Dwarf Novae in the Shortest Orbital Period Regime. I
A New Short Superhump Period Dwarf Nova, OT J055717+683226

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Abstract

We report on the observation of a new dwarf nova (DN), OT J055717+683226 (OT: optical transient), during the period of its first-recorded superoutburst in 2006 December. Our observation shows that this object is an SU UMa-type dwarf nova having a very short superhump period of 76.67 ± 0.03 min (0.05324 ± 0.00002 d). The next superoutburst was observed in 2008 March. The recurrence time of superoutbursts (supercycle) is, hence, estimated to be ~480 d. The supercycle (~480 d) is much shorter than those (≥10 yr) of WZ Sge-type dwarf novae which are in the major of dwarf novae in the shortest orbital period regime (≤85 min). Using a hierarchical cluster analysis, we divided the dwarf nova in the shortest orbital period regime in seven groups. We found that objects, which have short supercycles, small outburst amplitudes, and large superhump period excesses compared with those of WZ Sge stars, form a small group. OT J055717+683226 probably belongs to this group.

Key words: accretion, accretion disks — stars: individual (OT J055717+683226) — stars: novae, cataclysmic variables

1. Introduction

Dwarf novae (DNe) are a subclass of cataclysmic variable stars (CVs) and consist of a close binary system containing a white dwarf and a Roche-lobe filling red-dwarf star (Warner 1995a). The orbital periods (P orb) of ordinary hydrogen-rich DNe range from 76 min to 5.7 d (Ritter & Kolb 2003). DNe having short orbital periods of 76 min ≤ P orb ≤ 3 hr tend to exhibit two types of outbursts: normal outbursts and superoutbursts. Such systems are called SU UMa-type DNe (hereafter, SU UMa stars). SU UMa stars exhibit short-term periodic modulations — that is, superhumps — during superoutbursts. Superhumps can be a fair indicator of the orbital period of a binary system because it is well known that their periods are slightly (~ a few percent) longer than the orbital period (e.g., Warner 1995b). The outburst behavior of SU UMa stars can be explained by the thermal–tidal instability model for the accretion disk around the white dwarf (for a review, see Osaki 1996).

It is widely believed that the evolution of a CV having P orb < 3 hr is driven by angular-momentum removal from the binary, associated with gravitational radiation (Paczynski 1981; Rappaport et al. 1982). By losing angular momentum, the CV does not cease from developing into a shorter P orb regime until the onset of degeneracy in the secondary star. After the onset of degeneracy, the CV begins to evolve from a shorter to a longer P orb regime, since the mass–radius relation of the secondary star changes. This scenario gives a qualitative explanation for the presence of a short-period cut-off at P orb ~ 76 min in the observed P orb distribution. However, the predicted period minimum (P min) is significantly shorter than the observed minimum (Kolb 1993; Kolb & Baraffe 1999; Renvoizé et al. 2002).

There are two notable exceptions of hydrogen-rich CVs having P orb, much shorter than the well-known P min at ~76 min: V485 Cen (P orb = 59.0 min) and EI Psc (P orb = 64.2 min). A characteristic feature of these two is the presence of clear TiO absorption bands observed in their quiescent spectrum, which indicates luminous secondary stars. It is proposed that these systems have evolved secondaries, and as a result their evolutionary paths are different from those of CVs having a main-sequence secondary (Augusteijn et al. 1996; Thorstensen et al. 2002a). Uemura et al. (2002) proposed that V485 Cen-like objects may be progenitors of
helium CVs — that is, AM CVn stars — which are recognized as being interacting double white dwarfs. If this is the case, we can expect that progenitors of V485 Cen-like objects are hidden in the CV population having $P_{\text{orb}} > 76$ min. Such objects should have evolved secondaries, and hence higher mass-transfer rates, compared with CVs having main-sequence secondaries (Podsiadlowski et al. 2003).

Thorstensen et al. (2002b) pointed out that there is a wide diversity in DNe having very short $P_{\text{orb}}$, particularly in terms of the recurrence time of superoutbursts (supercycle: $T_s$). It is well known that most systems have quite long supercycles of $T_s \geq 10$ yr in the shortest period regime of 76 min $\lesssim P_{\text{orb}} \lesssim 85$ min. These are called WZ Sge-type dwarf novae (hereafter, WZ Sge stars) (Kato et al. 2001b). The shortest $P_{\text{orb}}$ regime also includes ER UMa stars such as DI UMa ($P_{\text{orb}} = 78.5722$ min) which have very short $T_s$ (20–50 d) (e.g., Kato & Kunjuya 1995; Ishioka et al. 2001a). V844 Her is a unique object also having a quite short $P_{\text{orb}}$ (78.6859 min) in terms of the intermediate $T_s$ (260 d), which is rather typical among DNe having longer periods of $P_{\text{orb}} \gtrsim 90$ min (Kato & Uemura 2000; Kato et al. 2003a). The nature of the diversity in $T_s$ is not fully understood.

According to the disk instability model, $T_s$ depends on the mass-transfer rate; a higher mass-transfer rate yields a short $T_s$ (Osaki 1995b). The mass-transfer rate at each $P_{\text{orb}}$ depends on the binary parameters, such as the structure of the secondary star. Hence, the diversity in $T_s$ possibly indicates that DNe in the shortest $P_{\text{orb}}$ regime include several groups with different secondary-star structures — that is, different evolutionary paths of the binary in other words. Alternatively, it is possible that the diversity in $T_s$ arises from the diversity of the disk structure or of the outburst mechanism. In order to investigate the origin of the $T_s$ diversity, detailed studies are required of the subgroups which may be present in the shortest $P_{\text{orb}}$ regime, though the number of the objects in the regime is small, apart from WZ Sge stars.

