

Letter

# V1006 Cygni: Dwarf nova showing three types of outbursts and simulating some features of the WZ Sge-type behavior

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## Abstract

We observed the 2015 July–August long outburst of V1006Cyg and established this object to be an SU UMa-type dwarf nova in the period gap. Our observations have

confirmed that V1006 Cyg is the second established object showing three types of outbursts (normal, long normal, and superoutbursts) after TU Men. We have succeeded in recording the growing stage of superhumps (stage A superhumps) and obtained a mass ratio of 0.26–0.33, which is close to the stability limit of tidal instability. This identification of stage A superhumps demonstrates that superhumps indeed slowly grow in systems near the stability limit, the idea first introduced by Kato et al. (2014, PASJ, 66, 90). The superoutburst showed a temporary dip followed by a rebrightening. The moment of the dip coincided with the stage transition of superhumps, and we suggest that stage C superhumps are related to the start of the cooling wave in the accretion disk. We interpret that the tidal instability was not strong enough to maintain the disk in the hot state when the cooling wave started. We propose that the properties commonly seen in the extreme ends of mass ratios (WZ Sge-type objects and long-period systems) can be understood as a result of weak tidal effect.

**Key words:** accretion, accretion disks — novae, cataclysmic variables — stars: dwarf novae — stars: individual (V1006 Cygni)

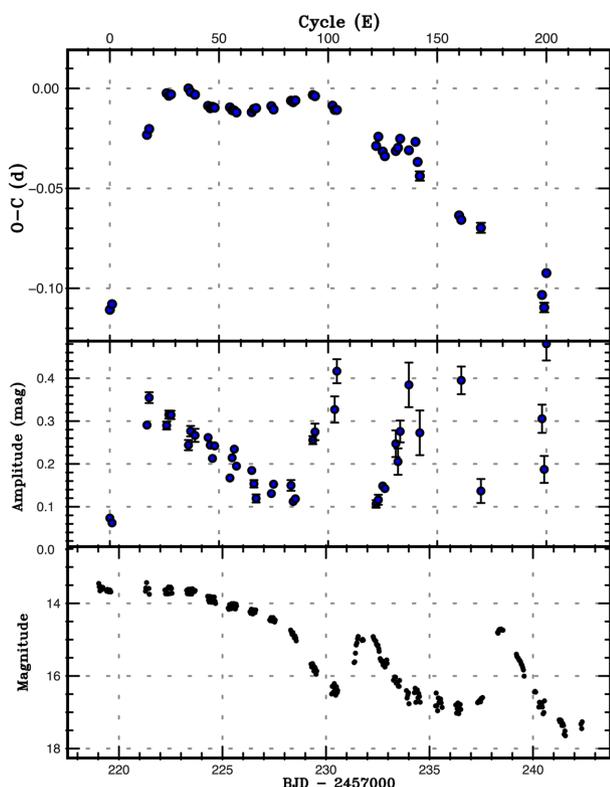
## 1 Introduction

Cataclysmic variables (CVs) are composed of a white dwarf and a red (or brown) dwarf that supplies matter to the white dwarf, forming an accretion disk. Dwarf novae are a class of CVs characterized by outbursts. SUUMa-type dwarf novae are a subclass of dwarf novae which show superoutbursts in addition to normal outbursts. During superoutbursts, superhumps that have periods which are a few percent longer than the orbital periods ( $P_{\text{orb}}$ ) are observed and are considered to be the defining characteristics of SUUMa-type dwarf novae. [For general information on CVs, SUUMa-type dwarf novae, and superhumps, see e.g., Warner (1995a).] The origin of superhumps and superoutbursts is currently understood as the consequence of the 3:1 resonance in the accretion disk resulting in tidal instability combined with thermal instability (thermal–tidal instability model: Osaki 1989; Osaki & Kato 2013a). Only systems having mass ratios ( $q = M_2/M_1$ ) smaller than  $\sim 0.3$  can hold the radius of the 3:1 resonance inside the tidal truncation radius (Whitehurst 1988; Smith et al. 2007) and the appearance of superhumps in these systems gave support to the tidal instability model for superhumps.

