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On the linewidth/K vs. mass ratio relation for SU Ursae Majoris stars and the removal of the inner disk

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Abstract. We have calibrated the linewidth/K vs. mass ratio relation for SU UMa stars using the "superhump" mass ratio derived from the tidal resonance model. We find that the relation by Jurcevic et al. (1994) is valid for dwarf novae above the period gap but not for SU UMa stars. Under the hypothesis of Keplerian disks, our results are compatible with the removal of the inner disk in SU UMa stars with extreme cycle lengths. The large long-term $FWHM$ variability observed in WZ Sge suggests that the fraction of mass removed from the disk is variable and possibly a function of the supercycle phase.

We show a new empirical formula between mass ratio and $FWHM/K$. It fits the mass ratio of dwarf novae above and below the period gap with a mean relative dispersion of 16% and 26%, respectively, except for the post-period minimum candidates EG Cnc and WZ Sge.

Key words: accretion, accretion disks – methods: statistical – stars: binaries: general – stars: evolution – stars: novae, cataclysmic variables

1. Introduction

The secular evolution of cataclysmic variable stars (CVs) is driven by mass transfer from the secondary star onto the primary star due to angular momentum loss from the binary system. The period gap is a region of the orbital period distribution, roughly between 2–3 hr, practically void of CVs. The main cause of the angular momentum loss above the orbital gap seems to be magnetic breaking of a stellar wind escaping from the secondary star. Below the period gap, gravitational radiation seems to be the dominant cause (e.g. Howell et al. 1997, Kolb 1993). Accordingly, the mass ratio changes when the binary evolves from long periods to ultra-short periods. For example, only low mass ratios ($q = M_2/M_1 < 0.3$) are found below the period gap and the ultra-short period systems apparently host two different populations of CVs (Howell et al. 1997). One of these populations consists of systems approaching the minimum period from the longer period side and the other consists of systems which have "bounced-off" from the period minimum and now are evolving to longer periods but with degenerate (brown dwarf-like) secondaries having masses between 0.02 an 0.06 $M_\odot$ and radii near 0.1 $R_\odot$ (Howell et al. 1997). These low-luminosity systems are interesting because they can be used to set a lower limit on the age of the Galaxy (Howell et al. 1997). In addition, they provide a unique laboratory to test models of late evolution stages of red dwarfs in close binary systems. Four stars were identified as candidate "period bouncers" by Patterson (1998), whereas Howell et al. (1997) speculate that at least some of the large amplitude dwarf novae are post-period-minimum cataclysmic variables. In general, these "period bouncers" should be hard to detect due to the faintness of their secondaries and the low brightness and long-recurrence time of their accretion disks associated with extreme low mass accretion rates ($\dot{M}$). In this paper we deal with an empirical relation potentially useful to separate the aforementioned populations of ultra-short period CVs, identifying the "period-bouncers" as the lowest q systems. Surprisingly, we found indirect evidence for distinct disk properties in dwarf novae above and below the period gap. A review of CVs including dwarf novae and SU UMa stars is given by Warner (1995).

2. The theoretical linewidth/K vs mass ratio relation

The linewidth/K vs mass ratio relation is based on the assumption that the emission lines are broadened by Doppler broadening in a Keplerian disk. Since the linewidth and the radial velocity semiamplitude K of the accreting primary have the same dependence on the inclination angle, the ratio R between these quantities is independent of i. If the accretion disk radius is a constant fraction of the Roche lobe radius of the primary then R should scale with the mass ratio.

