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The accretion discs in WZ Sge-type stars in deep quiescence. How do they outburst?

Vitaly Neustroev,[a,*] **Paula Kvist,**[a] **Miikka Siitonen**[a] **and Veera Vuolteenaho**[a]

[a] *Space Physics and Astronomy research unit, PO Box 3000, FIN-90014 University of Oulu, Finland*

E-mail: `vitaly@neustroev.net`

WZ Sge-type stars are an extreme subclass of dwarf novae characterised by very rare, large-amplitude superoutbursts. Within the disc instability model (DIM), such events are explained as being triggered by enhanced mass transfer from the donor star. We present an analysis of observations of a sample of WZ Sge-type systems in deep quiescence to assess the consistency of DIM predictions with their observed properties. We find that accretion discs in quiescent WZ Sge-type systems have very low mass-accretion rates of a few $\times 10^{-13}$ M$_\odot$ yr^{-1}. The discs are entirely optically thin, and their physical conditions – such as surface density and effective temperature – remain well below the DIM thresholds required to trigger an outburst. Observationally, no increase in disc brightness is detected prior to the superoutburst, indicating the absence of a transition to an optically thick state, in contrast to DIM predictions of a gradual disc thickening preceding the instability. We therefore find no observational evidence that superoutbursts in WZ Sge-type systems are triggered by enhanced mass transfer from the donor. Furthermore, the inferred mass-transfer rates in these objects ($\dot{M}_{\rm tr}\sim 5\times 10^{-12}$ M$_\odot$ yr^{-1}) are at least an order of magnitude lower than commonly assumed. We argue that the widely adopted value of $\dot{M}_{\rm tr}$ for the prototype object WZ Sge is likely overestimated. Finally, we show that in quiescence the accretion disc radius in all systems is close to the tidal truncation radius and exceeds the 3:1 resonance radius, confirming earlier results and calling into question the standard interpretation of superhump formation.

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1. Introduction

Cataclysmic variables (CVs) are interacting binary systems with a white dwarf (WD) as the primary component and a low-mass star as the secondary component. The Roche-lobe filling secondary loses matter via the inner Lagrangian point to the primary. In the absence of a strong magnetic field, the material transferred from the donor star forms an accretion disc around the WD and progressively spirals down onto its surface [1]. The mass transfer rate in CVs decreases as they evolve from longer to shorter orbital periods [2]. When the mass-transfer rate falls below a critical threshold, the disc may undergo thermal instability, leading to outbursts [3]. CVs which undergo such outbursts are named dwarf novae (DNe). The disc instability model (DIM) is the most commonly used model to explain outbursts and their onset (see [4, 5] for review).

The DIM reproduces reasonably well many of the main characteristics of ordinary DNe. However, the DIM, in its basic form, was unable to account for certain defining features observed in other DN subclasses, such as the Z Cam- and SU UMa-types of DNe. The model must be enriched by including physical processes that may enable the reproduction of those objects' observational properties [6]. For example, in SU UMa-type stars[1], the binaries with low mass ratios q ($\equiv M_2/M_{\rm wd}$, where M_2 and $M_{\rm wd}$ are the masses of the donor and WD, respectively), their superoutbusts and superhumps are due to a tidal-thermal instability (TTI), first proposed by Osaki [7]. According to the TTI model, during a normal outburst, the accretion disc expands and then, during the following quiescence period, contracts with time, settling into a slightly larger radius than before the outburst. After several cycles, the disc radius reaches the 3:1 resonance radius that triggers the TTI, which, in combination with the standard thermal-viscous instability, results in a superoutburst [4, 8–10].

However, despite its success in explaining observational features of superoutbursts in ordinary SU UMa-type DNe, the DIM fails to reproduce some of the fundamental properties of superoutbursts in WZ Sge-type stars. DNe of the WZ Sge type compose an extreme subgroup of SU UMa-type stars, which show very rare (approximately once a decade), large-amplitude (up to 9-10 mag) superoutbursts lasting for 3–5 weeks, while normal (lower amplitude and shorter duration) outbursts are extremely sporadic or not observed at all. Although WZ Sge-type stars were rare until recently, their number has increased dramatically since the mid-2000s, with a discovery rate of a few dozen per year, approaching now to 300-400 objects.[2] There is a strong reason to believe that this number (~10% of a few thousand of currently known CVs) is just the tip of an iceberg. According to standard evolutionary theory [2], the majority of the present-day CVs should have already evolved to short orbital periods and now concentrate close to the so-called period minimum [12]. Being faint and beyond our ability to detect or recognise them, they create a dormant population of accreting white dwarfs (AWDs). However, such objects will eventually, sooner or later, undergo a superoutburst and become WZ Sge-type CVs if we are fortunate enough to discover them.

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[1] SU UMa-type stars are short-period DNe ($P_{\rm orb}\lesssim$2 hr, with a few longer period examples) exhibiting two types of outbursts — normal outbursts lasting a few days, and superoutbursts which have a larger amplitude and a longer duration of a few weeks. The defining property of superoutbursts is the presence of superhumps, low-amplitude modulations with a period of a few per cent longer than the orbital one.

[2] Unfortunately, there is currently no up-to-date catalogue of WZ Sge-type DNe accessible to the community. To address this gap, we are in the process of compiling a new catalogue tailored to the needs of our study (Neustroev et al., in prep). It already includes more than 300 objects, more than triple the number since Kato's (2015) review [11].

Thus, WZ Sge-type stars are among the most populous subtypes of CVs. However, despite their great importance for a vast range of astrophysical questions, the DIM still fail to reproduce their behaviour properly. To explain the large amplitude, long recurrence time, and long duration of the superoutbursts, the DIM requires extremely low viscosity in the quiescent disc, with $\alpha \lesssim 10^{-4}$ [13, 14], the physical reason for which is unknown. If one wants to keep viscosity's value at a "normal" level of $\alpha \sim 0.01$, then the inner disc should be sufficiently truncated and a superoutburst must be triggered by enhanced mass transfer from the donor, which should persist during the superoutburst [15, 16].

In this conference paper, we probe the physical properties of accretion discs in a sample of WZ Sge-type objects in deep quiescence. We present some already published and also preliminary results of high-quality observations obtained with the Very Large Telescope at the Paranal Observatory in Chile, using the medium-resolution spectrograph X-shooter. We complement our observations with archival spectroscopic and photometric data obtained at other facilities such as the Nordic Optical Telescope, the Hubble Space Telescope (HST), the Neil Gehrels Swift Observatory, using both the X-ray Telescope (XRT) and the UV/Optical Telescope (UVOT), and Wide-field Infrared Survey Explorer (WISE). We show that observations are inconsistent with certain predictions of the DIM.

2. WZ Sge-type stars and ordinary SU UMa-type DNe in comparison

Originally, the DIM was developed to reproduce the normal outbursts observed in ordinary DNe. Adopting the TTI model, it can also satisfactorily explain superoutbursts in SU UMa-type stars. However, as noticed above, the very long interval between superoutbursts of a larger amplitude and a longer duration in WZ Sge-type objects, and also rebrightenings (echo outbursts), observed after the main superoutburst in many such objects [11] (but not all!) require additional assumptions, the physical reason for which is not known.

What is the principal difference between accretion discs in these two types of DNe? Both types of binaries are essentially the same: having similar orbital periods, they have a similar size, and their accretion discs must also be of a similar size. Probably, the only significant difference is the mass-transfer rate $\dot{M}_{\rm tr}$ from the donor, at least during the quiescent period. As the total accretion luminosity $L_{\rm acc}$ is directly proportional to $\dot{M}_{\rm tr}$, the accretion discs in lower $\dot{M}_{\rm tr}$ systems must be less luminous. This is what we indeed observe in optical spectra of DNe.

