Late Superhumps in WZ Sge-Type Dwarf Novae

Taichi Kato
Department of Astronomy, Kyoto University, Sakyo-ku, Kyoto 606-8502
tkato@kusastro.kyoto-u.ac.jp

Hiroyuki Maehara
Kwasan and Hida Observatories, Kyoto University, Yamashina, Kyoto 607-8471

and

Berto Monard
Bronberg Observatory, PO Box 11426, Tijgerpoort 0056, South Africa

(Received 2000; accepted 2000)

Abstract

We report on the detection of very stable modulations with periods unexpectedly (~0.5%) longer than superhump periods during the slowly fading stage of WZ Sge-type superoutbursts in three systems, GW Lib, V455 And and WZ Sge. These periods are naturally explained by assuming that these modulations are superhumps arising from matter near the tidal truncation radius. This finding provides an additional support to the hypothetical idea of expansion of the accretion disk well beyond the 3:1 orbital resonance in some low mass-ratio systems. Combined with the effect of 2:1 resonance, we present an explanation of the origin of positive period derivatives in certain short-period SU UMa-type dwarf novae.

Key words: accretion, accretion disks — stars: novae, cataclysmic variables — stars: dwarf novae — stars: individual (GW Librae, V455 Andromedae, WZ Sagittae)

1. Introduction

Dwarf novae (DNe) are a class of cataclysmic variables (CVs), which are close binary systems consisting of a white dwarf and a red-dwarf secondary transferring matter via the Roche-lobe overflow. SU UMa-type dwarf novae are a class of DNe, which show superhumps during their long, bright outbursts (superoutbursts) [see e.g. Vogt (1980); Warner (1985) for basic observational properties]. The origin of superoutbursts and superhumps in SU UMa-type dwarf novae is basically understood as a consequence of thermal and tidal instabilities in the accretion disk (Osaki 1989; Osaki 1996), the latter being excited by the 3:1 orbital resonance in the disk (Whitehurst 1988; Hirose, Osaki 1990; Lubow 1991). The basic observational properties of ordinary SU UMa-type dwarf novae have well been reproduced by this picture.

WZ Sge-type dwarf novae (see e.g. Bailey 1979; Downes 1990; Kato et al. 2001) are a subgroup of dwarf novae characterized by large-amplitude (typically ~ 8 mag) superoutbursts with very long (typically ~ 10 yr) recurrence times. Although WZ Sge-type dwarf novae are recognized as a subgroup of SU UMa-type dwarf novae, WZ Sge-type dwarf novae are known to have a number of properties hardly, but not necessarily exclusively, observed in “textbook” SU UMa-type dwarf novae. These properties include: (1) the presence of early superhumps (Kato 2002), (2) (sometimes repetitive) rebrightenings (Kato et al. 2004a), (3) nearly constant to positive period derivative (Pdot = P/P) of superhumps (Kato et al. 2001; Kato et al. 2003), and (4) long-lasting fading tails.

The implication of phenomenological relations between some of these properties was first addressed by Kato et al. (1998) [see also Kato et al. (2004a) for more discussions]. Kato et al. (1998) presented an idea that the accretion disk can expand beyond the 3:1 resonance during energetic outbursts in low mass ratio (q = M2/M1) systems exemplified by WZ Sge-type dwarf novae. They argued that the matter beyond the 3:1 resonance can serve as a reservoir supplying matter to the inner disk resulting rebrightenings, and the eccentricity wave propagating outward the 3:1 resonance can explain positive Pdot of superhumps. This idea thus has a possibility to naturally explain many of peculiar properties of WZ Sge-type dwarf novae. Hellier (2001) further introduced an idea of decoupling of thermal and tidal instabilities beyond the 3:1 resonance, and extended the application to ER UMa-type dwarf novae, another subclass of SU UMa-type dwarf novae with similarly low q.