The deduction by Warner (1973) assumes binary synchronus rotation, circular orbits and that particles ejected from the inner Lagrangian point L_1 at thermal velocities, conserve their angular momentum about the primary and eventually take up a circular orbit about the primary at a radius r_l. Using the Kepler's third law for circular orbits along with the relation between K and the orbital period, he found:

$$R \equiv \frac{v sin i}{K} = \frac{(1+q)^2}{g_q^2 q^3} \qquad (1)$$

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⋆ On leave in Harvard-Smithsonian Center for Astrophysics, 60 Garden St, MA 02138, Cambridge, USA where $vsini$ is the projected rotational velocity of the disk at the radius r_l, deduced from the width of the emission lines at some intensity level and g_q is the distance from the center of the primary to the inner Lagrangian point in units of the semi-major axis of the orbit. Expressing this distance in units of the binary separation as f_q, Shafter (1983) obtained:

$$R = \frac{1}{q f_q^2} \quad (2)$$

Using the Roche approximation (Kopal 1959), an expression for f_q can be obtained:

$$f_q = 0.5–0.227 \log q \quad (3)$$

which is accurate to $\sim$ 1% for $0.1 < q < 10$, as deduced from the tables of Plavec and Kratchovil (1964). From the above arguments, we should expect a relationship:

$$R = \frac{\alpha}{q f_q^2} \quad (4)$$

where α is a calibration parameter depending on the line intensity level where $vsini$ is measured. The above relation has been used but almost always restricted to dwarf novae above the period gap (Warner 1973, Piotrowski 1975, Robinson 1976, Shafter 1983 and Jurcevic et al. 1994). For example, Jurcevic et al. (1994, hereafter J94) used $vsini = FWHM$ (the full width at half maximum of the $H\beta$ emission line) and found α = 2.00 $\pm$ 0.02 calibrating a sample of 12 dwarf novae, including only 2 SU UMa stars, viz. HT Cas and WZ Sge. Looking in their Fig. 5, it is evident that their relationship is relatively well established for above-the-gap dwarf novae, but a large data gap is seen in the domain of SU UMa stars (the low q, upper right corner of their Fig. 5). In fact, J94 extrapolated the relationship to the domain of SU UMa stars basically using the data of WZ Sge. They claim that removing this star from their sample α changes only by 5%. We think that this extrapolation deserves an empirical confirmation, moreover considering that the gas dynamics in the disks of dwarf novae above and below the period gap could be substantially different.

3. The "superhump" mass ratio as a calibrator

To calibrate the Linewidth/K vs. mass ratio in SU UMa stars we will use results of the tidal resonance model. Osaki (1985) derived an analytical expression for the precession rate of the eccentric Keplerian orbit of matter at the disk's outer edge under the influence of the secondary's perturbing gravitational force:

$$\frac{\Omega_{pr}}{\Omega_o} = \frac{3}{4} \frac{q}{\sqrt{1+q}} (\frac{r_d}{a})^{3/2} \quad (5)$$

where Ω_{pr}, Ω_o, r_d and a are the precession and orbital frequencies, the disk outer radius and the binary separation, respectively.

If the superhump frequency (Ω_s) reflects the displacement between the orbital and precession frequency, then:

$$\Omega_{pr} = \Omega_o - \Omega_s \quad (6)$$

Table 1. Comparison of observed (q_o) and predicted (q_{sh}, from Eq. 7) mass ratios. The ϵ parameter is from Patterson (1998) and references therein.

Star	ϵ	q_o	q_{sh}	Ref (q_o)
OY Car	0.0203(15)	0.102	0.090(7)	Wood & Horne (1990)
HT Cas	0.0330(30)	0.15(3)	0.149(14)	Horne et al. (1991)
Z Cha	0.0364(9)	0.15(3)	0.165(5)	Wade & Horne (1988)
WZ Sge	0.0080(6)	0.075(15)	0.035(3)	Spruit & Rutten (1998)