Figure 1 shows normalised spectra of four ordinary SU UMa-type stars (HT Cas, BZ UMa, V436 Cen, and T Leo) and four WZ Sge-type objects (SSS J122221.7-311525, hereafter SSS J1222, EG Cnc, WZ Sge, and BW Scl). Both samples cover similar ranges of orbital periods. We note that the spectra of the ordinary SU UMa-type stars are similar in appearance to those of longer-period DNe, such as SS Cyg or U Gem. They are dominated by hydrogen and neutral helium emission lines superposed on a smooth continuum. In contrast, the WZ Sge-type spectra exhibit much fainter helium lines, and, more importantly, the clear presence of broad Balmer absorption lines from the WD. The latter is a direct indication of much lower disc luminosity in the WZ Sge-type objects than in other classes of DNe. It is easy to verify that in order to hide the underlying WD absorption lines, the accretion disc must be at least 10 times brighter than the WD (Figure 2), while various

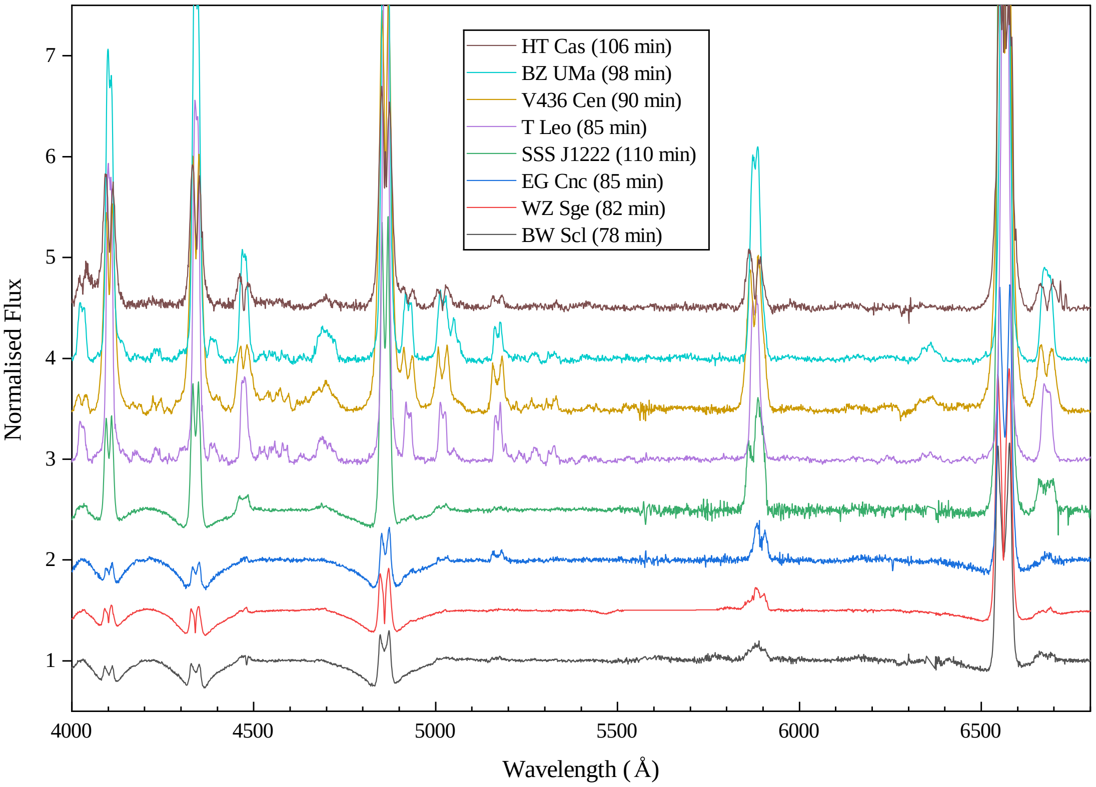

Figure 1: Normalised spectra of ordinary SU UMa-type stars (HT Cas, BZ UMa, V436 Cen, and T Leo – four upper spectra) and WZ Sge-type objects (SSS J122221.7-311525, EG Cnc, WZ Sge, and BW Scl – four lower spectra). The orbital periods of all the objects are indicated in the plot legend. The plot emphasises the Balmer absorption features and continuum, thus, the Balmer emission lines in some objects do not fit in the plot. The spectra of the WZ Sge-type objects clearly exhibit the presence of the broad Balmer absorption lines from a WD, whereas the ordinary SU UMa-type stars do not.

studies indicate that in the WZ Sge-type objects the disc contributes only a few dozen per cent of the total system light in the blue optical spectrum [17].

3. Accretion disc spectrum

Thus, accretion discs in WZ Sge-type stars have a very low luminosity. What physical characteristics do these disks have? Even the spectra (continuum) of such discs are poorly known, making it challenging to determine their properties. The optical spectrum is hard to derive because the WD dominates the system spectrum. To extract the accretion disc spectrum, we used the approach described in [17], which provides all details. Shortly, we first derive the WD parameters ($\log g$ & $T_{\rm eff}$) by fitting the object spectrum between the Hβ and Hδ lines to a grid of synthetic spectra of DA WDs, to which the power-law or blackbody flux (mimicking a disc contribution) was added. In this range of wavelengths, the contribution of the disc is minimal (Figure 3, left), enabling the fitting procedure to constrain both the WD parameters and the WD contribution to the total light [18]. We then subtract the found underlying WD spectrum from the object's broadband spectrum. The latter is constructed from a combination of the optical spectrum, an archival HST UV spectrum

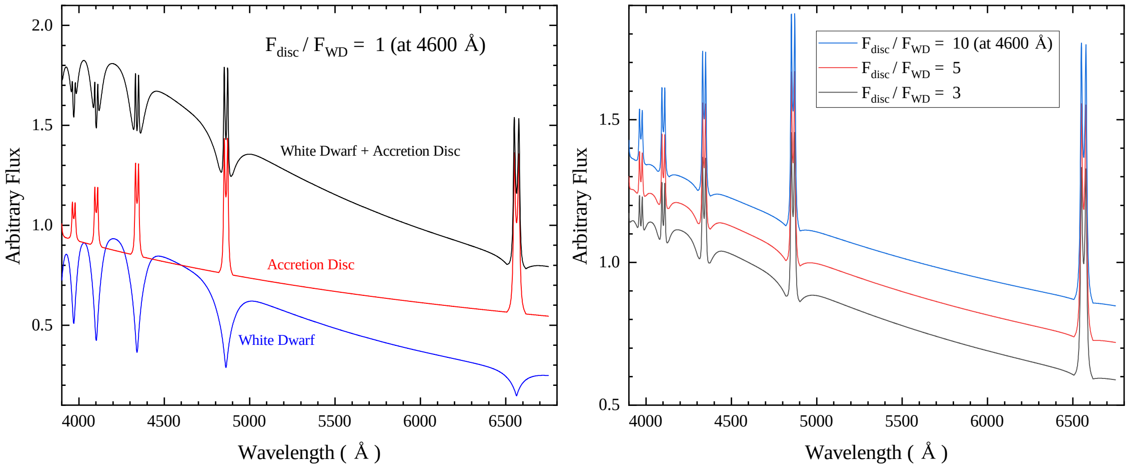

Figure 2: Simulated spectra of a CV calculated as a sum of a WD model spectrum and a power law with added double-peaked emission lines of arbitrary strength, mimicking an accretion disc spectrum. The left panel shows the WD and disc spectra with the same flux at 4600 Å, along with their combination. The right panel shows three combined spectra with different flux ratios.