In line with these ideas, Osaki, Meyer (2002) and Osaki, Meyer (2003) presented an overview of an WZ Sge-type outburst based on the disk-instability model of SU UMa-type dwarf novae (Osaki 1989; Osaki 1995), and proposed a new conceptual scheme of classifying SU UMa-type dwarf novae based on q and achievable disk radius. Osaki, Meyer (2003) also explored the dependence of outburst properties on the matter reaching beyond the 3:1 resonance, and presented a scheme of understanding a variety of superoutbursts. The expanded disk beyond the 3:1 resonance in WZ Sge-type dwarf novae and related objects has thus been favored by theoretical sides. Observational evidence, however, for such an expanded disk had long been rather scarce [see Kato et al. (2004a) for description of historical observations], while the recent discovery of
different $P_{\text{dot}}$ of superhumps in a variety of superoutburst in the same system (Uemura et al. 2005) well matched the scenario by Osaki, Meyer (2003), thus strengthening the expanded disk beyond the 3:1 resonance. The infrared excess during the late stage of WZ Sge-type outbursts (e.g. Uemura et al. 2008a; Uemura et al. 2008b) also supports this idea.

In 2007, two spectacular superoutbursts of WZ Sge-type dwarf novae, namely GW Lib and V455 And occurred (Waagen et al. 2007; vsnet-alert 9530). During the later course of these outbursts, we discovered “late superhumps” with unexpectedly long periods and with exceptionally high coherence and stability in their periods. In this letter, we present an interpretation of these late superhumps originating from the very matter beyond the 3:1 resonance.

2. Late Superhumps in GW Lib and V455 And

Both outbursts of GW Lib and V455 And were extensively observed photometrically by the VSNET Collaboration using a network of small telescopes (Kato et al. 2004b). The details of these observations will be presented in separate papers. In addition to early superhumps signifying the WZ Sge-type dwarf nova (in V455 And), ordinary superhumps during the superoutburst plateau (in GW Lib and V455 And), we detected additional hump features persisting after the termination of the superoutburst plateau. The periods of the last modulations were substantially longer than those of orbital periods, and even longer than those of ordinary superhumps, ruling out the possibility of modulations arising from orbital humps. After detecting unequivocal signals in GW Lib and V455 And, we reanalyzed the archival data of the 2001 outburst of WZ Sge (cf. Ishioka et al. 2002) and detected a corresponding signal.\(^1\) The representative periods of these late superhumps are summarized in table 1. Figure 1 shows a comparison of averaged profiles of late superhumps in these three WZ Sge-type dwarf novae.

Figure 2 shows nightly profiles of late superhumps in GW Lib. Although the figure covers 18 d (\(\sim\)330 cycles), the stability of the hump phases is striking. The period changes were almost absent, or the variation was even more exactly periodic than ordinary superhumps. The stability of the periods was less convincing in higher inclination systems V455 And and WZ Sge due to the strong overlapping orbital signals, though the $O-C$ diagram shown in Patterson et al. (2002) suggests a similar degree of stability.

3. Interpretation of WZ Sge-Type Late Superhumps

The most striking feature of late superhumps common to all three WZ Sge-type dwarf novae is their long periods. The fractional superhump excesses ($\epsilon = P_{\text{SH}}/P_{\text{orb}} - 1$) lie between 1.2% and 1.7%, typically \(\sim\)0.5% longer than the ordinary superhump period of the respective object. These very long periods are hard to understand, since period excesses are generally understood to arise from a precessing eccentric disk (Osaki 1985; Hirose, Osaki 1993), whose angular velocity ($\omega_p$) has radial dependence of $\omega_p \propto R_d^{3/2}$, where $R_d$ is the radius of the accretion disk (Osaki 1985), and the disk is expected to have shrunk after the outburst.\(^2\)

The situation, however, drastically varies by simply assuming the accretion disk beyond the 3:1 resonance contributes to these late superhumps. Using the radial dependence of $\omega_p$ and assuming that ordinary superhumps arise from the radius of 3:1 resonance ($R_{3:1}$), we can expand the disk beyond the radius of 3:1 resonance in a different context of disk evolution.

\(^{1}\) Patterson et al. (2002), using a slightly different set of data from ours, also detected the same periodicity and gave a period of 0.05736(5) d but they identified it as being traditional late superhumps (Vogt 1983; Hessman et al. 1992)

\(^{2}\) Howell et al. (1996) suggested an interpretation assuming the
Late Superhumps in WZ Sge-Type Dwarf Novae

Table 1. Periods of late superhumps.

| Object     | $P_{\text{orb}}$ | $P_{\text{sh}}$ | $P_{\text{lsb}}$ | JD range | $q$ (adopted) | $R_d$ |
|------------|------------------|------------------|------------------|----------|---------------|-------|
| GW Lib     | 0.055322(2)      | 0.053925(4)      | 0.054156(1)      | 2454230–245 | 0.062         | 0.58  |
| V455 And   | 0.05630921(1)    | 0.05697(1)       | 0.057280(4)      | 2454367–378 | 0.064         | 0.61  |
| WZ Sge     | 0.0566878460(3)  | 0.05721(5)       | 0.057408(4)      | 2452182–210 | 0.050         | 0.59  |

* Orbital period (d).
† Period of ordinary superhumps (d) (see text).
‡ Period of late superhumps (d).
§ Range of JD for determining the periods of late superhumps.
∥ Radius (unit in binary separation) corresponding to the fractional period excess of late superhumps (see text).