Replacing the precession frequency in Eq. 5, defining the observable $\epsilon = \frac{(P_s - P_o)}{P_o}$ and assuming a disk radius equal to the 3:1 tidal resonance radius, i.e. about 0.46a (Whitehurst 1988a, Osaki 1989, Lubow 1991) we roughly obtain:

$$q = \frac{1}{0.23\epsilon^{-1} - 0.27} \quad (7)$$

Due to the success of the tidal resonance model in reproducing the superhumps seen in SU UMa stars (e.g. Osaki 1985, Whitehurst 1988a,b, Hirose & Osaki 1990, Hirose et al. 1991, Lubow 1991, Whitehurst & King 1991, Lubow 1992, Hirose & Osaki 1993, Murray 1998), Eq. 7 seems to be a good tool for estimating the mass ratio in non eclipsing SU UMa stars. A test for Eq. 7 can be made with the data of the 4 eclipsing SU UMa stars for which independent mass ratios are available. The result of this comparison, given in Table 1, indicates that the model reproduces well the observed mass ratio, within the observational uncertainties.

However, Eq. 7 was derived for one orbiting particle assuming gravity as the main driving force for precession, whereas the real phenomenon involves the collective motion of many particles probably influenced by pressure forces and viscosity (Murray 1998). Murray's main result is that ϵ is not only a function of the mass ratio (as previous studies suggested) but also a function of the gas pressure and viscosity. For example, ϵ increases by 15% when the gas pressure is incremented by a factor 5 in one of his simulations. In general, the ϵ changes found by Murray are of the same order of magnitude as that observed during superoutbursts of SU UMa stars. However, they can also be explained uniquely as changes in disk radius through Eq. 5. This was done by Patterson et al. (1993) in order to explain the $\dot{P}_s \sim -6 \times 10^{-5}$ d/d commonly observed in SU UMa stars. Therefore, in our current stage of knowledge, we cannot discriminate between a shrinking disk or viscosity/pressure changes as causes for the ϵ changes.

As a working hypothesis we will assume that Eq. 7 is a first order approach to the mass ratio of SU UMa stars. We will call the mass ratio so derived the "superhump" mass ratio (q_{sh}). We estimate an intrinsic uncertainty $\epsilon_{q_{sh}} \approx 0.017\, \frac{q_{sh}^2}{\epsilon}$, obtained by propagating errors in Eq. 7 and assuming a typical ϵ variation of 15% through superoutburst.

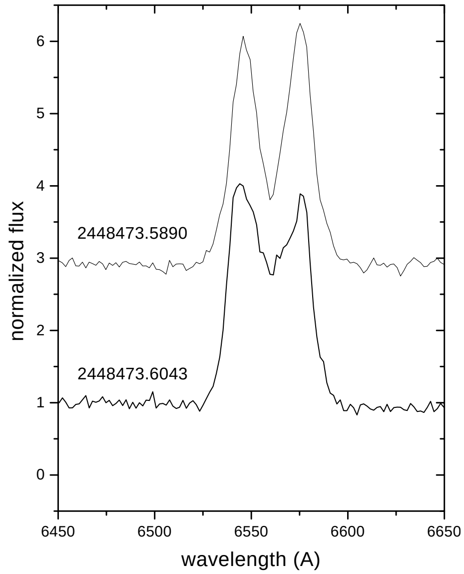

Fig. 1. Hα profiles of WZ Sge taken with 15-minute integration time and 3 Å spectral resolution. The spectra are labeled with the heliocentric julian day. The upper spectrum has been displaced by 2 continuum units for clarity.

