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WZ Sge-type dwarf novae: an extreme laboratory in cataclysmic variables

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WZ Sge-type dwarf novae form one of the most intriguing classes of compact accreting binaries. They are recognized as the most evolved population of hydrogen-rich cataclysmic variables. Yet they exhibit energetic disk-powered outbursts with an amplitude of 6–9 mag, duration of a month, and decade-long outburst cycles. Despite the dramatic increase in the number of WZ Sge stars over the last decades, there are many unresolved questions, both in terms of their binary evolution and outburst mechanism. In this proceeding paper, I review the recent studies on WZ Sge stars, focusing on their outbursts. Recent observations, both photometrically and spectroscopically, have found the absence of enhanced emission from the hotspot during the early outburst rise in WZ Sge stars, casting doubt on the occurrence of the enhanced mass transfer. Meanwhile, several WZ Sge stars are newly suggested to harbor a magnetic white dwarf, inferring an inner disk truncation in quiescence. Diversity among systems has been discovered: a WZ Sge star with superoutbursts both accompanying and lacking an early superhump phase, one possibly harboring an ONe and massive white dwarf, and one showing optical spectra strongly affected by disk winds. I introduce the connections of WZ Sge stars to period bouncers, helium-rich AM CVn stars, and low-mass X-ray binaries. Finally, prospects of WZ Sge stars in the upcoming time-domain surveys, such as the Rubin Observatory LSST, are presented.

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1. Introduction

Among various subtypes of dwarf novae (DNe; see a review [1, 2]), WZ Sge-type DNe are characterized by their short orbital period ($P_{\rm orb} \simeq 0.05$–0.06 d), low mass-transfer rate ($\dot{M}_{\rm tr} \sim 10^{15}$ g s^{-1}), and small mass ratio ($q \leq 0.1$), yet showing energetic accretion-powered outbursts with an outburst amplitude of 6–9 mag, outburst duration of 3–4 weeks, and outburst cycle of decades in optical [3]. Indeed, the prototype star WZ Sge was initially classified as a recurrent nova due to its large amplitude and long outburst cycle. This view was altered around 1980, when various authors [4–6] found that its photometric and spectroscopic properties in the 1978 outburst are consistent with DN outbursts rather than nova eruptions. This was exactly when the disk instability model (DIM) of DN outbursts had been established [7, 8]. Soon after, various authors have pointed out that the simple DIM with a low mass-transfer rate cannot explain its outburst energetics (e.g., [9]).

1.1 Optical light curves

As mentioned above, WZ Sge stars show the most energetic outbursts among DNe (Figure 1). All their outbursts are accompanied by small modulations with a period close to the orbital one, known as superhumps (right panels of Figure 1). Based on the changes in superhump periods and profiles, a superoutburst in a WZ Sge star is divided into several phases. Approximately in the first half of the superoutburst, double-peaked modulations with a period equal to the orbital one are observed, known as early superhumps. This is understood as a geometrical effect of the vertically extended double arm structure excited by the 2:1 tidal resonance, only in a system with a mass ratio lower than 0.08 [10, 11]. The detection of early superhumps is regarded as a criterion of a WZ Sge star in the current classification regime of DNe. They are followed by ordinary superhumps, with a single-peaked profile and a period a few percent longer than the orbital one, excited by the 3:1 tidal resonance [12]. These ordinary superhumps show essentially the same behavior as those in SU UMa-type DNe without the excitement of 2:1 resonance, explained in the thermal-tidal instability (TTI) model [13, 14].

1.2 Discovery statistics

As of July 2025, about 350 systems are registered as a WZ Sge star (or its candidate) in the AAVSO VSX [17]. The left panel of Figure 2 shows the annual number of new WZ Sge stars discovered through an outburst. This is limited by the performance of time-domain surveys and, more importantly, the limiting magnitude of small-aperture telescopes, which are used to determine the superhump properties. Hence, WZ Sge stars fainter than 16 mag at outburst maximum are largely missed. The right panels of Figure 2 show the distribution of WZ Sge stars in the Galactic coordinate. This clearly indicates their Galactic disk origin.