References: GW Lib: Thorstensen et al. (2002); vsnet-outburst 7773; V455 And: Araujo-Betancor et al. (2005); vsnet-alert 9326, 9642; WZ Sge: Steeghs et al. (2001); Patterson et al. (2002); Ishioka et al. (2002)

4. Positive Period Derivatives of Superhumps – Toward Unified Picture of Variety of Superoutbursts

Some of WZ Sge-type dwarf novae and short-period SU UMa-type dwarf novae show positive $P_{\text{dot}}$ of ordinary superhumps (Kato et al. 2001; Kato et al. 2003). Uemura et al. (2005) interpreted that this period increase reflects the propagation of eccentricity wave beyond the $R_{3:1}$ [see also Kato et al. (1998)]. It was unclear, however, what regulates the wave propagation.

We here propose that the 2:1 resonance occurring in the outermost disk governs the range where 3:1 resonance can appear. Following the discussion in Osaki, Meyer (2003), the 2:1 resonance suppresses the growth of 3:1 resonance. In extreme cases as in the early stage of WZ Sge-type superoutbursts, the 2:1 resonance can be strong enough to entirely suppress the 3:1 resonance. As the superoutburst proceeds and the matter is swept from the outer region, this effect weakens and enables the 3:1 resonance to grow in the inner region. As a natural extension to this interpretation, we consider that the strength of the
2:1 resonance determines the limit of radius inside which eccentricity can grow. When this radius is smaller than \( R_{3:1} \), ordinary superhumps cannot grow [this corresponds to the delay in appearance of ordinary superhumps in WZ Sge-type dwarf nova (Osaki, Meyer 2003)].

Ordinary superhumps grow when this limit becomes larger than the radius of the 3:1 resonance. Subsequent behavior will depend on the mass and state of the disk beyond \( R_{3:1} \). In extreme cases as in typical WZ Sge-type dwarf nova, the strength of the 2:1 resonance can be strong enough to accrete much of the matter beyond \( R_{3:1} \) (as in the snow-plowing effect in SU UMa-type superoutburst, Osaki 1989), leading to a cold, low-mass disk outside \( R_{3:1} \). Even if the eccentricity wave can propagate into this region, it would not produce a strong superhump signal. This could explain why \( P_{\text{dot}} \) is almost zero in most WZ Sge-type dwarf nova. In less extreme cases with similar or slightly larger \( q \) but with weaker 2:1 resonance (assuming that the disk can transiently expand beyond the tidal truncation radius, see also Osaki, Meyer 2003), the resonance itself or its effect diminishes before the matter beyond \( R_{3:1} \) is efficiently cleared. In such cases, still ionized sufficient matter beyond the 3:1 resonance could produce ordinary superhumps with increasing periods as the limit moves outward. The recent discovery of short-lived early superhumps and positive \( P_{\text{dot}} \) in a larger \( q \) system, BC UMa (Maehara et al. 2007), as well as an earlier example of RZ Leo (Ishioka et al. 2001), supports this idea. In most SU UMa-type dwarf nova with larger \( q \), the mass beyond \( R_{3:1} \) is too small to show increasing periods regardless of the condition of the 2:1 resonance. This interpretation can explain why systems with large positive \( P_{\text{dot}} \) are restricted to a relatively small region with intermediate orbital periods.

