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WX Ceti: a closer look at its behaviour in quiescence and outburst⋆,⋆⋆

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ABSTRACT

Context. WX Cet is a dwarf nova with rare outbursts of large amplitude.
Aims. We compile the available data of WX Cet, compare the results with other SU UMa stars, and discuss our findings in the context of current theories of superhumps and superoutbursts to progress with our understanding of SU UMa stars.
Methods. We analyse all recorded outbursts of WX Cet, based on the AAVSO archive and other published sources, and present new CCD photometry during two recent superoutbursts, including the determination of the corresponding periodicities. We perform numerical disc instability model calculations and compare its predictions with the observations.
Results. WX Cet is a SU UMa type dwarf nova with a superoutburst cycle of 880 days on average, and short eruptions every 200 days. It seems that the outburst cycle length increased by nearly a factor of 2 during the past 70 years. According to our numerical simulations, this can be explained in the context of the disc instability model by assuming enhanced mass transfer during outburst and a decreasing mean mass transfer rate during the last decades. Using the data available, we refine the orbital period of WX Cet to 0.0582610 ± 0.0000002 days and interpret the orbital hump found in quiescence as emission from the hot spot. During two recent superoutbursts in July 2001 and December 2004 we observed superhumps, with a rather large positive period derivative of $\dot{P}_s/P_s = 1.6 \times 10^{-4}$, present only during the first 9 days of a superoutburst. Afterwards and during decline from the "plateau" phase, a constant superhump period of about 0.05922 days was observed. Late superhumps are present for at least 12 days after the decline from the "plateau", with a period of 0.05927 days. We find this phenomenology difficult to interpret in the context of the standard explanation for superhumps, i.e. the thermal tidal instability model.
Conclusions. We interpret the long-term light curve of WX Cet as the result of a significantly decreasing mean mass transfer rate. Highlighting the complexity of the observed superhump light curves, we emphasise the importance of WX Cet for a proper understanding of the SU UMa star outburst physics and the evolution of ultra-short period cataclysmic variables.

Key words. stars: individual: WX Ceti – stars: variables: general – stars: novae, cataclysmic variables

1. Introduction

The "Zoo" of dwarf novae among the cataclysmic variables has, during the last decades, evolved into a rather large variety of different sub-classes. The General Catalogue of Variable Stars (GCVS: Kholopov et al. 1985) distinguishes only three main classes with the prototypes SS Cyg, SU UMa, and Z Cam. The common features of SU UMa systems are superoutbursts that are significantly longer and brighter than normal dwarf nova outbursts and periodic humps found in the light curves during superoutburst, the so-called superhumps. In particular, the SU UMa class suffered a quite impetuous development since the eighties: ER UMa, RZ LMi, and V1159 Ori were detected to reveal a very rapid SU UMa type behaviour with super-cycle lengths between 19 and 43 days (Robertson et al. 1995), probably because of an unusual high mass transfer rate in these systems (Schreiber et al. 2004). At the other extreme of the SU UMa scale we can mention WZ Sge with its extremely infrequent outbursts every 2–3 decades (Patterson et al. 2002, and references therein).

SU UMa stars differ from normal dwarf novae not only due to their superoutbursts, but also due to periodic humps – so called superhumps – appearing in the light curves during superoutburst. The periods of these superhumps are usually a few percent longer than the orbital period, but the detailed phenomenology of superhumps has become rather complex during the last years: we distinguish early, normal, and late superhumps that appear at different times of the superoutbursts and that show different period changes. Early superhumps found near the maximum magnitude of WZ Sge superoutbursts appear to be constant and have periods close to the orbital period. In contrast, the periods of normal superhumps during the plateau of the superoutbursts are longer than the orbital period and usually decrease with time. Finally, late superhumps are typical features occurring several days after the rapid decline from the "plateau" of a superoutburst, revealing persistent periodic variations with superhump periods after a phase shift of typically 0.5 Ps (Schoembs & Vogt 1980; Rolfe et al. 2001).