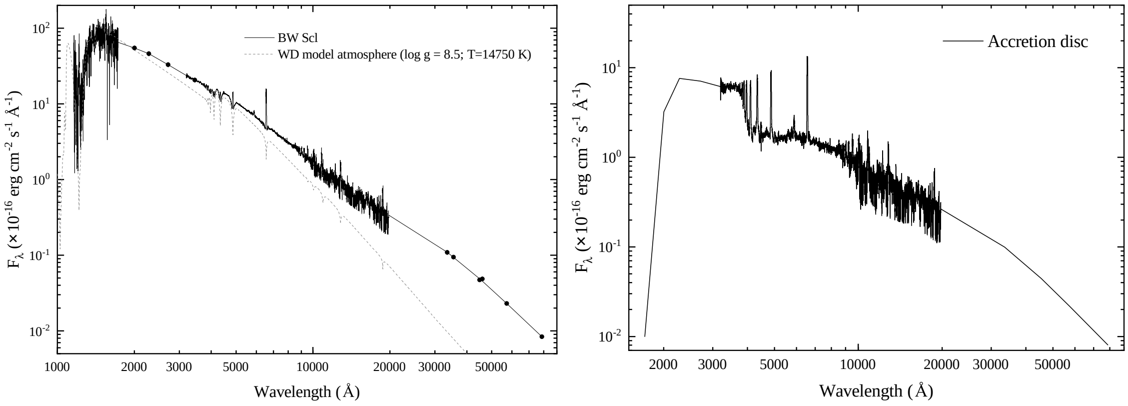

Figure 3: Left: the spectrum of BW Scl, shown together with the best-fitting WD model spectrum. The WD emission (grey dashed line) contributes 90 cent of the total system flux at 4600 Å. Right: The accretion disc spectrum obtained after a subtraction of the WD spectrum from the spectrum of BW Scl. Its colour temperature is 10580±40 K.

and/or Swift/UVOT photometry in the UV, and WISE photometry in the mid-NIR. In most cases, we used an X-shooter spectrum spanning a broad range of wavelengths from the near-UV to the near-infrared. The resulting spectrum can be considered the accretion disc spectrum. Two examples of the extracted disc spectra of BW Scl and EG Cnc can be seen in Figures 3 (right) and 4.

We must note, however, that the obtained spectrum is a combination of contributions from the disc itself, the hotspot, and the donor star. The latter mostly contributes in the NIR, and, for all the considered objects here, this contribution is negligible, as the donor is a brown-dwarf-like object (e.g., [17, 19]). On the other hand, the hotspot can be a major contributor, having luminosity even higher than that of the disc itself. In the following calculations, we will assume that their contributions are equal, as we are currently unable to separate the disc and hotspot shares.

4. Probing accretion disc physical parameters

4.1 Bolometric Luminosity, Mass-Transfer, and Mass-Accretion Rates

Using the above approach, we extracted the disc spectra from 5 WZ Sge-type stars. For BW Scl and EG Cnc, two spectra were obtained using observations performed before and after their most recent superoutbursts (in 2010 and 2018, respectively). By integrating the disc SEDs over all wavelengths and adopting the *Gaia* distances, we can put a conservative upper limit on the bolometric luminosity of the disc $L_{\rm d,bol}$ (Table 1). All the objects were also observed with the Swift/XRT, allowing us to estimate the unabsorbed X-ray luminosity $L_{\rm x}$, also showed in the table.[3] Note that in most cases, $L_{\rm x} < L_{\rm d,bol}$.

The found values of $L_{\rm d,bol}$ can be used to evaluate the mass-accretion $\dot{M}_{\rm acc}$ and mass-transfer rate $\dot{M}_{\rm tr}$. We calculated $\dot{M}_{\rm acc}$ using

$$\dot{M}_{\rm acc} = \frac{2\xi L_{\rm d,bol} R_{\rm wd}}{G M_{\rm wd}}\,, \tag{1}$$

where $R_{\rm wd}$ and $M_{\rm wd}$ are the radius and mass of the WD, G is the gravitational constant, and ξ=0.5 is the adopted fraction of the system luminosity produced by the accretion disc. Note that Eqn (1) is valid for steady accretion, while for quiescent discs it provides an upper limit on $\dot{M}_{\rm acc}$.

$\dot{M}_{\rm tr}$ can be estimated from the luminosity of the hotspot, which is $(1-\xi)L_{\rm d,bol}$. The luminosity is determined by the release of gravitational potential energy as material falls from infinity to the impact point at the rim of the accretion disc [1], or by the conversion of the gas stream's kinetic energy into radiation [21, 22]; both are proportional to $\dot{M}_{\rm tr}$. Then we can use one of the following equations:

$$\dot{M}_{\rm tr} \approx \frac{(1-\xi)}{\eta}\frac{r_{\rm hs} L_{\rm d,bol}}{G M_{\rm wd}} \approx \frac{2(1-\xi)}{\eta}\frac{L_{\rm d,bol}}{\Delta V^2}\,, \tag{2}$$

where $r_{\rm hs}$ is a disc radius at which the hotspot is located, ΔV is the impact velocity of the gas stream relative to the disc (then $\Delta V^2/2$ is the energy dissipation per 1 gram of the stream material), and η is an efficiency factor. With η<1, one can take into account that (in the first equation) the material falls from the inner Lagrangian point, not from ∞, that the stream meets the rotating disc obliquely, and that (in the second equation) not all kinetic energy is converted into the luminosity of the spot. In order to be on the conservative side, we adopt η=0.5 below.

Using the second equation and assuming η=1, Smak [13] estimated $\dot{M}_{\rm tr}$ in WZ Sge to be 2×10^{15} g s^{-1}. This value remains, in fact, the only measurement of this parameter in this type of DNe and is now commonly adopted for the whole class of WZ Sge-type stars, including within the DIM [8]. However, Smak's calculations were based on parameters later shown to be incorrect, leading to a notable overestimation of the result. First and foremost, the WD mass in WZ Sge is actually about twice as large, which affects the predicted impact velocity of the gas stream. ΔV was determined from the kinematics of the stream colliding with the outer rim of the disc. The latter was evaluated from a peak-to-peak separation of double-peaked emission line profiles. However, we show below that this approach is incorrect, as the hotspot is located well inside the disc. Finally, our hotspot

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[3] Assuming that X-ray spectra of these objects are similar to other WZ Sge-type stars such as GW Lib and SSS J1222 [20], we estimated $L_{\rm x}$ in the 0.3–10 keV range by using the count-rates as the scale-factor.

Table 1: Bolometric and unabsorbed X-ray luminosities (in the 0.3–10 keV range) of the disc and the mass-accretion and mass-transfer rates in a sample of WZ Sge-type DNe.

Object	Year of observation	$L_{\rm d,bol}$ $\times 10^{30}$ erg s^{-1}	$L_{\rm x}$ $\times 10^{30}$ erg s^{-1}	$\dot{M}_{\rm acc}$ $\times 10^{13}$ g s^{-1}	$\dot{M}_{\rm tr}$ $\times 10^{13}$ g s^{-1}
BW Scl	2010	3.2		$\lesssim$2.0	45.8
	2017	4.0	0.86	$\lesssim$2.5	57.3
EG Cnc	2003	1.3	0.61	$\lesssim$0.6	20.1
	2019	2.2		$\lesssim$0.9	34.0
EZ Lyn	2018	1.5	0.14	$\lesssim$0.9	23.0
SSS J1222	2019	2.0	3.09	$\lesssim$1.2	36.0
WZ Sge	2025	1.6	0.94	$\lesssim$1.0	23.9

luminosity is at least 2 times lower than that of Smak, who, based on a number of assumptions and adopting a bolometric correction, arrived at a higher value.