1.3 Binary evolution

In addition to the importance of WZ Sge stars in the context of the DIM, they are a benchmark population among close binary systems, because they represent the most evolved state of low-mass binary systems. However, it has been pointed out that there is a large discrepancy between the volume density of CVs in models and observations [18]. The population models also predict that a large fraction (40–70%) of Galactic CVs must evolve beyond the period minimum, which does not

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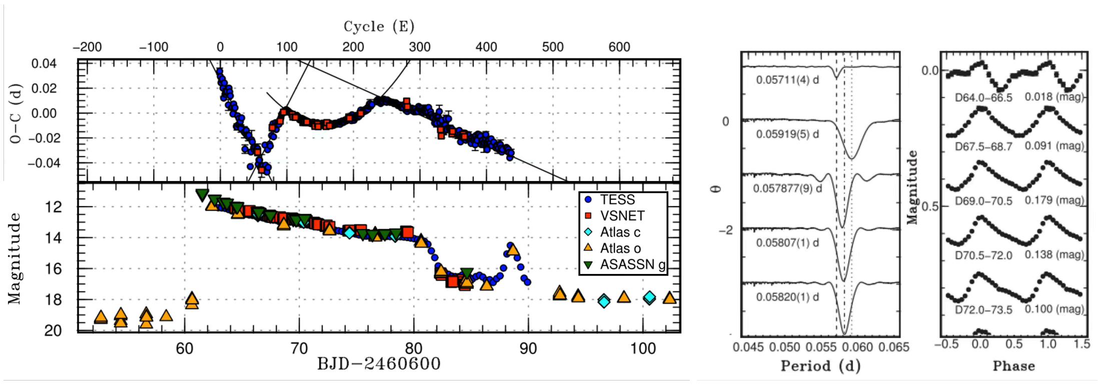

Figure 1: Left panels; the $O - C$ diagram of superhump maxima (top) and optical light curve (bottom) of a WZ Sge star ASASSN-24hd observed by TESS (blue circles) and through the VSNET collaboration (red squares; [15]). The solid lines in the $O - C$ diagram represent the periods of early, stage-A, stage-B, and stage-C superhumps. Right panels: best periods in PDM analysis (left) and phase-averaged profiles of superhumps of different phases (right). Data is taken from [16].

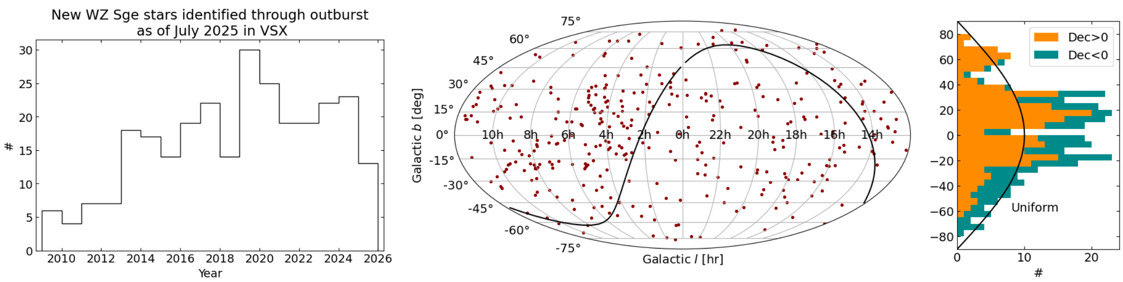

Figure 2: Left panel; the yearly number of new discoveries of WZ Sge stars through their outburst, according to VSX. Right panel; the sky distribution of WZ Sge stars in the Galactic coordinate. The black line on the right panel represents the uniform distribution on the sky sphere ($\propto \cos b$).

agree with the observations [18]. It is worth noting that since the period bounce happens around a mass ratio of 0.08 [19], an outburst in a period bouncer system must be a WZ Sge-type DN outburst. Superhump observations of WZ Sge stars are advantageous in studies of CV evolution because (1) early superhumps provide the orbital period, and (2) superhump excess over the orbital period is linked to the mass ratio [20, 21]. Moreover, these observations are done when a system is in outburst and bright, compared to the eclipse and radial velocity observations obtained in faint quiescence.