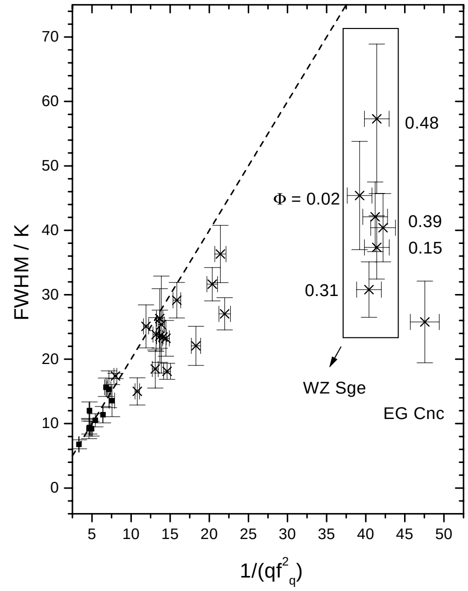

Fig. 2. The dashed line represents the Jurcevic et al. (1994) calibration of Eq. 4. Data for dwarf novae above the period gap (filled boxes, mostly from J94, see text) and SU UMa stars ($\times$, from Table 2) are also shown."Period bouncer" candidates are labeled. WZ Sge data is enclosed inside the solid line rectangle. These points are slightly displaced in the horizontal axis for clarity. They are labeled accordingly to their supercycle phases (T = 32.5 years). The J94 relations fails in the domain of SU UMa stars.

4. The observed linewidth/K vs mass ratio relation in dwarf novae

In this section we investigate the validity of the linewidth/K vs mass ratio relationship among SU UMa stars using new spectroscopic data and predictions of the tidal resonance model. For comparison, we also include published data of dwarf novae above the period gap.

As a working hypothesis we will assume that the mass ratio of SU UMa stars is actually given by the "superhump" mass ratio q_{sh} derived from Eq. 7, an assumption that seems well founded as previously discussed.

In order to calibrate Eq. 4 we selected 17 SU UMa stars with orbital and superhump period known and published $FWHM$ and K values. We also included EG Cnc measuring their linewidth from published spectra. For WZ Sge, 6 very discrepant $FWHM$ values spanning a time interval of four decades were included. Two of these measures were made by the author on two Hα spectra obtained at the 2.5 m telescope of Las Campanas Observatory in August 5, 1991 (Fig. 1). Multiple $FWHM$ records were just found for WZ Sge, due to the far more abundant literature existing for this star. The data are shown in Table 2.

In the following analysis we also include the 10 above-the-gap dwarf novae used by J94 along with CZ Ori[1]

From Fig. 2 it is evident that the linear relation found by J94 (the dashed line) is not valid for SU UMa stars. The relation fits well data for dwarf novae above the period gap but clearly deviates for SU UMa stars. The larger deviations are observed in the the post-period-minimum candidates EG Cnc and WZ Sge. In addition, it is remarkable the large dispersion observed in the R values of WZ Sge. The supercycle phase was assigned to each observation of this star (T = 32.5 yr, e.g. Patterson et al. 1981). The path followed by R seems to be phase-dependent, with a minimum at phase 0.3 and a maximum at phase 0.5 (Fig. 2). However, the supercycle is not completely resolved in our limited dataset, so is not clear if the variation is smooth or random through the whole cycle. However, the observed behaviour contrasts with the monotonic increase of the peak separation during the supercycle (Neuostroev 1998). In addition, the $FWHM$ variability (up to 60% of the mean value) is larger than the variability shown by the peak separation (less than 15% of the mean value, Neuostroev 1998). This probably indicates important changes in the disk structure during the superoutburst cycle. A long-term monitoring of this star – likely obtaining just a few snapshot spectra through quiescence – is needed to fully clarify any dependence of the line parameters on the supercycle phase.

The fact that the post-period-minimum candidates show the larger residuals of Eq. 4, suggests the possibility of a dependence of the residuals on the mass accretion rate. To check that possibility, we choose the minimum time between outbursts as a comparison parameter. Current outburst models indicate that this parameter is inversely related to $\dot{M}$ (e.g. Osaki 1996). As a result, Fig. 3 suggests that the larger deviations are found in the

[1] We found only CZ Ori after searching for new above-the-gap dwarf novae with mass ratios published after 1993. No discrepant new entry for the stars listed by J94 were found. In general we used the sources listed by J94 for the parameters R, q, K and their errors, except for CZ Ori (Spogli & Claudi 1994) and WW Cet (q, K and errors from Tappert et al. 1997).

