OT J002656.6+284933 (CSS101212:002657+284933): An SU UMa-Type Dwarf Nova with Longest Superhump Period

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Abstract
We observed the 2016 outburst of OT J002656.6+284933 (CSS101212:002657+284933) and found that it has the longest recorded [0.13225(1) d in average] superhumps among SU UMa-type dwarf novae. The object is the third known SU UMa-type dwarf nova above the period gap. The outburst, however, was unlike ordinary long-period SU UMa-type dwarf novae in that it showed two post-outburst rebrightenings. It showed superhump evolution similar to short-period SU UMa-type dwarf novae. We could constrain the mass ratio to less than 0.15 (most likely between 0.10 and 0.15) by using superhump periods in the early and post-superoutburst stages. These results suggest the possibility that OT J002656.6+284933 has an anomalously undermassive secondary and it should have passed a different evolutionary track from the standard one.

Key words: accretion, accretion disks — stars: novae, cataclysmic variables — stars: dwarf novae — stars: individual (OT J002656.6+284933)

1 Introduction
SU UMa-type dwarf novae are a class of cataclysmic variables (CVs) which show superhumps during long-lasting outbursts called superoutbursts [for general information of CVs, dwarf novae and SU UMa-type dwarf novae and superhumps, see e.g. Warner (1995)]. These superhumps and superoutbursts are now considered to be a consequence of the 3:1 resonance between the rotation in the accretion disk and the secondary star (Whitehurst 1988; Osaki 1989; Hirose, Osaki 1993; Lubow 1992). Such a resonance can occur when the mass-ratio ($q = M_2/M_1$) of the binary is small enough to accommodate a large accretion disk. It had long been known that SU UMa-type dwarf novae are restricted to objects below the famous CV period gap [cf. Knigge (2006) and Knigge et al. (2011) for the period gap and modern summary of CV evolution]. The only well-established exception was, and has long been, one of the earliest known SU UMa-type dwarf novae, TU Men (Stolz, Schoembs 1981; Stolz, Schoembs 1984), whose orbital period ($P_{\text{orb}}$) and superhump period ($P_{\text{SH}}$) are 0.1172 d and 0.1257 d, respectively (Mennickent 1995).

The lack of SU UMa-type dwarf novae above the period gap impressed many researchers and led Whitehurst (1988) to propose his idea of tidal instability and its stability condition. Although more than 700 SU UMa-type dwarf novae have been identified at the time of this discovery ([cf. Kato et al. 2016a], TU Men, together with the recently reported faint object OGLE-GD-DN-009 [$P_{\text{SH}}$=0.1310(3) d, Mroz et al. 2013], have been the only objects above the period gap. Here, we report on the discovery of an SU UMa-type dwarf nova which has the longest $P_{\text{SH}}$. OT J002656.6+284933 (hereafter OT J002656) was discovered as a possible dwarf nova by the Catalina Real-time Transient Survey (CRTS; Drake et al. 2009) on 2010 December 12 at an unfiltered CCD magnitude of 18.52 with the detection name CSS101212:002657+284933. Due to the faintness, this object did not receive much attention at the time of this discovery. There was a faint, blue ($g$=21.6, $u-g=-0.2$) SDSS counterpart SDSS J002656.59+284932.9 (Ahn et al. 2012) and a GALEX counterpart with a near ultraviolet (NUV) magnitude of 21.5(3) (Martin et al. 2005). Kato et al. (2012) estimated the orbital period to be 0.165(13) d from SDSS colors using a neural network. The object was also recorded in outburst at $t=15.65$ on 2002 July 22 by the Carlsberg Meridian Telescope (Niels Bohr Institute et al. 2014). The object was reported to be in a bright ($V=15.5$) outburst on 2013 July 6 by the ASAS-SN (Shappee et al. 2014) team (vsnet-alert 15926). This outburst, however, did not receive special attention. The dwarf nova-type classification has become certain after these multiple outburst detections.

The object received attention by the detection of another bright outburst ($V=14.95$) on 2016 October 23 by the ASAS-SN CV patrol (Davis et al. 2015). The past light curve in the ASAS-SN CV patrol strongly suggested that

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1. <http://nesssi.caltech.edu/catalina/>.
2. <http://nesssi.caltech.edu/catalina/AICV.html>.
3. <http://cv.asassn.astronomy.ohio-state.edu/>.
4. The light curve can be seen from <http://cv.asassn.astronomy.ohio-
the 2013 July outburst bore characteristics of a superoutburst (vsnet-alert 20258) and an observational campaign of the 2016 outburst was launched. Subsequent observations detected superhumps (vsnet-alert 20265), which further developed into our familiar superhumps with an astonishingly long (~0.13 d; figure 1; E-figure 1) \(P_{\text{SH}}\) (vsnet-alert 20271). Further observations confirmed the long-period nature of this object (vsnet-alert 20279, 20286, 20310, 20326, 20331). The resultant period was longer than that of TU Men.