2. Remaining questions on WZ Sge-type dwarf novae

Besides the successful explanation of DN outbursts of SS Cyg stars and SU UMa stars with DIM, it has been found that the DIM simply lowering the mass-transfer rate may not reproduce the long faint quiescence and following energetic outbursts of WZ Sge stars. This is mainly because the total disk mass not triggering an outburst $M_{\rm disk,max}$ (Equation 1; [9]) and outburst recurrence time $t_{\rm rec}$ (Equation 2; [22]) are described as a function of the disk viscosity in quiescence $\alpha_{\rm c}$ and the mass transfer rate $\dot{M}_{\rm tr}$.

$$M_{\rm disk,max} = 5.6 \times 10^{21} {\alpha_{\rm c}}^{-0.79} \text{ g} \tag{1}$$

$$t_{\rm rec} \sim 4 \left(\frac{\alpha_{\rm c}}{10^{-2}}\right)^{-0.8} \left(1 - \frac{\dot{M}_{\rm acc}}{\dot{M}_{\rm tr}}\right)^{-1} \text{ yr} \tag{2}$$

From these equations, it is clear that lowering just the mass-transfer rate (and accretion rate) results in outbursts with a longer outburst cycle but similar energetics to standard SU UMa stars, triggered at the inner disk due to a lower mass-transfer rate. To solve this, two possibilities have been mainly proposed. The first is the TTI model with very low disk viscosity in quiescence ($\alpha_{\rm c} \leq 0.001$ compared to 0.01 in standard SU UMa stars) [9, 23], as clear in the equations above. Another approach with the 'standard' quiescence viscosity ($\alpha_{\rm c} \simeq 0.01$) is the truncation of the inner disk by either the magnetosphere of the white dwarf (WD) or the evaporation effect in quiescence [22, 24], which prevents the matter from inflowing into the inner disk and stabilizes the disk. These authors also claim that, in this case, an outburst in WZ Sge stars must be triggered and maintained by the enhanced mass transfer from the secondary star, because such a truncated disk only contains disk mass an order of magnitude less than that required to trigger an outburst. Some works employ a hybrid approach with a low quiescence viscosity, inner disk truncation, and constant mass transfer rate [25, 26]. Here in this section, I review some recent works that provide insight into understanding their outburst scenarios and diversity.

2.1 What enables a long outburst cycle?

As mentioned above, a large magnetosphere of the magnetized WD is one of the proposed mechanisms of the inner disk truncation. Although the intermediate-polar (IP) nature of WZ Sge itself was initially proposed in the 1980s [27], it remains unclear if this is a universal characteristic of the subtype. Thanks to the development of observation facilities, the number of short-$P_{\rm orb}$ CVs with the detection of the (possible) WD spin period has increased dramatically over the last decade [28–34]. Figure 3 shows the orbital and spin periods of these samples. Although once an empirical evolutionary path of the orbital and spin periods has been suggested (gray area in Figure 3; [30]), it is clear that they widely spread around on this diagram, suggesting a diverse nature of their inner disk truncation, rather than uniform. In addition, QPOs observed in some WZ Sge stars in quiescence are also attributed to the magnetic nature of the WD [35]. It must be noted that, however, this is not a comprehensive view of the magnetic WDs in short-$P_{\rm orb}$ CVs at all, as the detection and confirmation of a spin period require high-quality data for a long enough baseline.

In the framework of DIM, an accretion disk must accumulate its mass over the years in quiescence. A possible evidence of this has been found in V3101 Cyg, one of the closest WZ Sge stars, which showed a gradual brightening ($\simeq -0.1$ mag year^{-1}) for five years before an outburst [36]. Since the typical quiescence brightness of WZ Sge stars is 20 mag or fainter, future time-domain surveys such as LSST will be capable of testing whether this is a universal trend in WZ Sge stars.

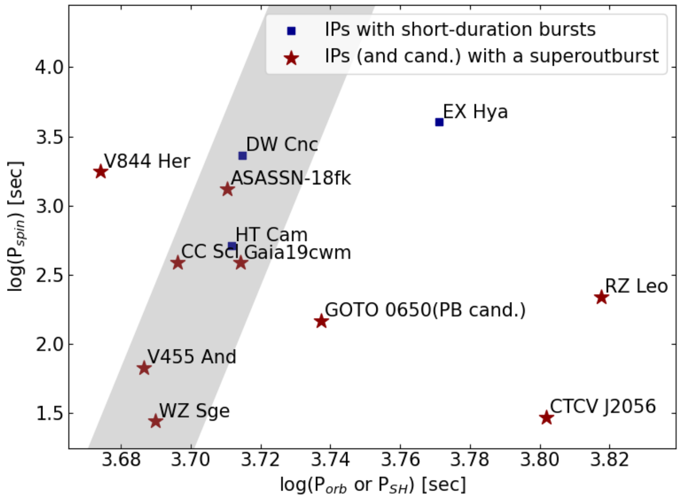

Figure 3: The orbital periods vs the spin periods of short-$P_{\rm orb}$ CVs with burst-like natures [28–34]. The stars represent a system with a superoutburst (i.e., triggered by thermal instability), while squares represent one with short-lived bursts which are not likely triggered by disk instability. PB stands for a period bouncer candidate. The gray area roughly represents the proposed evolutionary path on this diagram [30].

