession rate of the growing superhumps (Osaki, Kato 2013; Kato, Osaki 2013), we report on the detection of a dwarf nova system with one of the smallest mass ratios \( (q = M_2/M_1) \) among hydrogen-rich CVs, hence one of the best candidates for true period bouncers, and discuss the interpretation of its peculiar superoutburst.

2. SSS J122221.7−311523

SSS J122221.7−311523 is a transient discovered by Catalina Real-time Transient Survey (CRTS, Drake et al. 2009) Siding Spring Survey (SSS) (=SSS130101:122222-311525, hereafter SSS J122221) on 2013 January 1 at \( V = 12.3 \) (Drake et al. 2013). No secure previous outbursts were recorded in ASAS-3 data (Pojmański 2002, 2000 November–2009 August, 627 nights)\(^1\) and CRTS SSS data (2005 August–2012 August, 79 nights), and the outburst amplitude of \( \sim 7 \) mag appeared to qualify the object to be a WZ Sge-type dwarf nova [for WZ Sge-type dwarf novae, see Bailey (1979); Kato et al. (2001); Kato et al. (2009)]. H. Maehara reported that this object was already in outburst on 2012 December 26 at \( V=11.80–12.02 \) (vsnet-alert 15240).\(^2\) Levato et al. (2013) reported that MASTER network recorded that this object at 11.8 mag (unfiltered CCD magnitude) on December 16.357 and 17.248 UT. The object must have been in a bright state for more than 16 d.

\(^{1}\) There was one possible detection at \( V=14.56 \) on 2006 May 1.
We regard it likely a noise since the object was recorded in usual quiescence three days later in the CRTS SSS data.

\(^{2}\) VSNET-alert archive can be accessed at https://ooruri.kusastro.kyoto-u.ac.jp/pipermail/vsnet-alert/.
Fig. 1. Light curves of SSS J122221 and the similar period bouncer candidate OT J184228. The data for OT J184228 were taken from Kato et al. (2013). The filled circles represents our observations (binned to 0.01 d). The symbols for the SSS J122221 are: CRTS SSS data (filled squares), Maehara Kyoto and Kiso Wide-field Survey data (filled triangles) and MASTER network data (filled diamonds). The observations were mainly performed with unfiltered CCDs, whose magnitude system is close to $V$ for outbursting dwarf novae.

Marsh et al. (2013) reported WHT spectroscopy taken on 2013 January 3, when double-peaked Balmer emission lines were observed. Although Marsh et al. (2013) noticed the absence of an absorption component and the weakness of the high-ionization lines which are unusual for an outbursting dwarf nova, the object may have already faded from the outburst at the time of the observation by Marsh et al. (2013), since the object already faded to a magnitude of 15.5 on 2013 January 5 (vsnet-alert 15248).

Kuulkers et al. (2013) conducted a Swift target-of-opportunity observation and reported optical spectroscopy on January 6, yielding a preliminary orbital period of 80–95 min. We should note that these observations were performed during the temporary fading (see the mark in figure 1) between the first outburst and the next outburst, which we call a rebrightening. As we will see later, this rebrightening bears characteristics of a superoutburst, and should be regarded distinct from short rebrightening(s) seen in many SU UMa-type dwarf novae.

The object remained faint until January 9. On January 11, the object started to brighten again rather slowly (vsnet-alert 15262, 15269). This phenomenon was also reported by Neustroev, Sjoberg (2013). There was a precursor-like structure in the early part of the rebrightening, and reached a local minimum on January 16–17 (BJD 2456309–2456310).

The object entered the rapid fading phase on February 12–13 (vsnet-alert 15385). The object remained brighter (16–17 mag) than in quiescence after this fading (see the upper panel of figure 1 for the outburst light curve).

3. Observation and Analysis

The data were acquired by time-resolved unfiltered CCD photometry (table 1). All the observed times were corrected to barycentric Julian days (BJD). Before making the analysis, we corrected zero-point differences between different observers by adding a constant to each observer. The data analysis was performed just in the same way described in Kato et al. (2009) and Kato et al. (2012).

In making period analysis, we used the phase dispersion minimization (PDM) method (Stellingwerf 1978). We subtracted the global trend of the outburst light curve by subtracting a smoothed light curve obtained by low-order (up to 3) polynomials for 1–33 d segments (depending on the complexity of the light curve) before the PDM analysis. The 1σ error of the PDM analysis was determined by the methods in Fernie (1989) for the Liller-Kinman-type period estimation.
4. Results

4.1. Superhumps

Despite the expectation as a WZ Sge-type dwarf nova, the superhump signal was not clearly detected. It finally
started to grow following the start of the rebrightening (vsnet-alert 15275). The true period was identified 10 d
after the rise to the rebrightening, and was unexpectedly long (longer than 0.07 d, which is well above the usual
range of WZ Sge-type dwarf novae; vsnet-alert 15302, 15306).