2 Observation and Analysis

The observations were carried out as in many campaigns (e.g., Kato et al. 2016a) led by the VSNET Collaboration (Kato et al. 2004). The observers used 20–60 cm telescopes during the outburst and a 1.25-m telescope (Nauchny, Crimea) after the superoutburst (November 30 and December 5). All observers used unfiltered CCD cameras except one run in the \(V\)-band on November 4 (E-table 1). They used aperture photometry and extracted magnitudes relative to comparison stars whose constancy has been confirmed by comparison with check stars. The remaining small zero-point differences between observers were corrected by adding constants to minimize the scatter. The analysis of superhumps was performed in the same way as described in Kato et al. (2009) and Kato et al. (2014). We mainly used R software\(^6\) for data analysis. In de-trending the data, we divided the data into three segments in relation to the outburst phase and used locally-weighted polynomial regression (LOWESS: Cleveland 1979, using a smoothing parameter \(f=0.1\)) for the superoutburst plateau and the post-superoutburst period. For a rapidly fading short segment, we used a linear fit to remove the trend. The times of superhumps maxima were determined by the template fitting method as described in Kato et al. (2009). The times of all observations are expressed in barycentric Julian days (BJD).

3 Results

3.1 Course of Outburst

As shown in the upper panel of figure 2, the object showed the superoutburst plateau until BJD 2457703 (2016 November 10) and then started fading quickly. The superoutburst lasted for at least 18 d. Although there was a gap in the observation for the four subsequent nights due to the interference by the bright Moon close to this object, we are confident that the object should have faded further since the object was observed to be fading quickly on the final night (BJD 2457705) of the main superoutburst. The object underwent a post-superoutburst rebrightening on BJD 2457710 (November 17; E-figure 2) and smoothly faded. Quite astonishingly, the object had yet another rebrightening on BJD 2457718 (November 25). Between these rebrightenings, the object remained brighter than 19.5 mag, which is 2 mag brighter than in quiescence (as inferred from the SDSS magnitudes). Following the second rebrightening, the object became very faint (fainter than magnitude 20, not plotted in the figure) and it was likely that the object returned to quiescence.

3.2 Superhumps

The times of superhump maxima during the superoutburst plateau are listed in E-table 2. The \(O – C\) diagram (middle panel of figure 2) shows our familiar pattern of stages A and B, characterized by a rising slope (stage A) and a quadratic curvature (stage B) as illustrated in figure 4 in Kato et al. (2009) for short-\(P_{\text{SH}}\) SU UMa-type dwarf novae.\(^7\) Stage C (segment with a shorter period following stage B) was absent or it occurred in the observational gap. It was, however, certain that stage B to C transition did not occur before the end of the superoutburst plateau. Using the segment before BJD 2457691.6, which corresponds to stage A in the \(O – C\) diagram, we obtained a superhump period of 0.13320(3) d by the phase dispersion minimization (PDM) method (Stellingwerf 1978) (E-figure 3).

\(^5\) This vsnet-alert announcement was based on the detection of a single superhump by T. Tordai. Later it became evident that K. Kasai had already reported two superhump maxima.

\(^6\) The R Foundation for Statistical Computing: \(<\text{http://cran.r-project.org/>}\).

\(^7\) In short-period SU UMa-type dwarf novae, the stage A-B transition usually coincides with the peak of superhumps amplitudes (Kato et al. 2009). It has become evident that in some systems, particularly in long-period systems, superhump amplitudes become maxima before the stage A-B transition (cf. Kato et al. 2016b). We relied on the \(O – C\) diagram to identify these stages.
By using the segment $30 \leq E \leq 112$ (which is well approximated by a parabola in the $O-C$ diagram), we obtained a positive period derivative of $P_{\text{dot}} = \dot{P}/P = +16.4(1.6) \times 10^{-5}$. The mean superhump period in this segment was $0.13225(1)$ d (E-figure 4).