In recent years, it has been established that superhump periods during superoutbursts show systematic variations. Kato et al. (2009) showed that the evolution of superhumps has three stages: stage A (long, constant superhump period), stage B (short superhump period with systematic period variations) and stage C (constant period shorter than that of stage B superhumps, typically by 0.5%; seen in the late phase of the superoutburst to the post-superoutburst phase). Stage A superhumps are now considered to be superhumps during which the 3:1 resonance is growing, and transition to stage B is considered to be caused by the pressure effect which produces a retrograde precession

(Osaki & Kato 2013b; Kato & Osaki 2013). The origin of stage C superhumps is still unknown. It has been well established that period variations during stage B are a good function of  $P_{\text{orb}}$  for systems with short  $P_{\text{orb}}$  (cf. Kato et al. 2009, 2015). In long- $P_{\text{orb}}$  systems, however, there have been a number of objects that show a strong decrease in the superhump periods [the best-known examples are MN Dra and UV Gem, see subsection 4.10 in Kato et al. (2009)]. The origin of strongly negative period derivatives had remained a mystery. Kato et al. (2014) proposed a working hypothesis that what looked like strongly negative period derivatives for stage B superhumps in such systems are actually caused by the stage A–B transition, based on the photometrically detected  $P_{\text{orb}}$  in MN Dra. Kato et al. (2014) suggested that the 3:1 resonance grows slower in systems that have large  $q$  close to the stability border of the resonance and that this is observed as long-lasting stage A. This interpretation violated the received wisdom that a long-lasting stage A reflects a small  $q$ , as is typically seen in WZ Sge-type dwarf novae (Kato 2015), which have completely opposite properties to long-orbital systems. Since the discussion in Kato et al. (2014) was based on the yet unconfirmed  $P_{\text{orb}}$  of MN Dra, further confirmation is clearly needed. We present the detection of long-lasting growing superhumps in a long- $P_{\text{orb}}$  system V1006 Cyg, which has a spectroscopically established  $P_{\text{orb}}$ .

V1006 Cyg was discovered as a dwarf nova (S 7844) (Hoffmeister 1963a, 1963b) with a photographic range of 16–18 mag. Gessner (1966) derived an outburst cycle length of 13.5 d. Bruch, Fischer, and Wilmsen (1987) recorded another outburst. Bruch and Schimpke (1992) obtained a spectrum and established this object as a dwarf nova. Due to the initially reported faintness, this object had not been well studied since then. Since 2005, American Association of



**Fig. 1.**  $O - C$  diagram of superhumps in V1006 Cyg (2015). Upper:  $O - C$  diagram. We used a period of 0.10541 d for calculating the  $O - C$  residuals. The superhump maxima up to  $E = 28$  are stage A superhumps; maxima between  $E = 36$  and  $E = 94$  have a positive period derivative and are identified as stage B superhumps. After this, the period decreased to a constant one (stage C superhumps). Middle: Amplitudes of superhumps. The amplitudes were small around  $E = 0$ . The  $O - C$  diagram suggests that stage A–B transition occurred somewhere between  $E = 28$  and  $E = 36$ . The superhump amplitudes monotonously decreased during the superoutburst. After  $E = 100$ , the amplitudes became large (0.3–0.4 mag) when the object faded. Lower: Light curve. The data were binned to 0.035 d. The initial outburst detection was on BJD 2457215.9, 3 d before the start of our observation. It took 6 d for this object to fully develop stage B superhumps. The maximum on BJD 2457232 is a rebrightening. The maximum on BJD 2457238 is the first normal outburst of regular series of outbursts following a superoutburst. (Color online)

Variable Star Observers (AAVSO) members started regular monitoring using CCDs and recorded an outburst reaching  $V = 13.6$  on 2006 June 24. This outburst lasted for at least 4 d. Sheets et al. (2007) performed a radial-velocity study and obtained  $P_{\text{orb}}$  of 0.09903(9) d. Since this period places the object in the period gap, the slowly fading 2006 outburst was suspected to be a superoutburst. Upon a bright (unfiltered CCD magnitude 13.6) outburst on 2007 August 14, a search for superhumps was conducted (vsnet-alert 9471). Although short-term modulations were detected, these variations were later found to be orbital variations (vsnet-alert 9489). This observation and the observation of a similar bright outburst in 2009 September (vsnet-alert

11490, 11508) were examined in detail by Pavlenko et al. (2014) and the absence of superhumps was confirmed.

On 2015 July 12, the All-Sky Automated Survey for Supernovae (ASAS-SN: Shappee et al. 2014; A. B. Davis et al. 2015<sup>1</sup>) detected an outburst at  $V = 14.1$  (vsnet-alert 18846). This outburst was detected sufficiently early and the initial phase of the outburst was observed. The object reached  $V = 13.6$  and low-amplitude superhumps were detected on July 15–16 (vsnet-alert 18851). The superhumps were observed to grow until July 18 (BJD 2457222) (see figure 1).