Table 4. Summary of time-resolved observations.

| Observer (telescope) | Dates (BJD−2456000, number of observations in the parentheses). |
|----------------------|---------------------------------------------------------------|
| Monard (35 cm)       | 297(412), 298(457), 299(551), 305(607), 306(542), 316(487), 317(417), 319(1098), 320(1029), 321(1239), 324(1102), 325(1092), 329(1121), 330 (1358), 331(1216), 332(1255) |
| Hambsch (40 cm)      | 301(44), 302(45), 304(43), 305(46), 306(51), 307(42), 308(75), 309(69), 310(45), 311(56), 315(108), 317(68), 318 (116), 319(119), 320(62), 321(45), 322(46), 324(112), 326(218), 327(115), 328(94), 337(124), 338(73), 339(116), 340(106), 341(109), 342(50), 343(72), 344(121), 345(100), 346(65), 347(34), 348(99), 349(116), 350(122) |
| Kiyota (20 cm)       | 305(293), 307(295), 309(336), 310(220), 312(106), 315(284), 317(310), 318(281), 319(320), 321(283), 323(246), 324(293), 326(228), 328(91), 334(122), 335(244), 337(177) |

By identifying the true superhump period, we have been
able to trace back the cycle counts and identified that the
superhump period was longer during the earlier half of
the rebrightening phase. The times of superhumps max-
ima and other information will be listed in our next sum-
mary paper on SU UMa-type dwarf novae (Kato et al. in
prep.). The pattern of period variation looks unusual for
a WZ Sge-type dwarf nova in that the period showed a
systematic decrease (figure 2), while the superhump pe-
riod usually increase in most of WZ Sge-type dwarf novae
(e.g. figure 89 of Kato et al. 2013). Helped by the new
finding and interpretation for the period variation of the
superhumps in the growing stage (Osaki, Kato 2013; Kato,
Osaki, 2013), however, we can now interpret that we ob-
erved unusually long-lasting stage A superhumps which
switched to stage B superhumps in the middle of the re-
brightening (see Kato et al. 2009 for the description of
stages A–C; while stages A–C usually refer to the super-
humps during the main superoutburst, the present stage
A and B superhumps were recorded during the rebright-
ening). The growth of the superhump amplitude during
the rebrightening indicates that these superhumps are not
a result of the remaining eccentricity but reflect the newly
excited eccentric instability.

Stage A superhumps lasted at least for 150 cycles (it
may be even closer to 200 cycles if we assume the start
of stage B at the O − C maximum). We have determined
the period of stage A superhumps to be 0.07721(1) d with
the PDM analysis for the segment $E \leq 136$, where $E$
is the cycle count since BJD 2456304.808. The period of
stage B superhumps (203 ≤ $E \leq 362$) was 0.07649(1) d. The
profile of stage B superhumps is shown in figure 3. Note
that the amplitude is much smaller than in ordinary
SU UMa-type dwarf novae, suggesting the very small tidal
torque. The period derivative $P / \dot{P} \approx -5$. There was
no clear evidence for a stage B–C transition as in most of
WZ Sge-type dwarf novae (Kato et al. 2009).

4.2. Post-Superoutburst Superhumps

After fading from the rebrightening, the object showed
a longer period than the stage B superhumps. The mean
period was 0.07670(3) d (442 ≤ $E \leq 562$. We should note
that we have no information whether there was a phase
jump between $E = 362$ and $E = 416$, and there may be
one cycle ambiguity in the cycle count). Although in-
dividual times of maxima were not well determined due
to the faintness of the object, a PDM analysis of the
later post-rebrightening period (BJD 2456348–2456369)
yielded a period of 0.07676(4) d. We adopted an averaged
value 0.07673(3) d of the two methods. This long super-
hump period appears to be consistent with late-stage su-
perhumps in some WZ Sge-type dwarf novae (Kato et al.
2009).
2008; Kato et al. 2010; Kato et al. 2012).

According to the CRTS SSS data, the object remained \( \sim 1 \) mag brighter than in quiescence even after 82 d of the initial CRTS detection (98 d after the initial MASTER detection). Such a long-lasting fading tail is characteristic to a WZ Sge-type dwarf nova.