In this paper we report on our observations of a new DN having a short $P_{\text{orb}}$ in detail. The object, OT J055717+683226 (hereafter, J0557+68), was discovered on an image taken on 2006 December 16.6 (UT) by W. Kloehr (Kloehr et al. 2006). A series of our observations showed periodic modulations analogous to superhumps observed in SU UMa stars (Uemura & Arai 2006). We also found that J0557+68 is a peculiar system in terms of its $T_s$, which is much shorter than those of WZ Sge stars.

In addition to J0557+68, several objects in the shortest $P_{\text{orb}}$ regime have recently been discovered and well studied. An increase of sample now allows us to attempt a quantitative classification of short-$P_{\text{orb}}$ DNe.

In the next section, we describe our observation equipments and image reductions. In section 3, we report on the detailed outburst features of J0557+68. In section 4, we provide a new exploratory classification of DNe using a hierarchical cluster analysis. We also discuss the nature of J0557+68 and the origin of the diversity in $T_s$ in the shortest $P_{\text{orb}}$ regime. In the final section, we summarize our findings.

2. Observations

We carried out optical and infrared observations of J0557+68 using TRISPEC, attached to the “KANATA” 1.5 m telescope at Higashi-Hiroshima Observatory. TRISPEC is a simultaneous imager and spectrograph with polarimetry covering both optical and near-infrared wavelengths (Watanabe et al. 2005). We used the imaging mode of TRISPEC with $V$, $J$, and $K_s$ filters. The effective exposure times for the $V$, $J$, and $K_s$ bands were 63, 60, and 54 s, respectively. After making dark-subtracted and flat-fielded images, we measured the $V$ magnitudes of J0557+68 using a comparison star located at RA = 05h57m29s105, Dec = +68°29′18″.88 ($V = 13.39$). The $J$ and $K_s$ magnitudes were measured using a comparison star at RA = 05h57m39s60, Dec = +68°33′34″.2 ($J = 12.255$ and $K_s = 11.937$). We took the $V$ magnitudes of the comparison stars from the HIPPARCOS and TYCHO catalogues (Perryman & ESA 1997) and the $J$ and $K_s$ magnitudes from the 2MASS catalog (Skrutskie et al. 2006). We checked the constancy of the comparison stars using neighboring stars, and found that they exhibited no significant variations over 0.01, 0.02, and 0.05 mag in the $V$, $J$, and $K_s$ bands. Unfortunately, we could obtain no more than $J$-band images on JD 2454088 and 2454089 during the first outburst due to a failure in the mechanisms of filters. Heliocentric corrections were made for each data set used for the period analysis.

We show two examples of optical CCD images in figure 1. J0557+68 is marked with the two black bars. The image in the left panel was taken on JD 2454088 during the outburst. The right image was taken on JD 2454411, about 11 months after the outburst, when the object was at quiescence.

We also performed optical photometric observations with other small telescope during the period of JD 2454087–2454114. The magnitudes with a clear filter and without filter were adjusted to the $V$-band system of TRISPEC/KANATA by adding constants.\(^1\) Table 1 shows our observation log and instrument at each observatory.

Using neighboring USNO B1.0 stars, we calculated the

\(^1\) The clear filter is made of the optical glass in a thickness comparable to
position of J0557+68 from ten \( V \)-band images on JD 2454088 obtained with TRISPEC/KANATA. The average coordinates of J0557+68 are \( \alpha = 05^h 57^m 18.487^s, \ Dec = +68^\circ 32' 27.01'' \) with a systematic error of 0.1'. Within the error of the position, a faint USNO B1.0 star with \( b = 19.04 \) and \( r = 19.23 \) could be observed, which is considered to be the quiescent counterpart of J0557+68. A ROSAT X-ray source being 25'' apart from J0557+68 could also be observed, which is probably the X-ray counterpart.

3. Short-Period DN, J0557+68

3.1. Overall Behavior of the 2006 and 2008 Outbursts

The upper panel of figure 2 shows the light curve of an outburst of J0557+68 in 2006. The outburst continued for 14 d from its discovery (JD 2454085.6: Kloehr et al. 2006), at an average fading rate of 0.10 mag d\(^{-1}\). These features are quite typical of superoutbursts in SU UMa-type DNe (Warner 1995b). This plateau phase terminated at a rapid fading starting on JD 2454100. The object experienced a short rebrightening on JD 2454109. The duration of the rebrightening was \( \sim 5 \) d. Such a single short rebrightening is occasionally observed in short-period SU UMa stars (e.g., Baba et al. 2000; Imada et al. 2006a) and WZ Sge stars (e.g., Ishioka et al. 2001b; Templeton et al. 2006). After rebrightening, the object again started gradual fading. The object had almost returned to its quiescent state before JD 2454120. Our observation at quiescence (JD 2454412) yielded \( \Delta V = 18.89 \pm 0.04 \). The observed amplitude of the outburst is \( \sim 4 \) mag. We note that this is the lower limit of the amplitude, since we possibly overlooked the early phase of the outburst.

We obtained simultaneous photometric data in the \( V \) and \( J \) bands on two nights and in the \( V \) and \( K_s \) bands on four nights. These near-infrared data are shown in figure 2. Using these multicolor data, we show temporal color variations in figure 3. As shown in figure 3, \( V - J \) and \( V - K_s \) remained \( \sim 0 \) during the plateau phase, which is typical of the outburst in DNe. In the rapid fading stage, a clear reddening of the object was observed in \( V - K_s \).

The next outburst was observed in 2008 March. We show the light curve of the 2008 outburst in the lower panel of figure 2. The object remained in a bright state for at least 4 d. The object was apparently fading at a rate of 0.07 mag d\(^{-1}\) during the outburst. These characteristics indicate that the 2008 outburst is another superoutburst. An interval of time between the two superoutbursts is \( \sim 480 \) d. We consider this interval to be a \( T_s \) of J0557+68, which is much shorter than those of WZ Sge stars (\( \sim 10 \) yr), or rather, comparable to those of normal SU UMa stars.