## 2 Observation and analysis

The data were obtained under campaigns led by the Variable Star Network (VSNET) Collaboration (Kato et al. 2004). We also used the public data from the AAVSO International Database.<sup>2</sup> Time-resolved observations were performed in 13 different locations by using 30-cm-class telescopes (supplementary table 2, available online). We deal with observations made until 2015 August 7. The data analysis was performed just in the same way described in Kato et al. (2009) and Kato et al. (2014), and we mainly used R software for data analysis.<sup>3</sup> In de-trending the data, we divided the data into four segments in relation to the outburst phase and used locally weighted polynomial regression (LOWESS: Cleveland 1979) except for the rising segment of a rebrightening. During the rising phase of the rebrightening a third-order polynomial fitting was used instead. The times of superhump 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 Discussion

### 3.1 Identification of superhump stages

The amplitudes of superhumps before BJD 2457220 were small, indicating that we recorded the growing stage (stage A) of superhumps. Although the observations before BJD 2457220 were short and the initial night suffered from poor conditions, observations between BJD 2457221 and 2457223 were of sufficient quality to determine the period in the early phase (supplementary table 3). The  $O - C$  analysis ( $17 \leq E \leq 28$ ) and PDM analysis yielded periods of 0.1073(2) d and 0.1076(1) d, respectively. The period of 0.1075 d (average of the two methods) is 8.5% longer than  $P_{\text{orb}}$ , giving an exceptionally large fractional

<sup>1</sup> Davis, A. B., Shappee, B. J., Archer Shappee, B., & ASAS-SN 2015, Abstract, AAS Meeting #225, id. #344.02

<sup>2</sup> (<http://www.aavso.org/data-download>).

<sup>3</sup> The R Foundation for Statistical Computing (<http://cran.r-project.org/>).

superhump excess. Since the amplitudes of superhumps on BJD 2457221 already approached the maximum, these periods are likely shorter than the true period of stage A superhumps, because the pressure effect starts to dominate when superhumps fully grow and reduces the precession rate (Kato & Osaki 2013). By using this period as an approximate period of stage A superhumps and with the strong expectation that the true period of stage A superhumps is longer than this period, we have been able to resolve the ambiguity in the cycle counts between BJD 2457220 and 2457221. The cycle counts in supplementary table 2 are based on this identification. The resultant mean period of stage A superhumps between BJD 2457219 and 2457223 by the  $O - C$  analysis is 0.1093(3) d, which we consider the best period from the present observations. This period gives  $\epsilon^*$  of 0.094(3), which corresponds to  $q = 0.34(2)$ .

The duration of stage A was at least 32 cycles. Although the true duration of the growing phase of superhumps is unknown in this object due to the observational gap, the close similarity of the  $O - C$  diagram and variation of superhumps amplitudes between V1006 Cyg and MN Dra (supplementary figure 2; available online) suggests it took a long time to develop superhumps in this system. It also took 6 d ( $\sim 60$  cycles) since the outburst detection to fully develop stage B superhumps based on the  $O - C$  diagram. Since this object has relatively frequent outbursts, it is likely that a Case A outburst of Osaki and Meyer (2003) classification should occur in this object. However, the observed delay in superhumps likely reflects the long growth time of superhumps (just like the Case B outburst for a low- $q$  system; in most ordinary SUUMa-type dwarf novae, the growing stage of superhumps is rarely recorded a few days after the outburst detection, see e.g., Kato et al. 2009). This delay in the appearance of stage B superhumps is unusually long for an ordinary SUUMa-type dwarf nova and is even comparable to the case of extreme WZ Sge-type objects (cf. Kato 2015).

After reaching the maximum amplitude, the superhump period became short as in stage B superhumps in ordinary SUUMa-type dwarf novae (Kato et al. 2009; Kato & Osaki 2013). We identified  $40 \leq E \leq 98$  as stage B and obtained a mean period of 0.10541(4) d and a period derivative  $P_{\text{dot}} = \dot{P}/P$  of  $+20.8(2.0) \times 10^{-5}$ . The  $O - C$  analysis indicates that the times of superhumps for  $E \geq 106$  can be expressed very well by a period of 0.10444(5) d, which we consider the period of stage C superhumps.

### 3.2 Mass ratio from stage A superhumps

As described in subsection 3.1, the modern method using stage A superhumps gives a very large mass ratio of

$q = 0.34(2)$ . Since the early part of the observations was not ideally obtained, we give a firmly determined lower limit of the period of stage A superhumps (0.1075 d), which corresponds to  $q \geq 0.26$ . This lower limit is close to the borderline ( $q = 0.24$ ) of the development of superhumps in 3D numerical simulation (Smith et al. 2007). Our best value is close to the limit  $q \sim 0.33$  required to develop the 3:1 resonance under the condition of reduced mass-transfer (Murray et al. 2000). Although our observation suffered from uncertainty due to a gap in the observation, we have demonstrated that the stage A superhump method is applicable to systems close to the stability limit.