2.2 How does a system undergo an outburst?

One of the natural expectations from the increase in the mass transfer rate is the enhanced emission from the hot spot. Thanks to the continuous coverage of TESS, the early rise of the outburst of V748 Hya was well traced, reporting the non-detection of the hot spot at the level of $\leq 1 \times 10^{31}$ erg s^{-1} [37]. This limits the corresponding mass-transfer rate to be below 1×10^{16} g s^{-1}. This value is well smaller than the expected mass-transfer rate $\simeq 1 \times 10^{18} (10^{19})$ g s^{-1} to transfer 10^{24} g over 10 (1) days, giving a strong constraint on the occurrence of the mass transfer burst at the beginning of an outburst. Another constraint is provided by the coincident time-resolved spectroscopy on the rise of the 2007 superoutburst of V455 And [38], which does not report any evidence of the enhanced hotspot in their Doppler maps during the outburst rise.

The well-observed Kepler and TESS light curves show a double-powerlaw rise in the flux scale [37, 39], broken when the system is just $\simeq 1\%$ brightness of the outburst maximum. Although its physical origin is yet unclear, the simulation work also shows a break at a similar flux level and timing, which is attributed to the start of the heating wave propagating across the entire disk [40].

2.3 What explains their diverse outbursts?

The modifications of either a lower quiescence viscosity or an inner disk truncation to the original DIM were initially proposed to explain the outbursts of WZ Sge itself. However, with hundreds of WZ Sge stars known today, a comprehensive view of their diversity is a key to deepening our understanding of the DIM.

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2.3.1 Borderline between SU UMa stars and WZ Sge stars

In the classification scheme of CVs, WZ Sge stars are categorized as a special subtype of SU UMa stars, characterized by the lowest mass ratios. However, it remains unclear if there is a clear borderline between standard SU UMa stars and WZ Sge stars. For example, several WZ Sge stars with a mass ratio presumably larger than 0.1 have been reported [41]. Moreover, various authors [36, 37, 42, 43] have found some WZ Sge stars that exhibit superoutbursts not only accompanied by the early superhump phase but also lacking one. The latter superoutbursts are characterized by smaller outburst amplitude and shorter outburst duration, observed within a few years after the main superoutburst with early superhumps. This fact proves that, although the mass ratio determines whether a system can excite the 2:1 resonance, the disk mass at the onset of an outburst is a more significant factor in determining whether the disk reaches the 2:1 resonance radius or not in a respective outburst.

2.3.2 MASTER OT J030227.28+191754.5

Among the known WZ Sge stars, MASTER OT J030227.28+191754.5 (hereafter J0302) showed a very distinctive light curve of the outburst [44, 45], with 10.2-mag amplitude and 60-d duration. Figure 4 compares it to other WZ Sge stars in its optical light curve (left) and absolute magnitudes (right), making it the most energetic DN outburst ever. However, its orbital period and mass ratio are well within the range of WZ Sge stars, and its superhump properties agree with the TTI model. Moreover, its X-ray spectrum at the outburst maximum exhibits a blackbody component with a luminosity of $\simeq 10^{34}$ erg s^{-1} and a temperature of $\simeq$30 eV. By interpreting that this blackbody comes from the optically-thick boundary layer around the WD, its WD mass is estimated as 1.15–1.34 $M_{\odot}$ [44]. Hence, J0302 is the first CV system with a massive ONe WD around the period minimum. Moreover, in the most massive case, the total mass in the binary exceeds the Chandrasekhar mass, proposing a new evolutionary path to the accretion-induced collapse of an ONe WD. It was discussed that, however, this massive WD itself may not fully explain the observed energetics of the outburst, but even lower quiescence viscosity than other WZ Sge stars may be required in the context of the TTI model [45].