⋆ Based on observations obtained at ESO La Silla, Las Campanas Observatory, Cerro Armazones Observatory, and the University of Concepción.
⋆⋆ The data are available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/463/1053
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We currently do not have a satisfying theory explaining both superoutbursts and superhumps in a consistent way. The general explanation for dwarf nova outbursts is the disc instability model (DIM), which is based on the existence of a thermal-viscous instability in regions where hydrogen is partially ionised, and the opacities strongly depend on temperature (Lasota 2001). To explain the superoutburst phenomenon in SU UMa stars, the DIM has to be generalised. There are currently two scenarios discussed. While Osaki (1989) added a "tidal instability" thereby developing the thermal tidal instability model (TTIM) (see Osaki 1996, for a review), Vogt (1983), Smak (1984), and Osaki (1985) suggested that superoutbursts are caused by enhanced mass transfers (EMT) from the secondary. Indeed, Hameury et al. (2000) showed that relating the mass transfer rate to the accretion rate, i.e., assuming that irradiation of the secondary is somehow increasing the mass transfer rate, allows us to reproduce the observed visual light curves. Recently, Schreiber et al. (2004) showed that EMT is probably the more promising model as its predictions are more sensitive to variations of the mean mass transfer rate, which allows us to explain the observed variety of light curves in SU UMa systems. On the other hand, at present only the TTI model provides an explanation for superhumps.

In principal, the broad range of different SU UMa phenomena provides an excellent testing ground for the two proposed scenarios. However, before systematically comparing the observations with model predictions one should carefully analyse the observations and classifications that have been made in the past. WX Cet was often mentioned as being similar to WZ Sge (Rogoziecki & Schwarzenberg-Czerny 2003). However, a compilation of all available sources for its outbursts shows that it is a rather ordinary SU UMa star with the characteristic two very distinct types of outbursts: normal, short eruptions and longer lasting superoutbursts (Sect. 2).

In this paper we analyse the long-term light curve of WX Ceti (Sect. 2), derive an accurate ephemeris of its orbital motion and discuss the origin of the hump light curve in quiescence (Sect. 3), present new photometric observations during two recent eruptions (Sect. 4), discuss the superhump phenomenology during superoutburst (Sect. 5), and finally we relate our results to current theories for superhumps and superoutbursts and the population of SU UMa stars (Sect. 6).

2. The general outburst behaviour

All known outbursts of WX Cet are listed in Table 1. A total of 17 different outbursts have been observed until now. We give the visual magnitude at maximum light V_{max}, the number of visual or photographic estimates (the latter ones from archival patrol plates) N_{obs} and the width W (in days) of those outbursts with sufficient observations to determine this quantity (W is defined as the time difference between the decline and the rise phase, both at a level of 3 mag below maximum light). In some cases, the magnitude of the maximum light is uncertain due to a lack of observations at early outburst stages. In these cases we give the corresponding limits. We also have determined the average decline rate in magnitudes per day and the outburst class (S = superoutburst, N = normal outburst). Finally, we list the time elapsed since the last previous outburst in cases whenever we can be rather sure that no outburst in between was missed. Δt_N refers to sequences S–N, N–N or N–S, while Δt_S refers exclusively to S–S. The AAVSO data contains regular ~60 d gaps when WX Cet is not visible. Assuming that superoutbursts of WX Cet last at least 15 days, we estimate the probability of missing a complete superoutburst to be $\lesssim 0.1$. Since the AAVSO continuously observes WX Cet, 7 superoutbursts have been identified and hence very probably only one – if any – superoutburst has been missed.

Table 1. Observed outbursts of WX Cet. Epoch of maximum (HJD−2 400 000), V_{max}, number of observations, decline gradient (mag d^{-1}), class, relevant time intervals, and references (R1 refers to visual and photographic estimates, R2 to phase-resolved photometry). The event of HJD 2431642 was probably observed at a late outburst state.