We must note that the structure of the hotspot in WZ Sge-type stars is very complex. As we show in Section 4.4 (for more detail see [17]), the hotspot is highly elongated. Although it becomes visible at the disc edge, its brightest part is located well inside the disc, close to its circularisation radius. It makes the use of any of the Equations (2) difficult as both the most important parameters $r_{\rm hs}$ and ΔV appear to be ambiguous. We believe that taking into account the reduction in stream speed while the stream is moving through the low-density disc is less certain. For this reason, we use the first formula with $r_{\rm hs}$ having a value of a brightness-weighted centroid of the hotspot estimated from the Dynamical Doppler maps by eye (Section 4.4). In most cases $r_{\rm hs}$ is close to $0.40a$, and only for EG Cnc we used $0.45a$, where a is the binary separation.

Table 1 shows our results. We find that all the obtained values are very consistent, being roughly $\dot{M}_{\rm acc} \lesssim (1\div2)\times10^{13}$ g s^{-1} $\approx (2\div3)\times10^{-13}$ M$_\odot$ yr^{-1} and $\dot{M}_{\rm tr} \approx (2\div4)\times10^{14}$ g s^{-1} $\approx (3\div6)\times10^{-12}$ M$_\odot$ yr^{-1}, about a factor of 10 smaller than those commonly assumed for WZ Sge-type stars.

4.2 Physical properties of the accretion discs

A drastic difference in disc luminosities in SU UMa-type and WZ Sge-type stars indicates that the discs in the latter might be in an optically thin regime. Indeed, it has been shown [23] that accretion discs in CVs with low mass accretion rates should have outer regions optically thin in continuum, and that at $\dot{M}_{\rm acc} = 5\times10^{13}$ g s^{-1} the entire disc becomes optically thin in continuum [24]. We found above that the observed $\dot{M}_{\rm acc}$ in the studied objects is lower than this limit (Table 1).

As a simple exercise, we can estimate the mean effective (blackbody) temperature $T_{\rm eff}$ of the disc using the definition of the luminosity $L_{\rm d}$ as the integral of the total flux over the disc surface:

$$L_{\rm d} = 2\pi(r_{\rm out}^2 - r_{\rm in}^2)\sigma T_{\rm eff}^4\,, \tag{3}$$

where $r_{\rm out}$ and $r_{\rm in}$ are the outer and inner radii of the disc and σ is the Stefan-Boltzmann constant. Assuming that $L_{\rm d}$=$0.5L_{\rm d,bol}$ (another half is emitted by the hotspot) and using the disc parameters found for BW Scl [17] ($L_{\rm d}$=1.6×10^{30} erg s^{-1}, $r_{\rm in}$=0.01 R$_\odot$$\approx$$R_{\rm wd}$, and $r_{\rm out}$=0.338 R$_\odot$), we obtain

Table 2: The EWs of the Balmer emission lines and the Balmer decrement (BD), measured in the accretion disc spectra of a sample of WZ Sge-type systems.

Object	Year of	Equivalent Width (Å)				Balmer Decrement
Object	observation	Hα	Hβ	Hγ	Hδ	Hα : Hβ : Hγ : Hδ
BW Scl	2010	341	210	190	170	1.71 : 1.00 : 0.86 : 0.71
— ıı —	2017	340	194	178	174	1.60 : 1.00 : 0.89 : 0.82
EG Cnc (with hotspot)	2019	280	121	97	140	2.31 : 1.00 : 0.63 : 0.53
— ıı — (without hotspot)		265	96	79	74	2.72 : 1.00 : 0.60 : 0.48
EZ Lyn	2018	703	205	141	102	1.80 : 1.00 : 0.71 : 0.49
SSS J1222	2019	842	332	211	164	2.10 : 1.00 : 0.63 : 0.45
WZ Sge	2025	303	118	79	73	1.86 : 1.00 : 0.74 : 0.65

$T_{\rm eff}$=1570 K (similar and even lower values are obtained for other objects). It is unlikely that such a low $T_{\rm eff}$ represents the true, kinetic temperature of the disc material, as no strong Balmer emission lines can be produced at such a low temperature, and the spectrum should be peaked at NIR wavelengths, thus providing additional support for the optically thin conditions in the disc.

Can a part of the disc still be in the optically thick regime? It is easy to show that even if it is so, such optically thick rings must be unrealistically narrow. Assuming the above parameters and that a ring with even relatively low $T_{\rm eff}$=4000 K produces the whole disc luminosity $L_{\rm d}$ (i.e. the optically thin part emits nothing), its size will be (1÷6) $R_{\rm wd}$, if it is located at the inner edge, or (0.984÷1) $R_{\rm out}$ = (33.3÷33.8) $R_{\rm wd}$, if it is at the outer disc edge. It should be emphasised that a blackbody spectrum with $T_{\rm eff}$=4000 K is already too red to match the observed disc SED colour temperatures, which consistently fall within a relatively narrow interval of 8500–10500 K across various objects and data sets (see, e.g., Figure 3, right). Furthermore, the strong Balmer jump and emission lines observed in the spectrum indicate that the second assumption is also overly simplistic, further narrowing the optically thick ring. Thus, based on the above arguments, we conclude that most of the accretion discs in WZ Sge-type objects, possibly the entire discs, are optically thin.

What are the physical conditions within such accretion discs? Unfortunately, there is no established methodology capable of directly constraining them in such discs. However, some clues about the temperature and density of the line-emitting regions can be evaluated from emission lines and the continuum shape. Having recovered not only a non-WD continuum but also higher-order Balmer emission lines that lie within the WD absorption troughs, we can use their equivalent widths (EWs) and the Balmer decrement to infer the temperature and density. It has been shown that the Balmer decrements (especially Hα/Hβ) are sensitive to a great extent to a gas density in the optically thin regime [25]. Comparing the measured parameters of the Balmer lines (Table 2) with the model predictions calculated by Williams [26], we find that they are roughly consistent with the disc temperature in the range of 8 000–10 000 K and the number density of hydrogen at the midplane of $\log N_0 \approx 12$ that corresponds to the surface density Σ of 0.006 g cm^{-2}.

It is important to note that the line parameters from Table 2 are heavily affected by the presence of the hotspot component in the lines. As we show below in Section 4.4, the hotspot feature seen in trailed spectra as an S-wave becomes progressively stronger in higher-order Balmer lines in

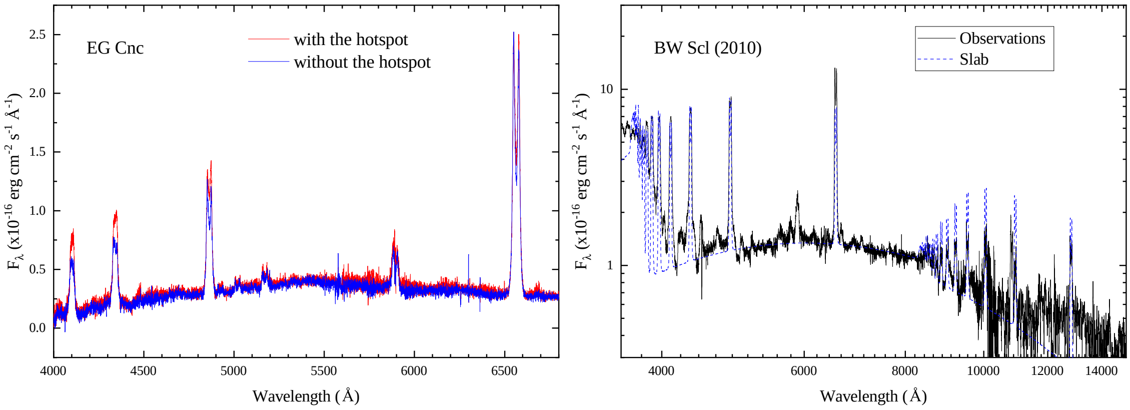

Figure 4: Left: Accretion disc spectra of EG Cnc with (red) and without (blue) hotspot contribution to the Balmer lines. Right: Accretion disc spectrum of BW Scl (black solid line) and an example (not the best-fit) of a hydrogen slab model (blue dashed line) calculated with the code of V. Suleimanov.