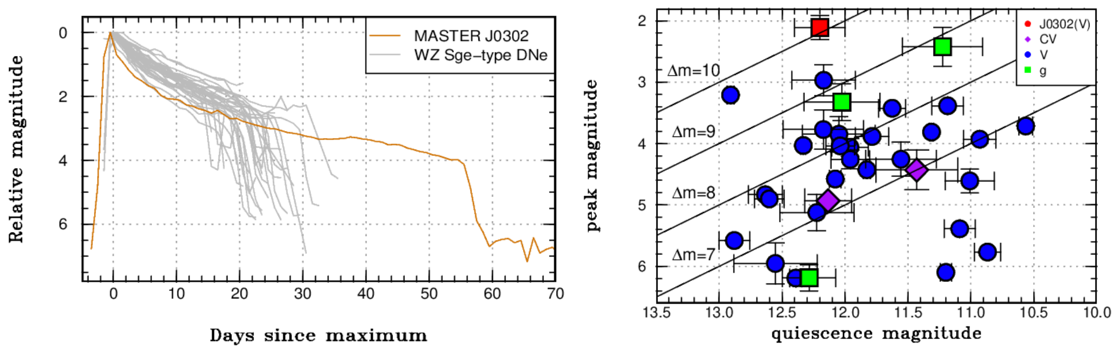

Figure 4: Left panel; the optical light curve comparison of J0302 (orange) and other WZ Sge stars (gray), normalized at the outburst maxima. Right panel; the absolute magnitudes in quiescence and at the outburst maximum of WZ Sge stars. The solid lines represent the outburst amplitudes of 7–10 mag.

2.3.3 Disk wind laboratory

Outflows in compact binaries, such as disk winds and jets, may also regulate disk instability and binary evolution [46, 47]. Our understanding of disk winds in disk-dominated CVs has been established mainly by UV spectra, which contain P-Cygni features in some resonance lines [48]. On the other hand, the disk atmosphere is attributed to the main source of optical emission lines in the majority of WZ Sge stars in outburst [49]. The left panel of Figure 5 represents the equivalent widths (EWs) of Hα and He II 4686 of WZ Sge stars around the outburst maximum, mostly observed with the Seimei telescope in Okayama, Japan [50]. The systems with Hα in absorption (positive EW) and no He II can be explained by a face-on optically-thick disk. Some systems with moderate emission of He II are in fact an eclipsing system, and show a double-peaked profile of emission lines. Thus, emission lines likely originate from the rotating disk atmosphere. There are two systems with distinctively strong emission lines in both Balmer and He II (V455 And and J0302) [45, 51]. Since their line profiles are dominated by the component narrower than the expectation from a Keplerian disk (right panels of Figure 5), their origin seems to differ from other systems.

A simulation effort has been performed to reproduce these peculiar spectral features (colored lines in the right panels of Figure 5; [52]). These authors find that the disk wind model (Model A in the figure), which has been developed to explain the UV spectral features [48, 53], can reasonably reproduce the observed spectrum of V455 And, once a disk accretion rate an order of magnitude higher than previous studies is applied (Model II in the figure). Such a high accretion rate of order of $\dot{M}_{\rm acc} \simeq 10^{-7} M_\odot\ {\rm yr}^{-1}$ is implied from their bright optical continuum. Thus, high accretion rates are presumably the main cause of the significant appearance of disk wind signatures in these intrinsically bright systems.