5. Discussion

5.1. Slow Evolution of Superhumps

As shown in subsection 4.1 it took 150–200 cycles to fully evolve the superhumps. Because of this very slow evolution of superhumps, the stage A–B transition, which usually occurs shortly after the outburst in ordinary SU UMa-type dwarf novae, occurred in the middle of the rebrightening and produced a peculiar \( O-C \) pattern. This phenomenon can be naturally understood assuming a very small mass ratio and very long growth time of the 3:1 resonance, which is expected to be inversely proportional to \( q^2 \) (Lubow 1991), and the superhump wave was confined to the 3:1 region for a long time due to the very small tidal effect.

The growth time of superhumps in SSS J122221 was 5–7 times longer than typical short-period SU UMa-type dwarf novae (cf. Kato et al. 2009), suggesting that \( q \) is 2–3 times smaller. Assuming a typical \( q=0.10-0.15 \) for short-period (\( P_{\text{orb}} \sim 0.06 \) d) SU UMa-type dwarf novae, we can expect \( q \sim 0.05 \) for this object.

5.2. Estimation of the Mass Ratio from Precession Rates

It was very unfortunate that there was no chance for time-resolved photometry during the initial outburst which is supposed to show early superhumps [double-wave modulations in the early stage of WZ Sge-type outbursts, whose period is very close to the orbital period (Kato et al. 1996; Kato 2002)].

Despite the evidence for a rather high inclination from spectroscopy, we could not detect any orbital signal in the post-rebrightening phase or the faint state before the rebrightening. We therefore cannot directly apply the determination of \( q \) using the stage A \( \epsilon^+ \) method (Kato, Osaki 2013). We can put, however, a certain constraint.

The outline of the method is as follows. The precession rate of the elongated accretion disk, which is the origin of the superhumps, can be determined by a combination of the dynamical precession rate, pressure effect, and the minor wave-wave interaction term (Lubow 1992; Hirose, Osaki 1993). The pressure effect produces a retrograde precession, and reduces the precession rate. This effect can become negligible when the superhump wave is still confined to the radius of the 3:1 resonance (growing stage of superhumps, observationally known as stage A superhumps) or when the disk is cold (post-superooutburst stage). During the growing stage of superhumps, the precession rate is suggested to be equal to the purely dynamical precession rate at the radius of the 3:1 resonance (Osaki, Kato 2013) and this has been confirmed by a
comparison with the objects with known mass ratios dynamically determined or determined by quiescent eclipses (Kato, Osaki 2013).

The dynamical precession rate, $\omega_{\text{dyn}}$, in the disk can be expressed by (see, Hirose, Osaki 1990):

$$\omega_{\text{dyn}}/\omega_{\text{orb}} = Q(q)R(r),$$

(1)

where $\omega_{\text{orb}}$ and $r$ are the angular orbital frequency and the dimensionless radius measured in units of the binary separation $A$. The dependence on $q$ and $r$ are

$$Q(q) = \frac{1}{2} \frac{q}{1+q},$$

(2)

and

$$R(r) = \frac{1}{2} \frac{1}{\sqrt{1+q}} b^{(1)}_{3/2}(r),$$

(3)

where $\frac{1}{2} b^{(j)}_{s/2}(r)$ is the Laplace coefficient

$$\frac{1}{2} b^{(j)}_{s/2}(r) = \frac{1}{2\pi} \int_0^{2\pi} \frac{\cos(j\phi) d\phi}{(1+r^2 - 2r\cos\phi)^{s/2}}.$$

(4)

This $\omega_{\text{dyn}}/\omega_{\text{orb}}$ is equivalent to the fractional superhump excess (in frequency) $\epsilon^* \equiv 1 - P_{\text{orb}}/P_{\text{SH}}$ and it is related to the conventional fractional superhump excess (in period) $\epsilon \equiv P_{\text{SH}}/P_{\text{orb}} - 1$ by a relation $\epsilon^* = \epsilon/(1+\epsilon)$.

We can now express fractional superhump excesses (in frequency unit) of stage A superhumps and post-superoutburst superhumps as follows:

$$\epsilon^*\text{(stage A)} = Q(q)R(r_{3:1})$$

(5)

and

$$\epsilon^*\text{(post)} = Q(q)R(r_{\text{post}}),$$

(6)

where $r_{3:1}$ is the radius of the 3:1 resonance

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

(7)

$\epsilon^*$ (post) and $r_{\text{post}}$ are the fractional superhump excess and disk radius immediately after the outburst, respectively. By solving equations (5) and (6) simultaneously, we can obtain the relation between $r_{\text{post}}$ and $q$. Since $r_{\text{post}}$ is expected to be smaller than $r_{3:1}$ and larger than the circularization radius ($0.20 A$ for $q = 0.05$ and $0.14 A$ for $q = 0.1$, Lubow, Shu 1975), we can put a constraint on the $q$ value.