3.2. Superhumps

During the 2006 outburst, we detected short-term periodic modulations. Examples are shown in figure 4. The modulations had saw-tooth profiles and decreased in amplitude with time. These features are typical characteristics of superhumps (Uemura & Arai 2006). Together with the features of the whole light curve, the detection of the superhumps established that J0557+68 is an SU UMa-type DN and that the 2006 outburst was a superoutburst.

We conducted a period analysis of the superhumps using the phase dispersion minimization (PDM) method (Stellingwerf 1978). Before the PDM analysis, a linear fading trend
Fig. 3. Temporal evolution of colors. The abscissa denotes JD and the ordinate the colors of $V - J$ and $V - K_s$. The open and filled circles are $V - J$ and $V - K_s$, respectively.

was subtracted from the light curves during the period of the superoutburst (JD 2454087–2454100). The light curves obtained with small telescopes have larger dispersions than those obtained with the KANATA telescope. Binning these light curves in neighboring three-point bins, we obtained data with similar dispersions. We excluded the observations on JD 2454092 and 2454093 from the sample for our period analysis since the phase of modulations changed on these nights, as mentioned below. As a result, we obtained 620 photometric points. Using these data, we calculated $\Theta$ defined in the PDM method for each frequency. The frequency–$\Theta$ diagram is shown in figure 5. A strong signal can be seen at $/\text{P}/\text{C}0.05341 \text{ d}$.

Figure 6 presents the temporal evolution of the superhump profiles. Short-term modulations observed after the superoutburst are also included in this figure. The light curves were folded by a period of 0.05341 d. As mentioned above, the superhump decreased in amplitude during the early phase of the superoutburst, as can be seen in figure 6 (labeled as “JD 2454087”, “88”, “89”, and “91”). As the main hump weakened, the secondary hump appears to become prominent. As a result, the hump had a double-peaked profile with the phase apparently inverted in several humps (“92”, “93”, “97”). Just before and after the rapid fading stage, the hump profiles became more complicated, while hints of superhumps and their secondary humps can be seen (“99”, “100”, “101”). During the rebrightening, clear humps were observed, while their phase was shifted compared with the superhumps. They had sinusoidal profiles rather than the typical saw-tooth profiles (“109”, “110”).

To explore the temporal variation of the superhump period, we calculated $O - C$ of the superhumps. The detailed procedure for determining the peak times of the superhumps is shown in Kato et al. (2009). We calculated $O - C$ for them with a period of 0.05341 d and the epoch of HJD 2454087.2836, the first superhump maximum time we observed. The $O - C$ and the time of the superhump maxima are listed in table 2. The $O - C$ diagram is depicted in figure 7. In the table and figure, $E$ denotes the cycle number of the superhumps and “Error” the 1/2 error. As described above, the phase of the prominent hump was inverted in the cycles 91, 92, and 94. The $O - C$ values (with $E$ in parentheses) for these secondary humps are also listed in the table and figure.

Figure 7 shows a possible period change of superhumps. Koen (2006) provides a method for testing the significance of a period change seen in $O - C$ diagrams. We applied this method to the $O - C$ of J0557+68. Koen (2006) considers two mechanisms that cause $O - C$ variations: random cycle-to-cycle jitter and a real period variation. Four models for $O - C$ variations are then introduced: neither cycle-to-cycle jitter nor period change (Model 1), significant cycle-to-cycle jitter and no period change (Model 2), a significant period change and no cycle-to-cycle jitter (Model 3), and significant cycle-to-cycle jitter and a period change both (Model 4). The goodness of model fitting is evaluated by two information criteria (IC): the Akaike IC (AIC) and the Bayes IC (BIC). The probabilities for the models are finally calculated by each IC. We calculated the probabilities using the $O - C$ observed in J0557+68 in an early phase of $0 \leq E \leq 74$ and a late phase...
of $109 \leq E$. The results are listed in table 3. In the table, $P_A$ and $P_B$ denote the probabilities calculated from AIC and BIC, respectively. Model 3 and Model 1 have the highest probabilities among the four models in the early and late phases, respectively.

The result of the Koen’s test indicates that the superhump period ($P_{SH}$) of J0557+68 changed with time in an early phase, and then became constant in a late phase of the superoutburst. The transition occurred in $74 < E < 109$. Assuming a constant period derivative, these features can be modeled as follows:

$$ (O - C)_{\text{early}}(E) = aE^2 + bE + c \quad (0 \leq E \leq T), \tag{1} $$
$$ (O - C)_{\text{late}}(E) = pE + q \quad (E > T), \tag{2} $$
$$ (O - C)_{\text{early}}(T) = (O - C)_{\text{late}}(T). \tag{3} $$

Equation (3) is needed in order to ensure the continuity of the $O - C$ variation. The best-fit parameters and their uncertainties were calculated with a Bayesian approach in which probability densities of the parameters were estimated by using a Markov chain Monte Carlo (MCMC) algorithm (Metropolis 1953; Gilks et al. 1996). Table 4 lists the obtained best-fit parameters for the observed $O - C$ of J0557+68. We confirmed that the obtained $T (= 108 \pm 7$ d) is consistent with that expected from the Koen’s test ($74 < E < 109$). The
model with those best-fit parameters is indicated by the dashed line in figure 7. The period derivative of the early phase ($P_{\text{dot}} = P_{\text{SH}}/P_{\text{SH}}$) and the period of the late phase ($P_{2}$) are also included in the table. The positive period derivative means a period increase of superhumps in the early phase.

According to Kato et al. (2009), SU UMa-type DNe generally have three stages in terms of $P_{\text{SH}}$: stage A with a long $P_{\text{SH}}$, stage B with a positive period derivative, and stage C with a short $P_{\text{SH}}$. The $O-C$ variation of J0557+68 can be interpreted as a transition from stage B to C. The duration of stage A is so short (1–2 d) that we missed an opportunity to observe stage A in the case of J0557+68. Kato et al. (2009) suggested that the minimum $P_{\text{SH}}$, either $P_{3}$ or $P_{\text{SH}}$ at the start of stage B, is regarded as a representative $P_{\text{SH}}$ of an object. The representative $P_{\text{SH}}$ of J0557+68 is, then, $P_{3} = 0.05324 \pm 0.00002$ d.