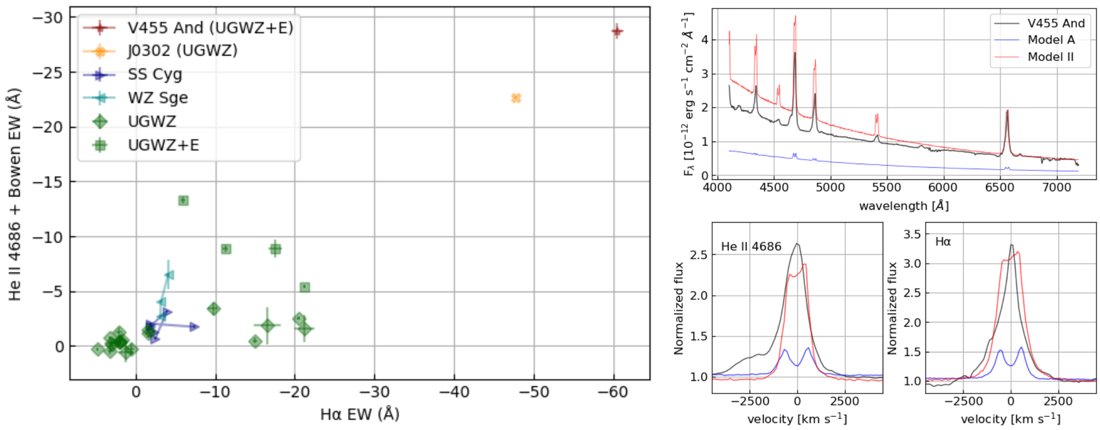

Figure 5: Left panel; the EWs of Hα and He II 4686 around the outburst maximum of WZ Sge stars (references in [49], [45, 51] and ATel reports with the observations from the Seimei telescope). Right panel; the observed spectrum of V455 And at its outburst maximum (black; [51]) and simulated spectra with disk wind models (blue and red; [52]).

2.4 Application to other accreting binaries

In addition to the intriguing nature of WZ Sge stars themselves, physics studied in WZ Sge stars has been applied to other compact binary systems. One such example is identifying a period bouncer candidate based on the outburst light curve, which is essentially a WZ Sge star with the lowest mass ratios. As many authors have pointed out (e.g. [14, 20]), superoutburst and superhump properties are strongly linked to the mass ratio of a system. For example, the dip in the middle of the superoutburst plateau (type-E rebrightening episode), as well as negative $P_{\rm dot}$ in stage-B ordinary superhumps and slow decline timescale in the ordinary superhump phase, are regarded as the smoking-gun features of a superoutburst in a period bouncer system [54, 55]. The mass ratio becomes lower than 0.1 for helium-rich AM CVn stars with an orbital period longer than ≃30 min [56], which enables the excitation of the 2:1 tidal resonance and WZ Sge-like behavior. Indeed, early superhumps and superhump properties, the same as hydrogen-rich WZ Sge stars, have been observed in some AM CVn systems [57–59]. Low-mass X-ray binaries (LMXBs) are not an exception. Both in WZ Sge stars and the LMXB MAXI J1820+70, the change of X-ray properties at the transition of the superhump stages has been observed [60, 61]. These authors interpret that this change in X-ray reflects the geometrical change of the inner disk by the propagation of eccentricity.

3. Bright future of WZ Sge-type dwarf novae

3.1 New catalogs of WZ Sge star candidates

It has been almost half a century since WZ Sge was confirmed as a DN system in its 1978 superoutburst, and even longer since its identification as an accreting WD binary (e.g., [62]). However, the vast majority of new WZ Sge stars are still discovered through their superoutbursts, and little is known about their quiescence and dormant systems. This has been changed thanks to Gaia and its parallax measurements. Combining with eROSITA and SDSS [63, 64], these authors compiled the list of new accreting WDs, including some candidates around or even below the period minimum. Long-term observations by time-domain surveys are expected to detect their infrequent outbursts, and indeed some are observed. Their superhumps in outburst offer a great opportunity to validate their binary parameters, such as orbital period and mass ratio.

3.2 WZ Sge stars in the upcoming instruments; LSST and LISA

The upcoming facilities and instruments are also expected to discover many new CVs and to improve our understanding of WZ Sge stars. The Rubin Observatory LSST is about to start its operation at the end of 2025. The mock observation simulations predict the detection of more than one thousand outbursts from WZ Sge stars every year down to 24 mag by LSST [65]. These authors also claim that LSST will provide a unique test case for the DIM and CV evolution models in globular clusters and Magellanic clouds, which have different star formation histories and environments compared to the solar neighborhood. Along with AM CVn stars, some WZ Sge stars are considered to be detected by the future space-based interferometer for gravitational waves like LISA [66, 67].

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3.3 Brightest WZ Sge stars

Lastly, the brightest systems should not be forgotten. The outburst cycle of the prototype WZ Sge varies between 23 to 33 years. Because it has already been 24 years since its last outburst in 2001, it may undergo a new outburst anytime now. GW Lib is expected to outburst in the 2030s based on its previous two outbursts in 1983 and 2007. It has also been more than 10 years since the last outburst of the bright systems V455 And in 2007 and BW Scl in 2011. Outbursts in these systems will provide the best observation opportunity to test various remaining questions above with cutting-edge multi-wavelength facilities. I finally stress that classical time-resolved observations of superhumps from both professional and amateur astronomers are also strongly encouraged.

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