This interpretation, as in Osaki, Meyer (2003), proposes that suppression of the 3:1 resonance by the 2:1 resonance is the significant cause of long delays of appearance of ordinary superhumps in WZ Sge-type superoutburst, rather than the effect of slow growth of the 3:1 resonance in small \( q \) systems in traditional view (Osaki 1996). In systems that somehow enables 2:1 resonance, this interpretation predicts variable delay times of appearance of ordinary superhumps even in the same object depending on the disk mass at the onset of superoutbursts (Osaki, Meyer 2003; Uemura et al. 2005). If the growth rate of the 3:1 resonance depending \( q \) is the main factor determining this delay, such variation would not be expected. This prediction seems to be confirmed by past observation in SW UMa (\( q = 0.11 \), Patterson et al. 2005): the delay was 6–11 d for a very bright \((m_v = 9.6 \text{ at maximum}) \) superoutburst in 1986 (Robinson et al. 1987), 5–6 d for a bright \((m_v = 10.1) \) one in 2006 September (vsnet-alert 9018) while it was only \( \lesssim 3 \) d for the 2002 one (Kato et al. 1992, \( m_v = 10.8 \) at maximum). Systematic future observations of superoutbursts of various scales will be a key in testing this interpretation.

The author is grateful to observers of VSNET Collaboration who supplied vital data.

References

Araujo-Betancor, S., et al. 2005, A& A, 430, 629
Bailey, J. 1979, MNRAS, 189, 41P
Downes, R. A. 1990, AJ, 99, 339
Heller, C. 2001, PASP, 113, 469
Hessman, F. V., Mantel, K.-H., Barwig, H., & Schoembs, R. 1992, A&A, 263, 147
Hirose, M., & Osaki, Y. 1990, PASJ, 42, 135
Hirose, M., & Osaki, Y. 1993, PASJ, 45, 595
Howell, S. B., DeYoung, J. A., Mattei, J. A., Foster, G., Szody, P., Cannizzo, J. K., Walker, G., & Fierce, E. 1996, AJ, 111, 2367
Ishioka, R., et al. 2001, PASJ, 53, 905
Ishioka, R., et al. 2002, A&A, 381, L41
Kato, T. 2002, PASJ, 54, L11
Kato, T., Hirata, R., & Mineshige, S. 1992, PASJ, 44, L215
Kato, T., Nogami, D., Baba, H., & Matsumoto, K. 1998, in ASP Conf. Ser. 137, Wild Stars in the Old West, ed. S. Howell, E. Kuulkers, & C. Woodward (San Francisco: ASP), 9
Kato, T., Nogami, D., Matsumoto, K., & Baba, H. 2004a, PASJ, 56, S109
Kato, T., et al. 2003, MNRAS, 339, 861
Kato, T., Sekine, Y., & Hirata, R. 2001, PASJ, 53, 1191
Kato, T., Uemura, M., Ishioka, R., Nogami, D., Kunjaya, C., Baba, H., & Yamada, H. 2004b, PASJ, 56, S1
Lubow, S. H. 1991, ApJ, 381, 259
Maehara, H., Hachisu, I., & Nakajima, K. 2007, PASJ, 59, 227
Murray, J. R. 2000, MNRAS, 314, 1P
Osaki, Y. 1985, A&A, 144, 369
Osaki, Y. 1989, PASJ, 41, 1005
Osaki, Y. 1995, PASJ, 47, 47
Osaki, Y. 1996, PASP, 108, 39
Osaki, Y., & Meyer, F. 2002, A&A, 383, 574
Osaki, Y., & Meyer, F. 2003, A&A, 401, 325
Patterson, J., et al. 2005, PASP, 117, 1204
Patterson, J., et al. 2002, PASP, 114, 721
Robinson, E. L., Shafter, A. W., Hill, J. A., Wood, M. A., & Mattei, J. A. 1987, ApJ, 313, 772
Smith, A. J., Haswell, C. A., Murray, J. R., Truss, M. R., & Foulkes, S. B. 2007, MNRAS, 378, 785
Steeghs, D., Marsh, T., Knigge, C., Maxted, P. F. L., Kuulkers, E., & Skidmore, W. 2001, ApJL, 562, L145
Thorstensen, J. R., Patterson, J. O., Kemp, J., & Vennes, S. 2002, PASP, 114, 1108
Uemura, M., et al. 2008a, PASJ, 60, 227
Uemura, M., et al. 2008b, Inf. Bull. Variable Stars, 5815, 1
Uemura, M., et al. 2005, A&A, 432, 261
Vogt, N. 1980, A&A, 88, 66
Vogt, N. 1983, A&A, 118, 95
Waagen, E. O., Schmeer, P., Stubbings, R., & Pearce, A. 2007, IAU Circ., 8829
Warner, B. 1985, in Interacting Binaries, ed. P. P. Eggleton, & J. E. Pringle (Dordrecht: D. Reidel Publishing Company), 367
Whitehurst, R. 1988, MNRAS, 232, 35