To date, GW Lib has the shortest $P_{\text{orb}}$ among ordinary hydrogen-rich CVs except for V485 Cen and EI Psc; that is, $P_{\text{orb}} = 0.05332 \pm 0.00002$ d (Thorstensen et al. 2002b). VS 0329+1250 possibly has a shorter $P_{\text{orb}}$ since its superhump period is quite short ($P_{\text{SH}} = 0.053394 \pm 0.000007$ d: Shafter et al. 2007). As shown in table 4, J0557+68 is definitely one of SU UMa stars having the shortest $P_{\text{orb}}$. V485 Cen and EI Psc are hydrogen-rich DNe having atypically short $P_{\text{orb}}$s ($\sim 60$ min). However, they are considered to have a different evolutionary path from those of CVs having main-sequence secondaries (for details, see sections 1 and 4).

3.3. Simultaneous Optical and Near-Infrared Observations of Superhumps

We successfully carried out a series of simultaneous $V$- and $J$-band observations on JD 2454088. Superhumps were observed in both bands. The phase-averaged profiles and colors are shown in figure 8. In the rising phase of the superhump, the $V$-band flux brightened more rapidly than the $J$-band. As a result, the bluest phase preceded the superhump maximum. After the superhump maximum, the $V$-band flux decreased rapidly, while the decrease in $J$-band flux was rather gradual. In addition, we can see a secondary hump at a phase of $\sim 0.7$ only in the $J$ band. The behavior in the $J$-band results in a rapid reddening, as can be seen in the lower panel of figure 8. The color during the period of the secondary hump was redder than that at the bottom of the superhump, as indicated by the dashed line in the figure. The reddest phase ($\sim 0.7$) significantly preceded the bottom of the superhump ($\sim 0.0$).

It is noteworthy that the primary and secondary humps exhibited different behaviors in $V - J$. In the “blue” primary hump, the observed feature can be explained by heating and subsequent cooling processes at the outermost part of the accretion disk. In superhumps, the heating mechanism is tidal dissipation (Osaki 1996). The precedence of the bluest phase suggests that the heating process finished before the superhump maximum. Then, the object reached its superhump maximum by an expansion of the low-temperature region in the accretion disk. In the “red” secondary hump, the latter effect, namely, the expansion of a low-temperature region, is probably more substantial.

### Table 3. Probabilities for the models in Koen (2006).

| Model* | $P_{A}$ † | $P_{B}$ † |
|--------|----------|----------|
| Early phase ($0 \leq E \leq 74$) | | |
| M1     | 0.02     | 0.02     |
| M2     | 0.20     | 0.20     |
| M3     | 0.64     | 0.63     |
| M4     | 0.14     | 0.15     |
| Late phase ($109 \leq E$) | | |
| M1     | 0.59     | 0.41     |
| M2     | 0.22     | 0.28     |
| M3     | 0.17     | 0.22     |
| M4     | 0.04     | 0.09     |

* For description of the models, see the text.
† Probability calculated from Akaike information criterion.
‡ Probability calculated from Bayesian information criterion.

### Table 4. Best-fit parameters for the $O-C$ model of J0557+68.

| Parameter | Value |
|-----------|-------|
| $a$       | $2.87 \pm 0.56 \times 10^{-6}$ |
| $b$       | $-2.15 \pm 0.37 \times 10^{-5}$ |
| $c$       | $1.78 \pm 5.28 \times 10^{-4}$ |
| $T$       | 108 ± 7 |
| $p$       | $-1.80 \pm 0.21 \times 10^{-5}$ |
| $q$       | $3.02 \pm 0.70 \times 10^{-2}$ |
| $P_{\text{dot}}$ † | $10.8 \pm 2.2 \times 10^{-5}$ |
| $P_{2}$ ‡ | $0.05324 \pm 0.00002$ |

† Period derivative in the early phase.
‡ Period in the late phase.
Fig. 8. Upper panel: Phase-averaged superhump profiles in the $V$ and $J$ bands on JD 2454088. The abscissa and ordinate denote the superhump phase and magnitude, respectively. The open and filled circles are observations in the $V$ and $J$ bands, respectively. Both the light curves are normalized to be readily compared. Lower panel: $V - J$ color variation associated with the superhump. The dashed line indicates the color at the bottom of the superhump.

4. Discussion

As shown in section 3, J0557+68 has a relatively short $T_s$ (480 d) and a quite short $P_{\text{orb}}$. $T_s$ is much shorter than supercycles of WZ Sge stars, which are a dominant population in the shortest $P_{\text{orb}}$ regime. The characteristics of J0557+68 remind us of V844 Her (Thorstensen et al. 2002b). In addition to J0557+68 and V844 Her, recent studies have shown several objects in the shortest $P_{\text{orb}}$ regime having observational features distinct from those of WZ Sge stars, such as PU CMa (Kato et al. 2003b) and LL And (Kato 2004). On the other hand, there is no established classification of DNe in the shortest $P_{\text{orb}}$ regime that includes the above anomalies.

To study the nature of J0557+68, it is important to identify its possible companions and search for their common features. In this section, we present a new exploratory classification of DNe in the shortest $P_{\text{orb}}$ regime using a hierarchical cluster analysis. We discuss not only the nature of J0557+68, but also the origin of the observed diversity in $T_s$ based on the identified clusters.