comparison with the underlying double-peaked line originating in the accretion disc. This makes the measured Balmer decrement flatter than that of the disc spectrum alone. It is not straightforward to properly separate the hotspot's contribution to the disc continuum, but it is relatively easy for spectral lines, using the following approach. In Section 4.4, we show that, although the hotspot has a complex, elongated structure, it remains relatively compact. Using time-resolved observations, we calculate two spectra, averaged between orbital phases 0.4 and 0.8, when the hotspot S-wave is blue-shifted, and between phases 0.9 and 1.3, when it is red-shifted. We then combine the right, red half of the line profiles from the first averaged spectrum with the left, blue half from the second. We applied this method to the data for EG Cnc and show the result in Figure 4 (left), and the values of the calculated EW and the Balmer decrement in Table 2. After removing the hotspot contribution to the emission lines, the Balmer decrement in the resultant disc spectrum appears steeper, indicating even lower hydrogen density ($\log N_0 \approx 11.5 - 12$ and $T \approx 8\,000 - 10\,000$ K) [26].

Another method to assess the physical properties of accretion discs is to fit the whole disc spectrum with a hydrogen slab [27] (see the right panel of Figure 4 for an example). We used this approach to probe the disc in WZ Sge. We found that the WD-subtracted spectrum must be fitted with separately modelled slabs for the hotspot and disc contributions. We found that the disc has an even lower temperature of 5400 K and a surface density of 0.03 g cm^{-2}. More details can be found in [28] (these proceedings).

We should note that the obtained values of Σ are likely underestimated, since with the measured $\dot{M}_{\rm tr}$, such surface densities would be reached within a relatively short time. One possible explanation is that both methods rely primarily on the properties of emission lines and therefore probe only the line-emitting regions, leaving the continuum-dominated emitting regions unaccounted for.

4.3 Double-peaked emission line profiles

Some important accretion disc parameters can be constrained from modelling of double-peaked emission line profiles, which are commonly observed in DNe and other types of CVs. A peak-to-peak separation in these profiles is defined by the velocity of the outer rim of the accretion disc $V_{\rm out}$, while the ratio of the disc inner and outer radii $r_{\rm in}/r_{\rm out}$ defines a full width of the line profile at zero

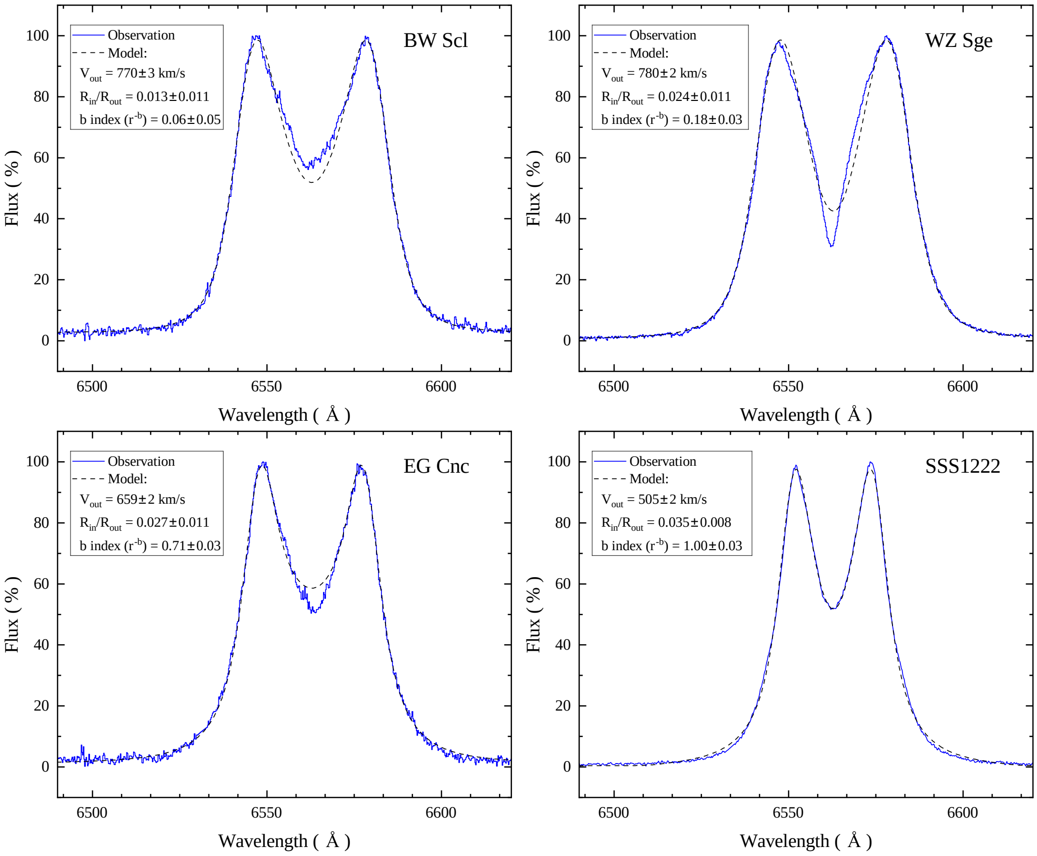

Figure 5: Profiles of the Hα emission lines shown together with the corresponding model fits.

Table 3: The parameters of the accretion discs in selected WZ Sge-type systems from the double-peaked profiles of the Hα emission line.

Object	Year of observation	$V_{\rm out}$ (km s^{-1})	b	$r_{\rm in}/r_{\rm out}$
BW Scl	2010	770±3	0.06±0.05	0.013±0.011
EG Cnc	2019	659±2	0.71±0.03	0.027±0.011
EZ Lyn	2018	686±2	0.52±0.03	0.032±0.009
SSS J1222	2019	505±2	1.00±0.03	0.035±0.008
WZ Sge	2025	780±2	0.18±0.03	0.024±0.011

intensity (FWZI) [29]. If the WD mass and a system inclination are known, the above parameters can be converted to the outer and inner disc radii, or vice versa.

Here we are mostly interested in the radial distribution of the local line emissivity, which defines the shape of the profile wings [30–33]. It is commonly assumed that the surface radial emissivity profile follows a power-law model of the form $f(r) \propto r^{-b}$, where r is the radial distance from the WD. A larger value of b makes the wings shallower. Modelling of double-peaked line profiles found in spectra of ordinary DNe and low mass X-ray binaries has shown that b is usually found to be in the range of 1–2, rarely being less than 1.5 [34–39].

However, the emission line profiles in the WZ Sge-type stars appear to be steeper, indicating a smaller b, and in turn, a flatter radial emissivity profile in their discs. To estimate the b and other disc parameters, we fitted the averaged Hα profiles of the same as above WZ Sge-type objects, using a code implementing a simple model of a uniform flat axisymmetric Keplerian geometrically thin disc [33, 38]. We find that b in most of these objects is notably smaller than 1.0 (see Table 3 and Figure 5). This finding indicates that the disc in these systems is close to being radially isothermal, with a surface density that varies only mildly with radial distance from the WD.