T_{max}	V_{max}	N	W [d]	grad	Cl	Δt_N	Δt_S	R1	R2
29 079	9.45	1	–	–	S			1	
29 567	10.2	1	–	–	S		488	1	
31 642	13.5	2	–	0.16:	S?			1	
38 294	10.5	4	–	0.15	S			2	
47 682	$\lesssim$10.8	53	20	0.14	S			3–7	9
47 864	12.55	10	$\lesssim$3	0.75	N	182		4, 9	
48 086	13.0	3	$\lesssim$3	0.4:	N	222		3	
48 191	13.3	1	–	–	N	105		4	
48 447	12.2	12	15	0.09	S	256	765	4, 8	10
49 375	$\lesssim$11.7	10	15	0.09	S		928	4	
49 618	13.6	1	–	–	N	243:		4	
50 283	$\lesssim$11.5	37	16:	0.17	S		908	4	11
50 697	12.5	10	3	1.00	N			4	
51 128	11.6	41	16	0.11	S		845	4	11–13
51 883	13.5	1	–	–	N			4	
52 087	$\lesssim$11.8	9	16	0.13	S	204	959	4,14	15
53 346	12.0	13	15	0.10	S		1259	4	15

References: 1: Gaposhkin (1976); 2: Strohmeier (1964); 3: McIntosh (1991); 4: AAVSO data base; 5: McNaught et al. (1989); 6: Overbeek & Pearce (1989); 7: Pearce et al. (1989); 8: Bateson & Jones (1991); 9: O'Donoghue et al. (1991); 10: Kato (1995); 11: Patterson et al. (2003); 12: Kato et al. (2001); 13: Howell et al. (2002); 14: ASAS3 data base Pojmanski (2001) 15: this paper.

The classification as superoutburst is based on the maximum brightness $V_{max} \leq 12.0$ and the slow decline rate $\leq$0.18 mag d^{-1}. In contrast, normal outbursts reveal $V_{max} \geq 12.5$ and decline rates between 0.4 and 1.0 mag d^{-1}. In addition, for the well-observed superoutbursts we can estimate the duration of the outbursts and find that they last 15 days or longer, while the widths of short (or normal) outbursts are only $\lesssim$3 days, and many of them have, without doubt, remained unobserved. Therefore, the values of Δt_N given in Table 1 have to be interpreted as upper limits. In addition, one should be aware that the early superoutburst identifications listed above are rather uncertain. Those at HJD = 2 429 079 and 2 429 567 are based on only one magnitude extracted from photographic plates and the superoutburst classification of the event in HJD = 2 431 642 is based on the decline rate derived from two magnitudes. In this sense, the first three rows of Table 1 should be taken as a reasonable representation of the available data, but not as precise observational facts. As WX Ceti is continuously monitored by the AAVSO since HJD = 2 447 682 only, we do not list upper limits for Δt_S for earlier measurements (with the one interesting exception of the very short quiescence time between the two – admittedly uncertain – superpoutburst idenfications on photographic plates, see Gaposhkin 1976).

Despite of all involved uncertainties, a fair explanation of the available data is the following. WX Cet is a SU UMa star with a rather long outburst cycle and superoutburst magnitude. It definitely reveals the two very distinct types of outbursts that are typical for SU UMa stars but not for WZ Sge. However, it seems that WX Cet displays a remarkable speciality: during the last seven decades, the superoutburst cycle length seems to have increased from ~500 days in the nineteenthirties to ~1000 days at present. In addition, although the early measurements are uncertain, there seems to be evidence for a simultaneous decrease of the maximum brightness. The only bright outburst (at HJD = 2 447 682) for which we can determine the width of the outburst W also lasted 25% longer ($W = 20$ d) than all the fainter superoutbursts observed since then. Thus, the available data indicate that superoutburst were more frequent, brighter, and longer seven decades ago.

WX Cet was often compared to WZ Sge because of its rare outbursts with rather large amplitude. According to our finding, the existence of short, normal eruptions, WX Cet may be considered as presenting a link between ordinary SU UMa stars and those of the WZ Sge subtype. Further investigation is needed to establish whether this subdivision is really justified.

3. The quiescent state: determination of the orbital period

Several attempts have been made to determine the orbital period of WX Cet from photometric observations. The most recent attempt by Rogoziecki & Schwarzenberg-Czerny (2001, hereafter RSC01) is based on a total of 52 hours of monitoring in quiescence, in four observing runs, two in 1990 and two in 1998. Although coherent periodic variations were found in all runs, these authors were not able to link the two distant epochs together to determine a unique ephemeris. Part of the problem is the variable nature of the light curve, which sometimes demonstrates two maxima per orbital cycle (in 1998), while in 1990 a pronounced single-hump was predominant. RSC01 determined as the best period value $0\overset{\mathrm{d}}{.}058260 \pm 0\overset{\mathrm{d}}{.}000002$, but they could not exclude another possible cycle count corresponding to an orbital period of $0\overset{\mathrm{d}}{.}058304$.