Table 2. Orbital and superhump periods (in days), and spectroscopic parameters $FWHM$ and K and their errors (in km s^{-1}) for a sample of SU UMa stars. The recurrence time (T_{rec} in days, sometimes corresponding to the mean value) is from Nogami et al. (1997) and references therein, except for BR Lup (Mennickent & Sterken 1998). These recurrence times are for normal outbursts except for WX Cet, EG Cnc and WZ Sge where are for superoutbursts. N/A means not available.

Star	$FWHM$	$error$	K	$error$	P_o	P_s	T_{rec}	$Note$
TU Men	1513	9	87	2	0.1172	0.1256	37	1
TY PsA	1706	26	68	9	0.08414	0.08765	40	2
BR Lup	1370	N/A	54	16	0.0795	0.0822	38	3
CU Vel	1780	3	49	6	0.0785	0.07999	390	4
HS Vir	1485	145	96	9	0.07696	0.0808	8	5
SU UMa	1051	N/A	58	4	0.07635	0.07877	13	6
Z Cha	3700	N/A	157	27	0.07481	0.0774	82	7
HT Cas	2460	N/A	105	N/A	0.07365	0.0761	450	8
CY UMa	1310	20	55	6	0.06957	0.0721	80	9
SX LMi	1500	N/A	57	10	0.06717	0.0695	35	10
AK Cnc	924	137	50	3	0.0651	0.06749	47	11
UV Per	640	N/A	29	4	0.06489	0.06641	390	12
VY Aqr	1550	N/A	49	4	0.06309	0.06437	350	12
EK TrA	1417	46	61	7	0.06288	0.0649	231	13
AQ Eri	1545	9	53	5	0.06094	0.06267	N/A	14
EG Cnc	1830	180	71	16	0.05997	0.06037	7000	15
WX Cet	1595	59	59	5	0.05829	0.05936	1000	16
WZ Sge	1830	152	49	5	0.05669	0.05714	12000	17
WZ Sge	1508	57	49	5	0.05669	0.05714	12000	18
WZ Sge	2064	56	49	5	0.05669	0.05714	12000	19
WZ Sge	1982	56	49	5	0.05669	0.05714	12000	19
WZ Sge	2807	281	49	5	0.05669	0.05714	12000	20
WZ Sge	2224	185	49	5	0.05669	0.05714	12000	21

Notes: $FWHM$ are for Hα, P_o and P_s from Patterson (1998) and references therein, except when indicated. $FHWM$ and K are from (1) Mennickent 1995a (2) O'Donoghue & Soltynski 1992, $FWHM$ from Mennickent 1995b (3) Mennickent & Sterken 1998, also P_o and P_s, $FWHM$ measured from Munari & Zwitter 1998 (4) Mennickent & Diaz 1996, also P_o, P_s is from Vogt (1981) (5) Mennickent et al. 1999, also P_o, P_s is from Kato et al. 1998. (6) Thorstensen et al. 1986 (7) Rayne & Whelan 1981, Hβ values (8) Horne et al. 1991, $H\beta$ values (9) Martin-Paris & Casares 1995 (10) Warner et al. 1998 (11) Arenas & Mennickent 1998, also P_o, P_s is from Kato (1994) (12) Thorstensen & Taylor 1997 (13) Mennickent & Arenas 1998, also P_o, P_s is from Vogt & Semeniuk (1980) (14) Mennickent 1995b (15) Patterson et al. 1998 (16) Mennickent 1994 (17) $FWHM$ from Honeycutt et al. 1987, as given by J94, Hβ values (18) $FWHM$ measured from Greenstein 1957, Hβ values (19) This paper (20) $FWHM$ measured from Neuostroev 1998 (21) $FWHM$ measured from Gilliland et al. 1986.

disks with the highest and lowest accretion rates. This impression remains valid inclusive after removing the objects showing only superoutbursts (WX Cet, EG Cnc and WZ Sge). More studies of extreme SU UMa stars are needed to confirm this point.