4.4 Accretion disc and hotspot structure in quiescence

High time- and spectral-resolution data for a sample of WZ Sge-type objects enabled us to establish some properties of accretion discs that are particularly important in the context of this paper. These properties seem consistent across the entire subclass.

1. From the trailed spectra one can see (Figure 6) that the accretion disc doesn't produce any helium emission as all the observed He I and He II lines come primarily from the hotspot (see [17] for more detail). Thus, the disc is not hot enough to excite any helium and even higher-order Balmer emission lines.
2. Doppler maps of objects with known accurate system parameters (e.g., BW Scl and WZ Sge – [17, 28], see also the ordinary SU UMa-type star HT Cas – [39, 40]) show that the accretion disc, even in quiescence, is large, reaching the truncation radius (Figure 7), which is larger than the 3:1 resonance radius.
3. The hotspot has a complex structure, and when Dynamical Doppler tomography[4] is applied (see [17] for more detail), it is seen that the hotspot is highly anisotropic. Two bottom rows of panels in Figure 7 show the Doppler maps calculated using 50 per cent of spectra centred on phases 0.0 (0.75–1.25) and 0.5 (0.25–0.75).
4. The Doppler maps show that the outer parts of the accretion disc have low density, allowing the gas stream to flow along a ballistic trajectory into the inner disc regions.
5. The elongated hotspot becomes visible at or even beyond the disc truncation radius, but its brightest part is located close to the circularisation radius of the disc [17].

Periodograms of optical light curves of WZ Sge-type stars are dominated by a coherent signal at half the orbital frequency, so-called double-wave modulations (Figure 8). Such photometric behaviour is naturally explained by an elongated, optically thick hotspot (whose viewing aspect varies with the orbital period) shining through/above an optically thin accretion disc. An almost transparent disc, as seen in these objects, allows the light from the elongated hotspot to escape in all directions, while the variable aspect of the hotspot modulates the observed flux.

5. Predictions of the DIM and comparison with observations

According to the DIM, the quiescent disc in a DN just before its outburst must be filled, at some radius, to the critical surface density $\Sigma_{\rm max}$ which corresponds to the turning point of the lower

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[4] Dynamical tomograms for BW Scl are available at `https://vitaly.neustroev.net/researchfiles/bwscl/`

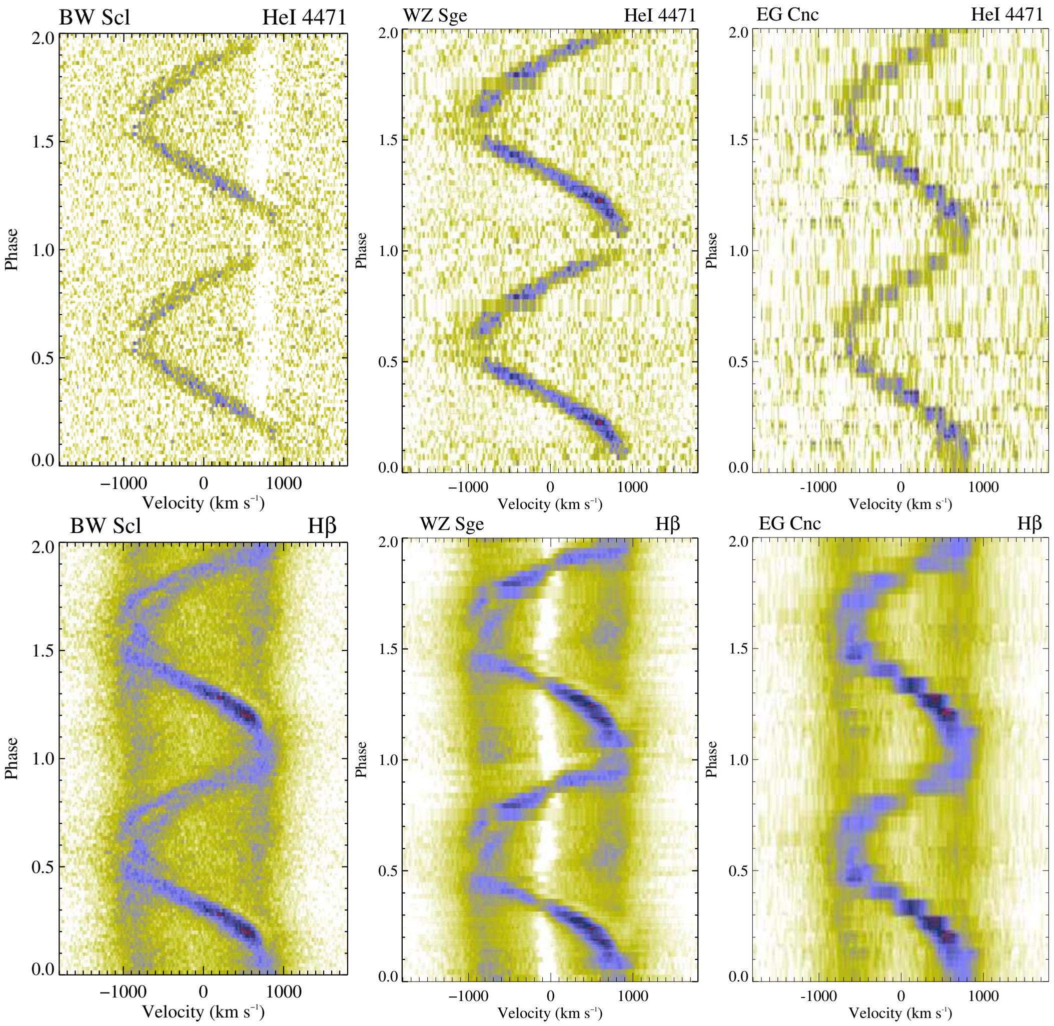

Figure 6: Trailed spectra of the He I 4471Å (upper panels) and Hβ (bottom panels) emission lines in BW Scl (left), WZ Sge (middle), and EG Cnc (right). In all these objects, the helium lines are dominated by the hotspot, while the accretion disc contribution is negligible. The Balmer lines, however, show a mixture of emission components from both the disc and hotspot. The hotspot S-wave of the Balmer lines exhibits a complex behaviour, splitting when it is blue-shifted, and displaying an absorption shadow when it is red-shifted. See [17] for more detail.

stable branch of the S-curve, connecting it to the intermediate, thermally and viscously unstable, branch (Figure 9).[5] $\Sigma_{\rm max}$ depends on the viscosity parameter α, the mass of the WD, and the radial distance from the centre. This parameter can be estimated directly from the S-curve, but can also be calculated using one of the published fits to $\Sigma_{\rm max}$ (e.g., eqns. A.1 in [4], 16 in [5], A3 in [42]). Thus, the smallest value of $\Sigma_{\rm max}$ is expected to be found at the inner disc radius, although both the observations and the TTI model support the outside-in outbursts in the WZ Sge-type DNe. For these two cases, the value of $\Sigma_{\rm max}$ in BW Scl for adopted α=0.01 ranges between ~10 g cm^{-2} at

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[5] $\Sigma_{\rm max}$ is the maximum surface density the accretion disc can sustain in a stable, cold quiescent state. If the surface density Σ locally exceeds this critical value, the disc becomes thermally unstable and transitions to a hot, high-viscosity state, leading to an outburst.