4.1. Classification of DNe in the Shortest $P_{\text{orb}}$ Regime by Hierarchical Cluster Analysis

We list SU UMa-type DNe having short $P_{\text{orb}} (<95$ min) in table 5. The table shows $T_s$, the outburst amplitude, $\Delta m$, and the superhump period excess, $\epsilon \equiv (P_{\text{SH}} - P_{\text{orb}})/P_{\text{orb}}$. The table only includes confirmed SU UMa stars in which superhumps were observed during their past superoutbursts. The objects and their parameters in the table are generally quoted from the Ritter and Kolb catalog ver. 7.9 (RKcat7.9: Ritter & Kolb 2003). Some of the parameters were updated by the references and recent superoutbursts shown in the table. For dates of the recent superoutbursts, we referred to the VSNET and ASAS-3 database (Pojmański 2002; Kato et al. 2004b).

According to the disk instability model, $T_s$ and $\epsilon$ can be indicators of the mass-transfer rate and the mass ratio of the binary, respectively (Osaki 1996; Patterson et al. 2005a); $\Delta m$ has historically been considered to be a key parameter for dividing DNe into WZ Sge and normal SU UMa systems (Howell et al. 1995; Kato et al. 2001b).

The parameters are plotted against $P_{\text{orb}}$ in figure 9. J0557+68 with its $P_{\text{SH}}$ is indicated by the large open circle. The anomalous features of J0557+68 are evident: short $T_s$ and small $\Delta m$, compared with the other short $P_{\text{orb}}$ systems having 76 min $\lesssim P_{\text{orb}} \lesssim 85$ min. According to the disk
Table 5. Parameters of DNe having a short period of $P_{\text{orb}} \leq 95$ min. *

| $P_{\text{orb}}$ (min) | $T_{\text{e}}$ (d) | $\Delta m$ (mag) | $\varepsilon$ (%) | Object | Group† | Outburst dates |
|-----------------------|-------------------|-----------------|-----------------|--------|--------|----------------|
| 59.0328              | 320               | 4.1            | 2.83±0.01       | V485 Cen | V485 | 2005.08, 2007.08 |
| 64.1765              | 730               | 3.2            | 4.04±0.02       | El Psc  | V485 | 2006.12, 2008.03 |
| —                    | 480               | 4.1            | —               | J0557+6832 | (X) | 2006.10 |
| 76.0320              | >5.8              | —              | —               | J0329+1250 | (WZ?)|(X)? | 2003.12 |
| 76.7808              | 8800              | 8.0            | 1.33±0.04       | GW Lib  | WZ | 1983.08, 2007.04 |
| 78.5722              | 35                | 2.8            | 1.33±0.06       | DI UMa  | DI | |
| 78.6859              | 260                | 5.5            | 2.43±0.09       | V844 Her | X | |
| 78.9120              | >4.6              | —              | —               | J0222+4122 | (WZ)? | 2005.11 |
| 78.9120              | 7.1               | 2.06±0.20      | —               | J0233−1047 | (WZ)? | 2006.01 |
| 79.2792              | 5000              | 5.0            | 2.90±0.36       | LL And  | X | |
| 79.6320              | 6.6               | —              | —               | V2176 Cyg | WZ | 1997.08 |
| 79.7054              | 6.1               | 2.48±0.20      | —               | J1037−0912 | (X) | 2003.12 |
| 80.2080              | >5.5              | 1.65±0.35      | —               | SU LMi  | WZ | 2006.10 |
| 80.4960              | 6.8               | —              | —               | J1021+2349 | (WZ) | 2006.11 |
| 80.5248              | ~4000              | 8.5            | —               | V592 Her | WZ | |
| 80.6400              | ~9100             | 9.0            | —               | PQ And  | (WZ) | |
| 80.6976              | 7.0               | 2.06±0.21      | —               | J0025+1217 | (WZ) | 2004.09 |
| 80.7840              | 4600              | 9.9            | —               | UW Tri  | (WZ) | 1983.09, 1995.03, 2008.10 |
| 80.9280              | 580               | 4.8            | 1.60±0.40       | J0532+6247 | X | 2006.06, 2008.01 |
| 81.8500              | 7.9               | 1.39±0.02      | —               | V455 And | (WZ) | 2007.09 |
| 81.6019              | 2200              | 8.7            | 1.20±0.07       | AL Com  | WZ | 1995.04, 2001.05, 2007.11 |
| 81.6307              | 10700             | 7.2            | 0.92±0.07       | WZ Sge  | WZ | |
| 81.6394              | 380                | 5.2            | 2.22±0.20       | PU CMa  | X | |
| 81.8136              | 1200              | 6.5            | 2.45±0.27       | SW UMa  | SU/WZ | 2000.02, 2002.10, 2006.09 |
| 81.8784              | 6.7               | 1.60±0.30      | —               | V1108 Her | (WZ) | 2004.06 |
| 82.1794              | 2900              | 7.5            | 2.00±0.09       | HV Vir  | (WZ) | 1992.04, 2002.01, 2008.01 |
| 82.9296              | 380                | 5.7            | 1.84±0.10       | MM Hya  | X | |
| 83.5200              | 7.6               | —              | —               | J1959+2242 | (WZ) | 2005.08 |
| 83.8598              | 880                | 7.8            | 1.99±0.15       | WX Cet  | SU/WZ | |
| 84.0960              | >7.1              | —              | —               | J1112−3538 | (WZ) | 2007.12 |
| 84.2400              | 19                | 3.3            | —               | RZ LMi  | (ER?)|(DI?) | |
| 84.6144              | 300                | 5.7            | 2.33±0.22       | KV Dra  | X | |
| 84.6288              | 7000              | 7.3            | 0.67±0.08       | EG Cnc  | WZ | |
| 84.7008              | 420                | 5.5            | 2.36±0.14       | QZ Vir  | X | |
| 84.7584              | >5.8              | —              | —               | FL TrA  | (SU) | 2005.07 |
| 84.9600              | >5.2              | 0.87±0.68      | —               | J0040+5103 | (WZ) | 2006.03 |
| 85.3920              | 7.2               | —              | —               | V585 Lyr | SU/WZ | 2003.09 |
| 86.2560              | 350               | 6.0            | 3.30±0.01       | 2219+1824 | SU | |
| 86.4000              | 7.3               | —              | —               | J0807+1138 | (SU/WZ) | 2007.11 |
| 86.4000              | 140                | 4.9            | —               | CI UMa  | (SU) | |
| 86.4000              | 7800              | 6.0            | —               | DV Dra  | (WZ) | 1984.06, 2005.11 |
| 86.5440              | 250                | >5.0           | 1.78±0.20       | RX Vol  | (SU) | 2006.10, 2007.06, 2008.02 |
| 86.7456              | 400                | 4.7            | —               | MM Sco  | (SU) | |
| 86.8320              | 210                | 4.5            | 3.10±0.27       | V1040 Cen | SU | |
| 86.9040              | 5.9               | —              | —               | KX Aql  | (SU) | 1980.11 |
| 86.9904              | 420                | 5.6            | —               | V1028 Cyg | (SU) | |
| 87.4080              | 4600              | 8.3            | —               | UZ Boo  | (WZ) | 1978.09, 2004.08, 2003.12 |
| 87.7536              | 350               | 5.0            | 2.84±0.21       | AQ Eri  | SU | 2006.11, 2007.12, 2008.12 |
| 87.8400              | 700               | 6.6            | —               | V1454 Cyg | (SU) | 2004.12, 2006.11 |
| 88.0690              | 370               | 5.3            | 2.70±0.16       | XZ Eri  | SU | 2007.12, 2008.11 |
| 88.7760              | 5.5               | —              | —               | J0918−2942 | (SU) | |
| 89.2800              | 7.1               | —              | —               | J1025−1542 | (WZ) | 2006.02 |
| 89.3088              | 340                | 4.5            | —               | V1141 Aql | (SU) | |
instability theory, the short $T_s$ suggests that the mass-transfer rate of J0557+68 is exceptionally high, compared with the system having a similar short $P_{\text{orb}}$.