In Fig. 4 we compare q and R showing the best (non-linear Levenberg-Marquardt) fitting function

$$q = 0.09 + 6.78(28)e^{-[\frac{R+1.86}{5}]} \qquad q \geq 0.09 \tag{8}$$

This equation basically reproduces the J94 relation above the period gap but improves the fit for *most* SU UMa stars. As shown in Fig. 4, the mean relative dispersion is 22% for all dwarf novae, above and below the period gap, except for the "period-bouncers" EG Cnc and WZ Sge. These stars do not fit the general tendency shown by other dwarf novae. Accordingly, we regard Eq. (8) as a new mass estimator for dwarf novae with the exception of post-period minimum systems.

5. Discussion

In the above section we have showed how the theoretical linewidth/K vs. mass ratio relation fails to reproduce the observations of SU UMa stars. To explain this new finding we critically examine the basic assumptions yielding Eq. 4.

The disk radius was assumed a constant fraction of the primary's Roche lobe and the linewidth a good tracer of the disk velocity at a fixed radius. The first assumption conflicts with the observations but not in a critical way. In fact, a smooth exponential-type decay of the disk radius after outburst has been observed in U Gem (Smak 1984), Z Cha (O'Donoghue 1986), IP Peg (Wolf et al. 1993) and WZ Sge (Neustroev 1998). Simulations by Ichikawa & Osaki (1992) also show this phenomenon. However, in all the above cases the disk radius varies by just 10% during most the outburst cycle; the larger changes occur only near outburst. As most data of Table 2 was obtained in quiescence, the cyclic variability of disc radius should be a second-order effect. The second assumption, that the linewidth is a good tracer of the disk velocity at a fixed radius, fails if

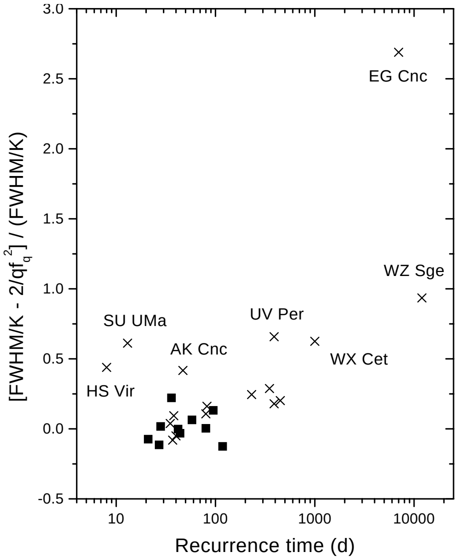

Fig. 3. The relative residuals of Eq. 4 for α = 2.0 (Jurcevic et al. 1994 's calibration) versus the recurrence time. Symbols are as in Fig. 2. The mean value of T_{rec} was used for dwarf novae above the period gap (Ritter & Kolb 1998). The mean R value of WZ Sge is plotted. Some stars with the larger residuals are labeled; in general they correspond to SU UMa stars with the longest and shortest recurrence times.