On the other hand, there are two independent determinations of the radial-velocity curve of the primary in WX Cet, one by Mennickent (1994, original data published by Mennickent et al. 2001), the other by Thorstensen et al. (1996). Since the observations in both cases are limited to a few subsequent nights, the determined periods are not very accurate. The Thorstensen et al. (1996) period ($0\overset{\mathrm{d}}{.}05829 \pm 0\overset{\mathrm{d}}{.}00004$) coincides with that of RSC01, while Mennickent (1994) ($0\overset{\mathrm{d}}{.}05497$) refers to a one-day alias of it. In both cases, however, we have a rather precise determination of the inferior conjunction of the white dwarf, namely HJD 2 448 965.5635 (Mennickent 1994) and HJD 2 449 255.7616 (Thorstensen et al. 1996), with an uncertainty of $\pm 0\overset{\mathrm{d}}{.}0006$ for each of them. The time interval between these two epochs ($290\overset{\mathrm{d}}{.}1981 \pm 0\overset{\mathrm{d}}{.}0009$) contains an entire number of orbital cycles. Using the most accurate period of RSC01 immediately gives the unique number of 4981 cycles for this time interval. This way, we can derive an improved ephemeris for the inferior conjunction of the white dwarf:

$$\begin{array}{lll} \mathrm{HJD} & 2\,448\,965.5635 + 0.0582610\,E. & (1) \\ \pm & .0006 \quad .0000002 & \end{array}$$

The error of the period value is entirely based on the uncertainty of the above epoch difference. Note that the accuracy of the period value has improved by a factor 10, as compared to RSC01. The other possible period mentioned by RSC01 does not give an entire cycle number for the above epoch difference within the errors quoted, and therefore can be disregarded.

Using the long-term ephemeris (1) we can now analyse the photometric behaviour of WX Cet in quiescence. In their Fig. 7, RSC01 give a mean hump light curve with an amplitude of about 0.18 mag, determined in several observing runs between September and December 1990. The hump maximum is observed around their phase 0.5, which corresponds to $\varphi = 0.4$ in (1). Since the inferior conjunction of the secondary – i.e., the expected phase of a central eclipse of the white dwarf – would be at $\varphi = 0.5$ in (1), we observe the hump maximum about one tenth of an orbital period before the conjunction epoch of the secondary, which just is as expected from the canonical model of a CV, and is observed in other well-known dwarf novae, as U Gem (Krzeminski 1965), Z Cha (Bailey 1979), and VW Hyi (Vogt 1974; Schoembs & Vogt 1981) among others. In addition, RSC01 give in their Fig. 8 another mean light curve obtained in October 1998. Here we observe a double hump, separated by a minimum, which just coincides with the phase of the hump maximum of 1990. We can interpret this as a partial eclipse of the hot spot by the secondary companion in 1998, while in 1990, no hot spot eclipse was present, probably because of a smaller disc radius at that time. Both light curves of RSC01, 1990 and 1998, show a pronounced minimum near their phase 0.95, i.e. 0.85 of (1), which corresponds to the upper conjunction of the hot spot seen from Earth (please note that we defined the inferior conjunction of the white dwarf as phase $\phi = 0$). Apparently, the disc is, at both epochs, sufficiently opaque to cover most of the hot spot radiation during this short phase interval.

A double-hump structure is also present in the quiescence light curves of other dwarf novae, for instance IP Peg. In this sytem the phenomenon has been interpreted by means of a patchy disc emissivity and some occulting material present in the disc (Froning et al. 1999). Also the SU UMa stars WZ Sge and AL Com show light curves with double hump or single hump structures during quiescence (Kitsionas et al. 2004; Patterson et al. 1996). The secondary star is invisible in these systems and the double hump structure probably originates in the accretion disc, which may be optically thin during quiescence (Howell & Skidmore 2000). Consequently, the hot spot could perhaps contribute to the emission when seen in upper *and* in lower conjunction (Robinson et al. 1978).