A hierarchical cluster analysis was performed by using four parameters: $P_{\text{orb}}$, $T_s$, $\Delta m$, and $\epsilon$. As the parameters have different dimensions, for the cluster analysis the observed $a$, $a_i$, and $\sigma_a$ are the parameter value, its average, and its standard deviation, respectively. The sample consists of 34 objects selected from table 5 whose all four parameters are known. HO Del and AQ CMi are not included in the sample because their $T_s$ are uncertain.

The calculation was performed with the pvclust package of R.\(^3\) Using the pvclust function, we could estimate the confidence level (or the probability value: $p$-value) for clusters via the multiscale bootstrap resampling method (Shimodaira 2004). The bootstrap samples were generated by randomly drawing $N$ samples with replacement from the original sample, where $N$ is the number of samples. The $p$-value was approximated at the probability that the cluster is obtained in the bootstrap replicates of the dendrogram, shown in percentages. A high value indicates great significance. In this paper, we discuss only the clusters having $\geq 95\%$ with $p$-values higher than 95 with $N=1000$.

The obtained dendrogram is depicted in figure 10. We identified six clusters having $\geq 95\%$ with $p$-values higher than 95 with a singleton cluster of DI UMa. The errors of the classification method, we used the Ward’s method in which the classification method, we used the Ward’s method in which the within-class variance is minimized and the between-class variance is maximized (Murtagh & Heck 1987). This method is commonly available in the case where the number of samples is small. It has an advantage of being able to derive small independent clusters, while avoiding the need to form large chain-shaped clusters containing small clusters (Milligan 1980). Since our sample size is small, it is suitable for our analysis.

The obtained dendrogram is depicted in figure 10. We identified six clusters having $\geq 95\%$ with $p$-values higher than 95 with a singleton cluster of DI UMa. The errors of the $p$-values were

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**Table 5.** (Continued)

| $P_{\text{orb}}$ (min) | $T_s$ (d) | $\Delta m$ (mag) | $\epsilon$ (%) | Object | Group\(^1\) | Outburst dates |
|------------------------|-----------|------------------|----------------|--------|---------|--------------|
| 89.5363 | 49 | 3.9\(^1\) | 3.20 ± 0.11\(^5\) | V1159 Ori | ER | 1991\(^{30}\) |
| 89.7120 | — | > 8.3 | — | CG CMa | (WZ)\(^{30}\) | 2005.10, 2006.08, 2007.07 |
| 89.7120 | 320 | 4.1\(^1\) | 4.02 ± 0.32\(^5\) | V402 And | (SU) | 2004.02 |
| 89.8963 | 230\(^7\) | 4.1\(^1\) | 2.81 ± 0.25\(^5\) | V2051 Oph | SU | 2004.02 |
| 90.0014 | 630\(^7\) | 4.0 | 2.12 ± 0.32\(^5\) | V436 Cen | SU | 2004.02 |
| 90.1584 | 800\(^31\) | 7.6 | 3.06 ± 0.14\(^5\) | BC UMa | SU/WZ | 2007.06 |
| 90.2880 | ~ 740\(^7\) | 4.3 | 2.76 ± 0.35\(^5\) | HO Del | (SU) | 2007.06 |
| 90.5472 | 490\(^7\) | 4.6 | 3.21 ± 0.25\(^5\) | EK TrA | SU | 2007.06 |
| 90.5760 | 400\(^32\) | 5.6 | 3.25 ± 0.32\(^5\) | TV Crv | SU | 2007.06 |
| 90.6624 | — | 4.6 | 3.72 ± 0.33\(^3\) | J1227+5139 | (SU) | 2007.06 |
| 90.8496 | 580\(^7\) | 6.7 | 2.03 ± 0.15\(^5\) | YY Aqr | SU/WZ | 2007.06 |
| 90.8942 | 350\(^7\) | 5.3 | 2.03 ± 0.15\(^5\) | OY Car | SU | 2007.06 |
| 91.2672 | — | 5.3 | 2.43 ± 0.07\(^3\) | J1600–4846 | (SU) | 2005.06 |
| 91.5840 | — | 6.0 | — | J1536–0839 | (SU) | 2004.02 |
| 91.5840 | 370\(^7\) | 4.4 | 2.59 ± 0.16\(^5\) | MR UMa | SU | 2004.02 |
| 91.6704 | 43\(^1\) | 3.0 | 3.14 ± 0.11\(^5\) | ER UMa | ER | 2004.02 |
| 92.1600 | — | 6.7 | — | DO Vul | (SU) | 2005.11 |
| 92.7360 | — | 3.8\(^1\) | — | J1653+2010 | (SU) | 2004 |
| 93.1680 | — | 7.4 | — | J0232–3717 | (WZ)\(^{32}\) | 2007.09 |
| 93.3120 | ~ 410\(^7\) | 4.4 | — | AQ CMi | (SU) | 2007.09 |
| 93.4560 | 960\(^7\) | 6.9 | 2.34 ± 0.23\(^5\) | UV Per | SU/WZ | 2007.09 |
| 93.5280 | 280\(^7\) | 5.9 | — | CT Hya | (SU) | 2007.09 |
| 93.7440 | 300\(^7\) | 6.1 | 3.68 ± 0.33\(^5\) | AK Cnc | SU | 2007.09 |
| 94.1890 | 250\(^7\) | 4.8 | 2.81 ± 0.31\(^5\) | DM Lyr | SU | 2007.09 |
| 94.7520 | 1300 | 7.0 | — | GO Com | (SU) | 1995.07, 2003.06, 2006.12 |
| 94.8960 | 1100 | 6.0 | — | V551 Sgr | (SU) | 2003.09, 2006.08 |