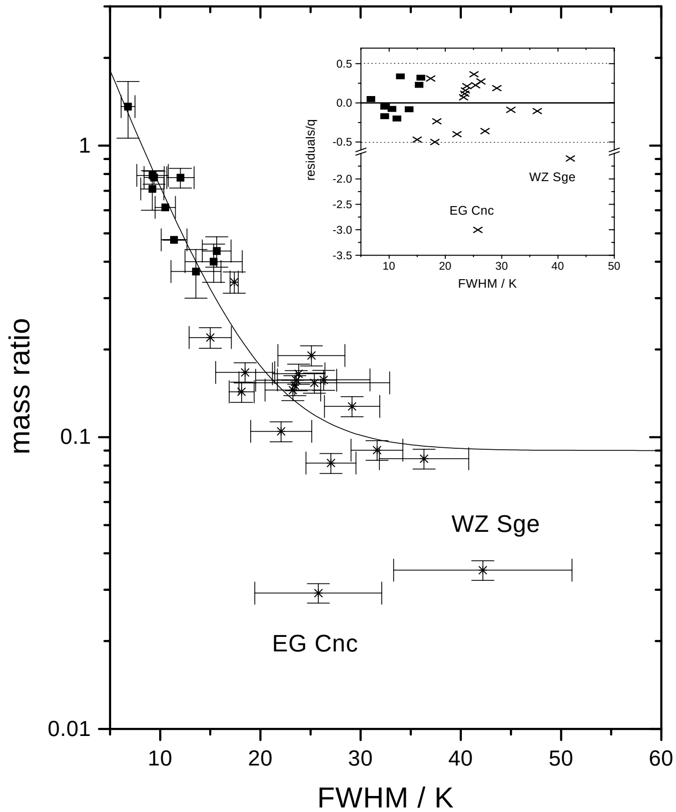

Fig. 4. The mass ratio versus the $FWHM/K$ ratio. The best fit, given by Eq. 8 (solid line) is also shown. Symbols are as in Fig. 2. Relative residuals are plotted in the enclosed graph. The dotted lines enclose the region with relative errors less than 50%. The mean relative dispersion is 16% above the period gap and 26% for SU UMa stars, excluding the post-period minimum candidates EG Cnc and WZ Sge which deviate from the general tendency. The mean R value of WZ Sge has been considered.

a significant non rotational contribution broadens the line. For example, the Stark effect could be efficient in some optically thick regions of the disk (Lin et al. 1988). This effect could be especially important in high inclination systems with prominent (eventually optically thick) hot spots. However, residuals of Eq. 4 are not inclination dependent, e.g. the eclipsing binaries WZ Sge, HT Cas and Z Cha do not show any especial trend. Therefore, we do not think that the above effects explain the SU UMa star deviations.

However, these could be explained if a large fraction of the inner disk is removed by some agent. In this cases the $FWHM$ indicates the disk velocity at a larger (fractional) radius than in a non truncated disk. To estimate the effect of a central hole on the $FWHM$ we generated synthetic profiles for several values of ρ ($\equiv r_{in}/r_{out}$). The range of ρ was chosen accordingly to recent spectroscopic studies suggesting the existence of central holes in the disk of long supercycle SU UMa stars (Mennickent & Arenas 1998). The extreme value (ρ = 0.3) corresponds to WZ Sge during 1991 whereas ρ = 0.03 is representative of non truncated disks. Our results, shown in Fig. 5, indicate that the larger the central hole, the larger the $FWHM$. The largest effect, for ρ = 0.3, implies a decrease of R by a factor 0.7. In order to compare with Fig. 2 we assume a constant outer disk radius. This is basically consistent with the lower cyclic variability shown by the peak separation when compared to the $FWHM$ (above section). We find that this effect is enough to explain the large deviations observed in some SU UMa stars. Moreover, the deviations associated to EG Cnc and WZ Sge are so large, that a truncation radius $\sim$ 60% of the outer radius is required to explain the observations at certain epochs.

The above picture is not valid if the assumption of a Keplerian disk is violated. In this case, K doesn't represent the white dwarf binary motion and Eq. 4 fails by two reasons: a bad interpretation of K and the wrong use of the Kepler third law for the disk. In this case Fig. 3 should indicate departures of Keplerian motions in the disks of SU UMa stars, specially in those of the post-period-minimum candidates EG Cnc and WZ Sge. In contrast, nearly Keplerian disks are observed in dwarf novae above the period gap. As the nature of K is unknown in non-Keplerian disks, we cannot decide between sub-Keplerian or super-Keplerian motions from the sign of the residuals of Eq. 4. Instead, Fig. 3 suggests a transition from a Keplerian to non-Keplerian stage when the mass accretion rate in the disk goes to an extremely low or high value. This view could be supported by the non-consistent system parameters occasionally found in the dynamical solutions of some SU UMa stars, e.g. HS Vir (Mennickent et al. 1999).