Since stage A was not very well observed and the resultant period may have already been affected by stage B superhumps, we independently estimated the period of stage A superhumps by using an empirical relation that the period of stage A superhumps is 1.0–1.5% longer than that of averaged stage B superhumps (Kato et al. 2009) [This relation has been confirmed in Kato, Osaki (2013) for well-observed systems]. This method gives a period of 0.13356–0.13422 d. Since the lower limit is close to our direct estimate, we used the upper limit as our upper-limit estimate of the period of stage A superhumps.

The superhump signal persisted after the first rebrightening (see E-table 3; E-figure 2). We used the segment before BJD 2457716. The superhump period after BJD 2457710 by the PDM method was 0.13192(7) d (E-figure 5). When we restricted the analysis after BJD 2457711 and 2457712, we obtained periods of 0.13183(6) d and 0.13174(6) d, respectively. These values do not greatly differ from each other, and we adopted a period of 0.1318(1) d for the period after the initial rebrightening.

## 4 Discussion

### 4.1 Mass Ratio from Superhump Periods

As demonstrated in Kato, Osaki (2013), we can estimate the mass ratio from the fractional superhump excess of stage A superhumps against the orbital period. In the case of OT J002656, the orbital period is unknown. In such a case, we can constrain the mass ratio by using the periods of stage A superhumps and post-supernova superhumps.

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

$$\omega_{\text{dyn}}/\omega_{\text{orb}} = Q(q)R(r),$$  \hspace{1cm} (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

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

and

$$R(r) = \frac{1}{2} \sqrt{r b_{3/2}^{(1)}(r)},$$  \hspace{1cm} (3)

where $b_{3/2}^{(1)}$ is the Laplace coefficient

$$\frac{1}{2} b_{3/2}^{(1)}(r) = \frac{1}{2\pi} \int_{0}^{2\pi} \frac{\cos(\phi) d\phi}{(1 + r^2 - 2r \cos(\phi))^{3/2}}.$$  \hspace{1cm} (4)

This $\omega_{\text{dyn}}/\omega_{\text{orb}}$ is equal to the fractional superhump excess in frequency: $e^{+} \equiv 1 - P_{\text{orb}}/P_{\text{SH}}$.

Following the treatment in Kato et al. (2013), we can describe:

$$e^{+}(\text{stageA}) = Q(q)R(r_{3:1}),$$  \hspace{1cm} (5)

and

$$e^{+}(\text{post}) = Q(q)R(r_{\text{post}}),$$  \hspace{1cm} (6)

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

$$r_{3:1} = 3^{3/2}(1+q)^{-1/3},$$  \hspace{1cm} (7)

e^{+}(\text{post}) and $r_{\text{post}}$ are the fractional superhump excess and disk radius soon after the supernova outburst, respectively. By solving equations (5) and (6) simultaneously, we can obtain the relation between $r_{\text{post}}$ and $q$. If we have knowledge about $r_{\text{post}}$, we have a more stringent constraint.

The result is shown in figure 3. The measurements of $r_{\text{post}}$ in SU UMa-type dwarf novae using the same method are within the range of 0.30 and 0.38 (Kato, Osaki 2013). The smaller values represent the values for WZ Sge-type
dwarf novae with multiple rebrightenings (after such rebrightenings). It is highly unlikely that \( r_{\text{post}} \) is larger than 0.38 in OT J002656, and it is expected to be somewhat smaller than 0.38 since the object experienced a rebrightening at the time of our measurement, although it was not after the final rebrightening. Figure 3 indicates \( q \leq 0.08 \) for \( r_{\text{post}} = 0.38 \) and \( q \sim 0.06 \) for \( r_{\text{post}} = 0.34 \) (this value was selected as an intermediate radius between objects without rebrightenings and with multiple rebrightenings). Using the upper limit of the period of stage A superhumps, these values become 0.15 and 0.10, respectively. The estimated \( P_{\text{orb}} \) for \( r_{\text{post}} = 0.34 \) is 0.1305 d and 0.1295 d for the period of stage A superhumps we measured and the upper limit estimated from stage B superhumps, respectively. We could not detect a periodic signal from observations near quiescence (19.9 mag on November 30 and 20.3 mag on December 5, E-figure 6).

Just for completeness, the \( q \) value estimated from \( P_{\text{orb}} \) of stage B superhumps using equation (6) in Kato (2015) is 0.13(1) (the errors reflects only the error of \( P_{\text{dot}} \)), although it is not certain whether this equation still holds in such a long \( P_{\text{orb}} \) system.