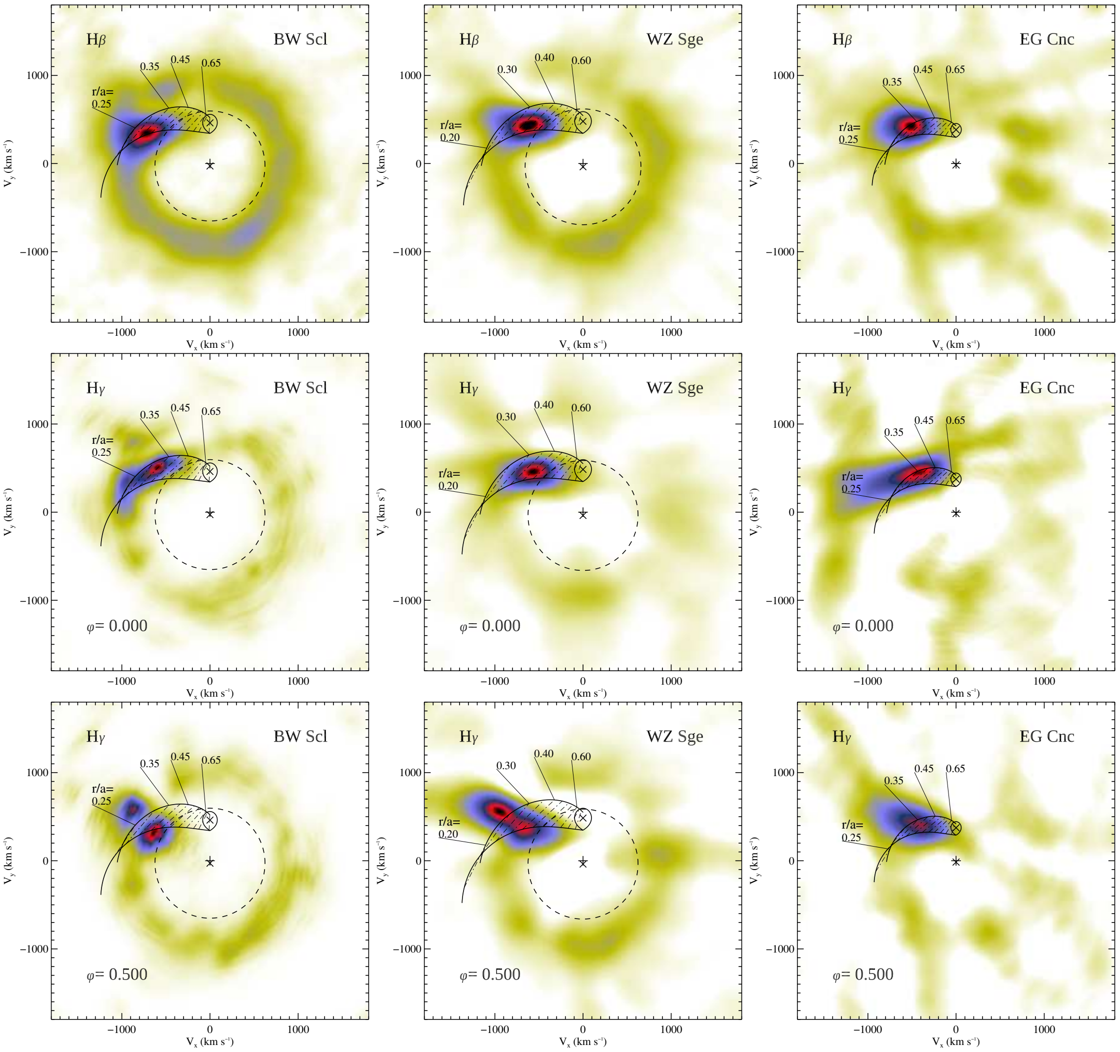

Figure 7: Doppler maps of BW Scl (left column, WZ Sge (middle column), and EG Cnc (right column). The upper maps of the Hβ emission line are calculated using the whole sets of spectra, whereas for the lower maps of the Hγ line, only 50 per cent of spectra between phases 0.75–1.25 (middle panels) and 0.25–0.75 (bottom panels) were used. The dashed circles show the tidal truncation radius. The dashed lines connect the velocity of the ballistic gas stream (lower curve) and the velocity on the Keplerian disc along the gas stream (upper curve) for the same points at distances labelled along the upper curve (in r/a units). These lines are separated by $0.05r/a$. See [17] for more detail.

the inner disc radius to ~1000 g cm^{-2} at the outer one, and it is larger for smaller α ($\Sigma_{\rm max} \propto \alpha^{-0.83}$ [5]). As even the smallest $\Sigma_{\rm max}$ value corresponds to optically thick conditions, it indicates that the whole disc at the onset of the outburst must be optically thick. This is, in fact, one of the defining assumptions of the DIM [4].

However, we found multiple lines of observational evidence that the entire accretion discs in WZ Sge-type stars in deep quiescence are optically thin. They have a very low bolometric luminosity (a few $\times 10^{30}$ erg s^{-1} which corresponds to a very low-mass accretion rate of a few $\times 10^{-13}$ M$_\odot$ yr^{-1}). An order-of-magnitude estimation of the average surface density of the disc

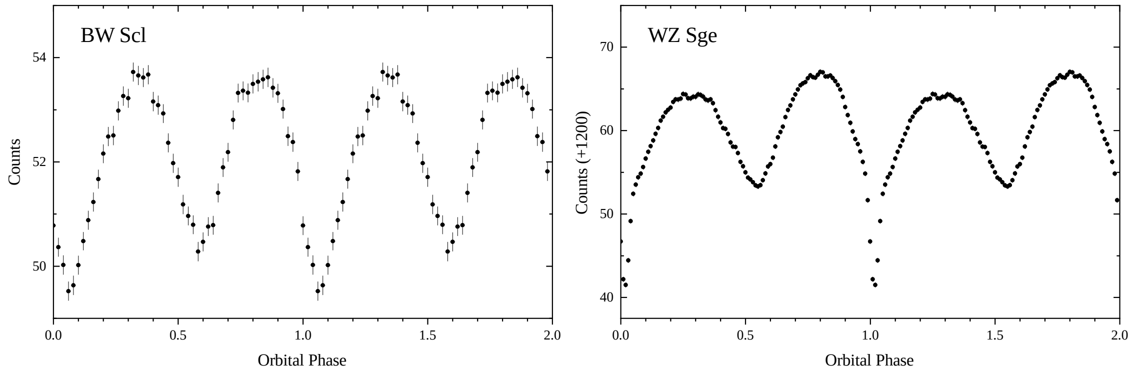

Figure 8: The TESS light curves of BW Scl (left) and WZ Sge (right) folded with their orbital periods and averaged in 50 phase bins. WZ Sge is an eclipsing CV showing, in addition to double-wave modulations, eclipses of the hotspot on the disc rim.

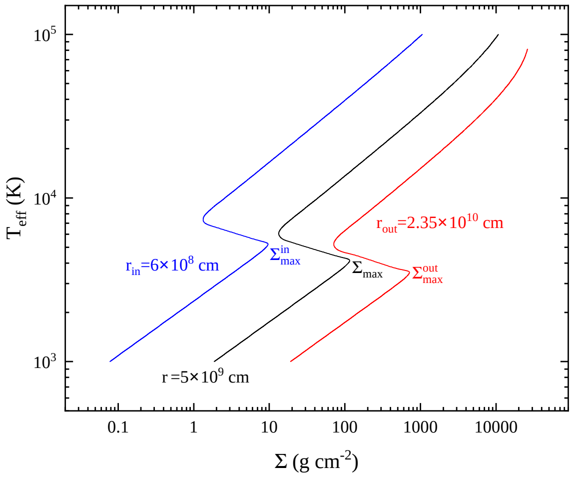

Figure 9: Example of $\Sigma - T_{\text{eff}}$ S-curves calculated for the mass of BW Scl M_{wd}=0.85 M$_\odot$ at its inner (6×10^8 cm) and outer (2.35×10^{10} cm) disc radii, and also at 5×10^9 cm. The cold and hot branches of the the S-curves were calculated with α = 0.01 and 0.1 respectively, using the code from [41].

gives $\overline{\Sigma} \ll \Sigma_{\text{max}}$. These conditions within the disc cannot trigger an outburst.