We can put a more stringent constraint on $q$ by using experimentally derived $r_{\text{post}}$ values. According to (Kato, Osaki 2013), the disk radius of WZ Sge-type dwarf novae after the superoutburst (and associated rebrightenings) was estimated to be $0.37-0.38 A$ for objects without rebrightenings and $0.30-0.32 A$ for objects with multiple rebrightenings. If we assume a range of $0.30 \lesssim r_{\text{post}} \lesssim 0.38 A$, the $q$ range is $0.023 \lesssim q \lesssim 0.036$ (corresponding to a range of acceptable orbital period of $0.07612 - 0.07650$ d). This makes SSS J122221 one of the smallest $q$ known in hydrogen-rich CVs (cf. Patterson 2011), and it is the smallest $q$ estimated other than from fractional superhump excess of stage B superhumps, which is not a good estimator due to the strong pressure effect (see Kato, Osaki 2013). Since SSS J122221 does not show helium enhancement (e.g. Marsh et al. 2013), this object is unlikely a core-stripped compact binary similar to SBS 1108+574 (Kato et al. 2013; Carter et al. 2013; Littlefield et al. 2013). Given the long $P_{\text{orb}}$ and low $q$, this object is a perfect candidate for a period bouncer.

5.3. Possible Orbital Period

An analysis of the CRTS data in quiescence around this range of the orbital period yielded a possible period of 0.075879(1) d (figure 4). This signal was present in an interval BJD 2454500–2455500, but became weaker in an interval BJD 2453500–2454500. This candidate photometric period may not be stable and needs to be tested by further observations. If this period is the orbital period, it corresponds to $\epsilon^* = 0.017$ for stage A superhumps and yields $q = 0.045$. The disk radius in the post-superoutburst phase can be estimated to be 0.40 A. Although this radius is larger than in other WZ Sge-type dwarf novae, a very small $q$ may be responsible. As described in Osaki (1995) the disk radius at the end of the superoutburst is a measure of the tidal strength and Osaki (1995) even assumed 0.42 A for a low-$q$ object. Hellier (2001) proposed a similar idea of decoupling between the thermal and tidal instability in low-$q$ systems. We therefore consider the radius of 0.40 A will not be unexpectedly large. The identification of the true orbital period is wanted.

5.4. Comparison with OT J184228.1+483742

The peculiar pattern of a double superoutburst in SSS J122221 is not unprecedented. OT J184228.1+483742 (=PNV J18422792+4837425; hereafter OT J184228)
showed a similar double superoutburst (Kato et al. 2013). The initial superoutburst in OT J184228 only consisted of early superhumps and (ordinary) superhumps only grew during the second superoutburst (rebrightening). Although the time-scales of the outbursts were longer in SSS J122221, the overall pattern is very similar (figure 1). Kato et al. (2013) considered that the low $q$ and resulting long growth time of the 3:1 resonance gives rise to this peculiar pattern of the outburst. Although we used “super-outburst” for the first outburst referring to its duration, the first outburst may bear characteristic of a prolonged precursor outburst whose long duration is sustained by the viscous depletion of the large amount of stored mass (as in the initial part of the “case B” outburst in Osaki, Meyer 2003). Kato, Osaki (2013) also suggested $q=0.042(3)$ for OT J184228 from stage A superhumps. These two objects indeed appear to be very alike.

We suggest that this kind of double superoutburst may be characteristic to typical period bouncers, especially with low $q$ and long $P_{\text{orb}}$. Until recently, a superoutburst with multiple rebrightenings such as in EG Cnc has been considered to a good indication of period bouncer (Patterson et al. 1998; Patterson 2011). As the number of objects with multiple rebrightenings has grown (ten objects at the time of the writing), it has become evident that many of these objects do not likely have $q$ as low as in EG Cnc (Nakata et al. 2013). We alternatively suggest that a double superoutburst as in SSS J122221 or OT J184228 may be more typical to period bouncers, and that the case of EG Cnc may be exceptional. Future measurement of $\epsilon^*$ for stage A superhumps in EG Cnc will test this interpretation.

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3 The $q$ value for EG Cnc was only estimated from $\epsilon$ for stage B superhumps, and this would suffer from an unknown pressure effect.