### 4.2 Similarity with WZ Sge-Type Dwarf Novae

In addition to the relatively small \( q \) suggested from analysis of superhump periods (subsection 4.1), the presence of two rebrightenings is also common to WZ Sge-type dwarf novae (Kato 2015). Very few systems with long \( P_{\text{orb}} \) show rebrightenings (cf. Kato et al. (2016b)) and only two systems V1006 Cyg and OGLE-GD-DN-014 are known to show two rebrightenings (Mroz et al. 2013). The \( O-C \) diagram of superhumps is also similar to borderline WZ Sge/SU UMa-type systems in two respects: (1) absence of stage B-C transition before the termination of the superoutburst plateau, (2) relatively large \( P_{\text{dot}} \) (cf. Kato 2015).

Although the absence of early superhumps during the 2016 outburst probably does not favor the WZ Sge-type classification, it was not completely excluded since there was a 4 d gap before the start of our observation and the phase of early superhumps may have been missed. Further observations during the next occasion are encouraged.

### 4.3 Evolutionary Status

With the estimated \( P_{\text{orb}} \sim 0.130 \) d, OT J002656 should have a mass of the secondary of 0.20M\(_\odot\) if it is on the standard CV evolutionary track (cf. Knigge et al. 2011), which corresponds to \( q \sim 0.25 \) for an 0.8M\(_\odot\) white dwarf. Our observation suggests an unusually low \( q \) (\(<0.15\)). We have three possibilities: (1) the object is a period bouncer, (2) the white dwarf is exceptionally massive, (3) the object evolved through an evolutionary path differently from ordinary CVs. The possibility (1) appears to be excluded since the object shows outbursts with relatively short intervals (at least as short as 3 yr), which cannot be expected for a period bouncer with a very low mass-transfer rate (cf. Nakata et al. 2014). The relatively short evolutionary time of superhumps and large amplitude of superhumps are also signatures disqualifying a period bouncer (cf. Kato 2015). Although an extremely massive white dwarf cannot be excluded, well-determined masses of white dwarfs in SU UMa-type dwarf novae are in a very narrow region (Savoury et al. 2011) and a very massive white dwarf appears to be rare.

It has been observationally known that some of CVs have undermassive secondaries (e.g. Thorstensen 2015). Evolutionary models also suggest that such objects can be formed if mass transfer occurs after the secondary has undergone significant nuclear evolution (e.g. Podsiadlowski et al. 2003; Goliasch, Nelson 2015). OT J002656 may be such an object. Future direct observation of the secondary or abundance studies may test this interpretation.

### 4.4 Implication on SU UMa-Type Dwarf Novae above Period Gap

We found the second known (and with the longest period) SU UMa-type dwarf nova above the period gap. The object, however, turned out to be a rather unusual one, probably not on the standard CV evolutionary track. It looks likely that the 3:1 resonance is very difficult to achieve above the period gap in dwarf novae on the standard evolutionary track. The result is consistent with the
“superhump success rate” in Patterson et al. (2005). Upon the present discovery, we propose that the mass ratio and evolutionary state of TU Men needs to be re-examined using stage A superhumps, although its superoutbursts are notoriously rare (Bateson et al. 2000).

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Supporting information
Additional supporting information can be found in the online version of this article. Supplementary data is available at PASJ Journal online.

Note added in proof (2017 March 21)
We have been informed that there is a WZ Sge-type dwarf nova above the period gap (OGLE-BLG-DN-0174, Mroz et al. 2015). The object showed a long outburst with a long rebrightening followed by three short rebrightenings in 2010. There was a short outburst in 2013 August. Mroz et al. (2015, Acta Astron., 65, 313) claimed a superhump period of 0.14474(4) d using the data between JD 2455380–2455388 (initial part of the long outburst). These observations, however, were not ideally sampled for detecting superhumps and there were only 43 points for the segment JD 2455380–2455388. Although our own analysis of the same data detected a period of 0.146(1) d (with a significant scatter in the phase diagram), another period of 0.126(1) d gave an equally acceptable phase diagram. We analyzed the later segment (JD 2455388–2455395, 38 points) of the later half of the outburst. The detected candidate periods were 0.139 d and 0.119 d. The periods of the second segment, if they are indeed true signals, were shorter than those in the first segment by about 5%. Such a large decrease of superhump periods during a superoutburst has not been recorded in any known system and we consider that these periods may not be the true superhump periods. Although the outburst light curve strongly suggests a WZ Sge-type dwarf nova, the data were too insufficient to draw a firm conclusion about the superhump period. We therefore do not include this object as confirmed SU UMa-type dwarf novae above the period gap. We appreciate the help by P. Mroz for providing the data and results of their period analysis.

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