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\(^1\) The groups with and without parentheses were identified based on the SVM analysis described in the last paragraph of subsection 4.3 and on the cluster analysis in subsection 4.1.

\(^2\) http://www.is.titech.ac.jp/~shimo/prog/pvclust/.

\(^3\) http://www.R-project.org.
Cluster dendrogram of short-$P_{\text{orb}}$ DNe. The vertical axis is a measure of the Euclidean dissimilarity. Shown are $p$-values for the clusters estimated to be less than 1% in the range of $p > 95\%$. The seven clusters are labeled “SU”, “DI”, “ER”, “WZ”, “V485”, “SU/WZ”, and “X” in the figure. The average parameters for each cluster are shown in figure 11 as filled circles. We describe the characteristics of each cluster as follows:

- **Group SU consists of normal SU UMa stars.** The minimum $P_{\text{orb}}$ is 86 min in this group. We consider that most SU UMa stars having $P_{\text{orb}} > 95$ min also have the same nature as this group.

- **Group WZ includes “WZ Sge stars”.** This group is characterized by short $P_{\text{orb}}$, long $T_s$, large $\Delta m$, and small $\varepsilon$, as can be seen in figure 11.

- **Group SU/WZ is located between Group SU and WZ in all parameter spaces, as shown in figure 11.** All of the systems in this group are listed as “large-amplitude SU UMa-type DNe” in Kato et al. (2001b), except for HV Vir. HV Vir has been considered to be a WZ Sge star, since it exhibited early superhumps, which are only seen in that group (Kato et al. 2001b). However, HV Vir is not classified as Group WZ, but rather as SU/WZ in our cluster analysis because of its relatively short $T_s$ and large $\Delta m$ compared with those in Group WZ. BC UMa is also a noteworthy member of this group. Maehara, Hachisu, and Nakajima (2007) reported on the detection of early superhumps in this object, while BC UMa has an atypically long $P_{\text{orb}}$ for WZ Sge stars. They propose that BC UMa is a WZ Sge star with a nature which is intermediate between normal SU UMa and WZ Sge stars. Group SU/WZ may be considered to be an intermediate evolutionary stage between Group SU and WZ.

- **Group V485 contains two peculiar systems: V485 Cen and E1 Psc.** They are indicated by open triangles in figure 9. As described in section 1, they have evolved secondaries, and hence are proposed to be on a different evolutionary path from those of CVs having main-sequence secondaries (Augusteijn et al. 1996; Thorstensen et al. 2002a; Uemura et al. 2002).

- **Group ER is “ER UMa stars”, which are characterized by quite short $T_s$.** This object is considered to be a member of “ER UMa stars”. Our cluster analysis divided ER UMa stars in Group ER and DI, probably because of a very short $P_{\text{orb}}$ of DI UMa compared with those of ER UMa and V1159 Ori.

- **Group X is a group established by our analysis for the first time.** The members of this group are indicated by small open circles in figure 9. They have quite short $P_{\text{orb}}$, although $T_s$ is about one order of magnitude shorter than those of “WZ” on the average, as can be seen in figure 11; $\Delta m$ is also much smaller than those of “WZ” and “SU/WZ”; $\varepsilon$ is significantly larger than those of “WZ”.

Our classification method adequately reproduced the previously known subgroups. In addition, we identified a new noteworthy group, Group X, which may be a key group for the study of the CV evolution.

4.2. On the Nature of J0557+68 and Group X

J0557+68 presumably belongs to Group X because of the short $T_s$ and small $\Delta m$. The result of the cluster analysis, therefore, predicts that J0557+68 has a relatively large $\varepsilon$ compared with those of WZ Sge stars. Using the average value of $\varepsilon$ in Group X ($\varepsilon = 2.2 \pm 0.3$), we calculated that the $P_{\text{orb}}$ of J0557+68 is $0.05209 \pm 0.00015 \text{d}$.