The pre-outburst state of DNe has been considered multiple times in the past [43–47], though without comprehensive observational support. Meyer in [46] (see also [47]) has explicitly shown that though the disc becomes totally optically thick almost simultaneously with the start of an outburst, the disc becomes gradually thick more than two weeks before the onset of instability, for the considered $\dot{M}_{\text{acc}}$=3×10^{-10} M$_\odot$ yr^{-1} (figure 4 in [46]). One can expect that this time interval will be much more prolonged for significantly lower $\dot{M}_{\text{acc}}$ estimated in WZ Sge-type stars.

As was discussed above, the optical flux difference between a totally optically thin and even a partially optically thick disc should be more than 2 magnitudes. Such an increase in brightness would be easily detected even by amateur astronomers. However, the pre-outburst photometry available for a few WZ Sge-type objects does not show any trend in brightness (Figure 10). For example, the prototype object WZ Sge had the same average brightness for more than 10 years, up to half a day before the 2001 superoutburst (the inset plot in the right-hand panel of Figure 10), the

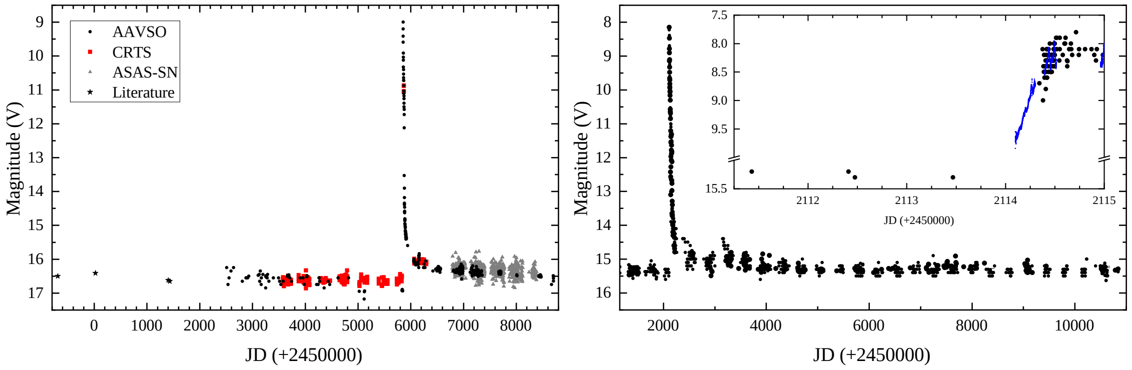

Figure 10: Long-term light curves of BW Scl (left-hand panel, see [17] for more detail) and WZ Sge (right-hand panel). The inset plot in the right-hand panel shows an enlarged region around the rising stage of the superoutburst. The blue data points represent observations by Ishioka et al. [48].

same as we observe it now. Now, 24 years after the previous superoutburst, the accretion disc in WZ Sge has a very low luminosity ($\lesssim 1.6\times10^{30}$ erg s^{-1}), indicating a very low mass-transfer rate ($\sim 1.0\times10^{13}$ g s^{-1}). We see no significant change in the accretion disc's overall brightness compared with this or the previous quiescent cycle. If this cycle follows the previous one, WZ Sge should outburst soon. There is no sign of the accretion disc becoming optically thick (for more detail on the long-term evolution of WZ Sge throughout quiescence see [28]).

To explain the extraordinary behaviour of WZ Sge-type systems, the DIM requires [8, 15, 16] that the inner disc be sufficiently truncated[6] and that a superoutburst be triggered by an enhancement of mass-transfer from the donor star. This increase of $\dot{M}_{\rm tr}$ must be very significant, by several orders of magnitude [16]. However, even without considering the reason for this increase or why it occurs regularly (e.g., in WZ Sge), this explanation has serious drawbacks. Even a very substantial rise in $\dot{M}_{\rm tr}$ prior to the outbursts will not immediately trigger a thermal and a viscous instability, as the low-density disc needs to accumulate enough material for the outburst. This will require at least days, or even weeks, during which the disc will first transition to a partially optically thick regime, which is readily observable, as shown above. Moreover, a sudden increase of $\dot{M}_{\rm tr}$ will proportionally brighten the hotspot. Even a modest 10-fold increase in hotspot luminosity will result in an average system brightening of 0.5-1 mag and extremely strong orbital modulations, which will still be seen during the rising stage of the outburst. Nothing of it was observed in WZ Sge (half a day before the 2001 superoutburst detection, it had the same brightness as before; see the inset plot in the right-hand panel of Figure 10) or in a few other similar objects.

Another hypothesis about disc truncation is also not supported by our observations. From the fit of double-peaked profiles of the Hα emission line, we obtained the ratios of the disc inner and outer radii for several WZ Sge-type objects. On average, $r_{\rm in}/r_{\rm out}\approx0.03\pm0.01$ which is in agreement with the estimated values of $R_{\rm wd}/r_{\rm out}$. For example, in BW Scl it was found to be $R_{\rm wd}/r_{\rm out}$=0.030 [17]. Adopting for $r_{\rm in}$ of the truncated disc to be $4\times R_{\rm wd}$, we obtain $r_{\rm in}/r_{\rm out}$=0.12. We note that the wings of double-peaked profiles are very sensitive to $r_{\rm in}/r_{\rm out}$ (see, e.g. figure 2 in [33]), and with such a value it will be definitely detected.

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[6] The truncation prevents the inner accretion disc from becoming thermally unstable, forcing material to accumulate in the outer, cooler parts of the disc where $\Sigma_{\rm max}$ is much larger than at lower radii.

6. Conclusion and open questions

We presented an analysis of observations of a sample of WZ Sge-type systems in deep quiescence, aimed at assessing how the predictions of the disc instability model (DIM) compare with their observed properties. In particular, we investigated whether superoutbursts in WZ Sge-type systems are indeed triggered by enhanced mass transfer from the donor star. By applying a consistent methodology to all objects in the sample, we obtained comparable and robust results. We found that the accretion discs in quiescent WZ Sge-type systems exhibit very low bolometric luminosities of a few $\times 10^{30}$ erg s^{-1}, corresponding to extremely low mass-accretion rates of $(2 \div 3) \times 10^{-13}$ M$_\odot$ yr^{-1}. Such discs are entirely optically thin. In this regime, the physical conditions within the disc, such as surface density and effective temperature, remain well below the DIM thresholds and therefore cannot trigger a superoutburst. Moreover, observationally, the disc brightness does not change prior to the superoutburst, confirming that there is no evidence for a transition to an optically thick regime, even though the DIM predicts that the disc should become progressively thicker for at least several days, and most likely weeks, before the onset of the instability.

Thus, we conclude that there is no evidence that superoutbursts in WZ Sge-type systems are triggered by an enhanced mass-transfer rate. Consequently, the fundamental question remains open: how do accretion discs in these systems enter outburst? Still, we admit that the observations of WZ Sge-type objects just prior to their superoutbursts are very limited. Multi-colour photometric and especially spectroscopic observations are critically needed to shed more light on the pre-outburst behaviour of these objects.

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