In the above paragraphs we have outlied two distinct scenarios compatible with the observations: removed inner disks and non-Keplerian disks. We favor the inner disk depletion hypothesis based on theoretical and observational evidence: it provides

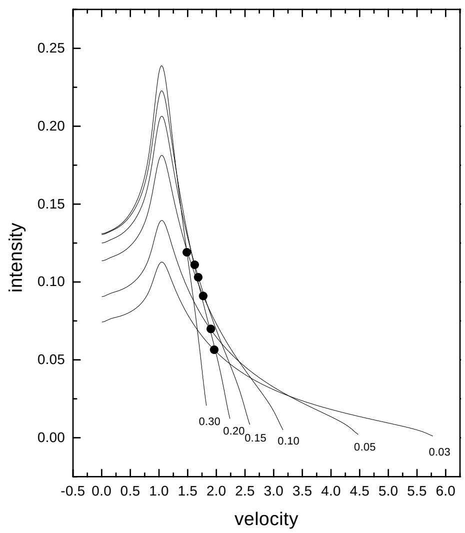

Fig. 5. Emission line profiles calculated with synthetic Smak's (1981) model. The integrated flux is normalized to the unity and the velocity to the half peak separation. The disk line emissivity was assumed proportional to r^{-2} and the normalized instrumental resolution 0.2 (see Smak 1981 for details about the model). The profiles are labeled according to the ratio between the inner and outer disk radius. The projection of the solid circles onto the velocity axis indicates the half $FWHM$ of each profile. We find that a hole in the inner disk decreases $FWHM$ and therefore R. This might explain the deviations observed in Fig. 2.

a natural explanation for the long recurrence time of WZ Sge (Lasota et al. 1995, on the observational side see Mennickent & Arenas 1998) and for the delay between optical and UV radiation at rise to outburst observed in some dwarf novae (Mineshige et al. 1998). In addition, promissory mechanisms to remove the inner disk have been proposed: the influence of a magnetosphere (Livio & Pringle 1992) or the effect of mass flow via a vertically extended hot corona above the cool disk (also referred as "coronal evaporation", Meyer & Meyer-Hofmeister 1994, Liu et al. 1997, Mineshige et al. 1998). The coronal-evaporation model has been used to model the evolution of the accretion disk of WZ Sge during quiescence (Meyer-Hofmeister et al. 1998). In this model, cyclic variations in the inner and outer disk radius are found; the results with the "standard parameters" (their Fig. 2) show a maximum $\rho \approx 0.26$ around supercycle phase $\Phi = 0.08$ whereas $\rho \approx 0.08$ is observed during most of the outburst cycle. The published spectroscopic data of WZ Sge are not enough to check this prediction, although Fig. 2 suggests maximum disk's depletion around supercycle phase 0.3.

6. Conclusions

1. We have found that the Jurcevic et al. (1994) relation is not valid for SU UMa stars.
2. Deviations from the above relation are observed in most SU UMa stars; the larger are seen in the post-period-minimum candidates EG Cnc and WZ Sge.
3. This is consistent with removed inner disks in some SU UMa stars, specially in "period-bouncer" candidates.
4. The inner disk depletion seems to be larger for systems with extreme cycle lengths (Fig. 3).
5. We cannot discard non-Keplerian disks as an alternative scenario, but we present arguments favoring the inner disk depletion hypothesis.
6. The long-term $FWHM$ variability observed in WZ Sge suggests that the fraction of mass removed from the inner disk is variable and possibly a function of the supercycle phase.
7. A new mass ratio estimator is given by Eq. 8. It is valid for dwarf novae above and below the period gap but not for post-period minimum candidates.

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