According to Podsiałowski, Han, and Rappaport (2003), CVs with evolved secondaries can have $P_{\text{min}}$ shorter than those of CVs having main-sequence secondaries. Such objects...
have high mass-transfer rates before evolving to longer periods compared with ordinary CVs, and finally evolve to AM CVn stars after passing $P_{\text{min}}$. V485 Cen and EI Psc may be objects on this evolutionary channel (Uemura et al. 2002). Besides V485 Cen and EI Psc, objects on this evolutionary channel are expected to be found in the CV population with $P_{\text{orb}} > 76$ min. Such progenitors of AM CVn stars and V485 Cen-like objects definitely have a comparable or higher mass-transfer rate compared with V485 Cen-like objects. As a result, they should have comparable or shorter $T_s$ than those of ordinary objects. This might cause the observed diversity in $T_s$ in the shortest $P_{\text{orb}}$ regime (Thorstensen et al. 2002b). Possible candidates for such anomalies are ER UMa stars and objects in Group X.

The mass-transfer rate in ER UMa stars should be one order higher than those of normal SU UMa stars in order to reproduce the quite short $T_s$ (Kato & Kunjaya 1995; Osaki 1995a). If ER UMa stars are a progenitor of V485 Cen-like objects, the mass-transfer rate must rapidly decrease by one order of magnitude from $P_{\text{orb}} \sim 90$ min to $\sim 60$ min. The evolutionary path calculated by Podsiadlowski, Han, and Rappaport (2003), however, shows a rather gradual decrease in mass-transfer rate before $P_{\text{min}}$. The small $\varepsilon$ of DI UMa, furthermore, indicates a small mass of the secondary. Thorstensen et al. (2002b) reported that the optical spectrum of DI UMa is typical of ordinary DNe at quiescence with none of the TiO absorption bands observed in V485 Cen and EI Psc. These observations are unfavorable for the scenario that ER UMa stars have evolved secondaries and are progenitors of V485 Cen-like objects.

The nature of Group X is still an open question. Imada et al. (2006a) propose that the short $P_{\text{orb}}$ DN, SDSS J013701.06$-$091234.9, has a luminous and evolved secondary since it shows significant TiO absorption and red–infrared colors. As shown in table 5, the $\Delta m$ and $\varepsilon$ of SDSS J013701.06$-$091234.9 suggest that it is a possible member of Group X. This implies that a small portion of DNe having $P_{\text{orb}} \gtrsim 76$ min has evolved secondaries and hence is progenitors of AM CVn stars or V485 Cen-like objects. Dynamical estimations of the secondary mass by radial velocity studies are required for DNe in the shortest $P_{\text{orb}}$ regime in order to explore the origin of the diversity in $T_s$. Our cluster analysis provides high-priority objects for future studies; that is, members of Group X.

**Fig. 11.** Same as figure 9, but for the averages of the parameters in subgroups defined by our cluster analysis (for detail, see the text). The filled circles and error bars indicate the averages and standard deviations, respectively. The solid curves indicate the decision boundaries for individual categories, calculated by the support vector machine (SVM) method.
4.3. Estimation of Boundaries of Groups by the Support Vector Machine Method

The above seven groups of DNe were defined in four-parameter space. Now, we estimate the boundaries of the groups in two-parameter spaces: $P_{\text{orb}}$ and the other three parameters. This is useful for categorizing objects if only some of the parameters are known.

The support vector machine (SVM) method provides a means for estimating the optimal decision boundaries of the groups (Vapnik 1998; Chen et al. 2005). The SVM constructs a linear classification into two groups by defining an optimal hyperplane which separates members of the groups. The optimal plane is determined by maximizing the margin between the opposing group members closest to the plane. The original SVM can be extended to nonlinear classifications by using kernels to project the data into a higher dimensional space (Boser et al. 1992). An improved SVM, called the soft-margin SVM, can tolerate minor misclassifications (Cortes & Vapnik 1995). In this paper, we used a soft-margin SVM with a radial-based kernel.

We estimated the boundaries of a group against the other groups using the result of the cluster analysis. The calculations were performed by the e$\text{svm}$ function (C-classification) in the e1071 package of R. The width of an allowable margin around the separating plane is defined by a parameter “C”. We determined the parameter “C” by maximizing the region of the group and minimizing the overlapping areas between the regions. The calculated boundaries are indicated by solid curves in figure 11. As can be seen in figure 11, the boundaries fail to identify several groups; no boundary is given for Group ER and SU/WZ in the $e-P_{\text{orb}}$ plane, and the boundary of Group DI is given only for $\Delta m-P_{\text{orb}}$. This is because the number of the sample is small and because the members of these groups are blended in the other group members in the $e-P_{\text{orb}}$ plane.

In table 5, we show the group identification in parentheses, for example “(SU)”, for objects which were not used for the cluster analysis. These objects were classified following the boundaries estimated by SVM. In addition, objects were labeled “(WZ)” when (i) early superhumps were detected and (ii) the system experienced the rebrightening phenomenon which characterizes WZ Sge-type superoutbursts (Kato et al. 2004a). Group SU, SU/WZ, and WZ and their possible members account for 70% of DNe with $P_{\text{orb}} < 86$ min and 95% with $86 \text{ min} \leq P_{\text{orb}} < 95$ min. Thus, we have confirmed that these three groups are the majority population in those $P_{\text{orb}}$ regimes.

5. Summary

We observed J0557$+68$ during the period of the outburst in 2006 December. Our observation revealed that the object is an SU UMa-type DN having a quite short superhump period of $P_{\text{SH}} = 0.05324 \pm 0.00002$ d. The next superoutburst occurred in 2008 March. Hence, the $T_{\text{r}}$ of this object is estimated to be 480 d, which is much shorter than those of WZ Sge stars. Using the cluster analysis, we found that a peculiar group characterized by a short $T_{\text{r}}$ has $P_{\text{orb}}$ slightly longer than $P_{\text{min}}$. J0557$+68$ probably belongs to the group. While the nature of this group still remains open to question, its peculiar feature of a short $T_{\text{r}}$ is possibly due to an atypically high viscosity in quiescent disks or the evolutionary sequence being different from ordinary CVs having main-sequence secondaries.

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