### 3.3 Mass ratio and disk radius from stage C superhumps

As described in Kato and Osaki (2013), the precession rate of stage C superhumps can be used to estimate the disk radius if the mass ratio is known, since the pressure effect can be neglected in cool post-superoutburst disks. If the disk radius can be estimated, we can constrain the mass ratio (e.g., Kato et al. 2013b). The measured  $\epsilon^*$  for stage C superhumps of V1006 Cyg is 0.0518(10). This value corresponds to a disk radius of  $0.37A$ , where  $A$  is the binary separation, for  $q = 0.26$ , and  $0.34A$  for  $q = 0.34$ .

### 3.4 Stage B–C transition and rebrightening

The stage B–C transition described in subsection 3.1 occurred during the rapid decline from the superoutburst plateau. This feature is different from the behavior of “text-book” SUUMa-type dwarf novae, in which the stage B–C transition usually occurs during the later part of the superoutburst plateau and is usually associated with a small brightening trend (Kato et al. 2009). In V1006 Cyg, the object instead faded and a rebrightening was recorded after the transition. Six days after this rebrightening, the object underwent another outburst. As judged from the subsequent behavior (E. Pavlenko et al. in preparation), this outburst was the first normal outburst of the regular cycle of normal outbursts.<sup>4</sup>

The origin of the stage B–C transition is still poorly understood. In the present case, it appears that the cooling front started before the termination of the plateau phase, since the first rebrightening occurred only three days after the rapid fading. Although such early occurrence of a rebrightening is rarely met in ordinary SUUMa-type dwarf novae, a similar one was observed in the long- $P_{\text{orb}}$  system MN Dra (see figure 3 in Antipin & Pavlenko 2002). We

<sup>4</sup> The identification as a rebrightening is also based on the similarity in behavior with the SUUMa-type dwarf nova QZ Ser in the period gap (T. Ohshima et al. in preparation), which shows only very infrequent outbursts.

propose that the mass ratio close to the stability border of the 3:1 resonance in V1006 Cyg made it difficult to maintain the tidal instability, and the thermal and tidal instabilities decoupled as proposed for ER UMA-type objects and WZ Sge-type rebrightenings by Hellier (2001). Although Hellier (2001) considered that small  $q$  is responsible for this phenomenon, we can extend the same discussion to objects with large  $q$  close to the stability border of the 3:1 resonance.

It would be worth mentioning that stage B–C transition is not usually observed in WZ Sge-type objects (Kato 2015). It is possible that rapid fading from the superoutburst plateau (often seen as a temporary dip) in WZ Sge-type dwarf novae has the same properties as in V1006 Cyg. The common behavior (termination of the plateau phase before appearance of stage C superhumps, dip-like fading and rebrightening) in WZ Sge-type objects and objects having mass ratios close to the stability border may be understood in a unified way: the small effect of the small tidal torque is unable to maintain the hot state when the cooling front starts.

### 3.5 Comparison with TU Mensae

Up until this work, TU Men was the only established dwarf nova that showed three types of outbursts (normal, long normal, and superoutbursts; the names here are given in modern sense) (Warner 1995b; Bateson et al. 2000). The only other possible example is NY Ser (Pavlenko et al. 2014) which showed outbursts with intermediate durations without superhumps. Since there were outbursts in V1006 Cyg lasting more than six days (2007) and more than five days (2009) without superhumps (Pavlenko et al. 2014), the present detection of a genuine superoutburst makes V1006 Cyg the second case showing three types of outbursts. This indicates that  $P_{\text{orb}}$  above the period gap is not an essential condition for displaying such behavior.

### 3.6 Comparison with other systems

The interpretation that superhumps slowly grow in systems with mass ratios close to the stability limit was first presented in Kato et al. (2014) for MN Dra. Although there still remains uncertainty about  $P_{\text{orb}}$  of MN Dra, and the identification of superhumps stages remains somewhat unclear, the present detection of growing superhumps in V1006 Cyg has established this interpretation. In supplementary table 1, we list the objects that have long orbital (or superhump) periods and long-lasting stage A superhumps. The suspected orbital periods for MN Dra and CRTS J214738.4+244554 are taken from Pavlenko et al. (2010) and Kato et al. (2013a), respectively. By using this period, we could also obtain the mass ratio for CRTS J214738.4+244554 from

stage A superhumps. All the obtained mass ratios are in the range of 0.20–0.34, consistent with the theoretical stability limit.

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## Supporting information

Additional supporting information can be found in the online version of this article:

Supplementary figure 2.

Supplementary tables 1, 2 and 3.

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