However, in 1990, WX Cet showed a single hump typical of the canonical CV model; in 1998, in contrast, a rather shallow drop in brightness was superimposed on the former hump maximum, causing a double hump structure with significantly different depths of the two minima. This seems to distinguish WX Cet from WZ Sge and AL Com with their W UMa-like light curves (quasi-sinusoidal double hump). It might therefore be justified to interpret WX Ceti's quiescence light curve in a different way, e.g., as outlined above.

4. The data

CCD frames were collected in 2001 and 2004 using the Danish 1.54-m telescope at ESO La Silla, the Polish 1.3-m telescope at Las Campanas Observatory, the 41-cm Schmidt-Cassegrain telescope at Cerro Armazones Observatory, and the 30-cm Schmidt-Cassegrain telescope at the University of Concepción. The data-reduction procedures, and all resulting magnitudes and individual light curves, are presented by Sterken et al. (2005).

5. Superoutbursts of WX Cet: two domains of the superhump periodicity

Superhumps are the most striking property of SU UMa type stars, reported first by Vogt (1974) for VW Hyi. They occur only during superoutbursts, and their period P_{s} typically exceeds that of the orbital motion P_{o} by a few percent. The period excess $\epsilon = (P_{\mathrm{s}} - P_{\mathrm{o}})/P_{\mathrm{o}}$ and its correlation to other parameters such as mass ratio, binary dimension, and mass-transfer rate have recently been discussed by Patterson et al. (2005). In most SU UMa stars, P_{s} is not constant over the course of a

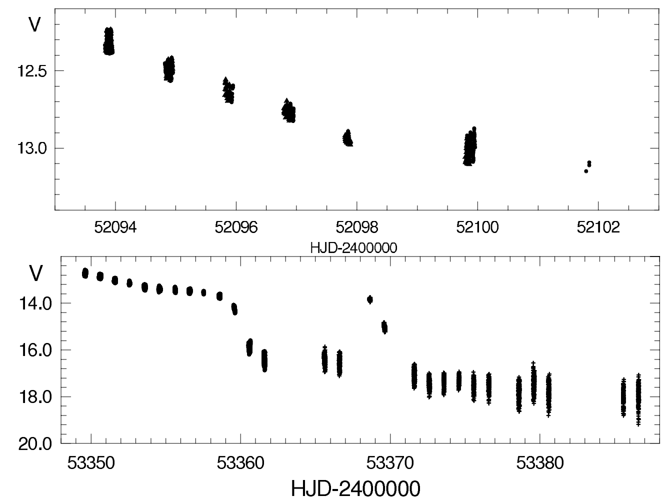

Fig. 1. V-light curve of the July 2001 superoutburst (*top panel*) and differential V-light curve of the superoutburst of December 2004 (*bottom panel*). The latter covers nearly the entire plateau phase, its decline, the echo outburst at JD 2 453 368–69, and the subsequent stage near quiescence with "late superhumps".

superoutburst: the prototype star VW Hyi, for instance, reveals a significant period decrease with a rate $\dot{P}_\mathrm{s}/P_\mathrm{s} = -7.4 \times 10^{-5}$ (Haefner et al. 1979). However, there are several other SU UMa stars with increasing P_s (Imada et al. 2006, and references therein), and WX Cet is one of these cases: for the first 8 days of the superoutburst of November 1998, Kato et al. (2001) found an increase rate $\dot{P}_\mathrm{s}/P_\mathrm{s} = +8.5 \times 10^{-5}$, a value very similar to that of VW Hyi, but with an opposite sign. The rich superhump phenomenology just described should be closely related to the superoutburst phenomenon, and, as mentioned in the introduction, our understanding of the physics of both superhumps and superoutbursts is currently very limited. We may progress with this situation by analysing in as much detail as possible the superhump phenomenology for as many SU UMa systems as possible. In this section we analyse our new data of WX Cet and combine it with early measurements of superhumps in WX Cet (Kato et al. 2001) to establish a detailed view of superhumps in WX Cet. We first describe the two observed superoutbursts, and then give a general description of the superhump phenomenology.

5.1. Superoutburst coverage

The light curves of the July 2001 and December 2004 superoutbursts are given in Fig. 1. The 2001 observations cover only part of the "plateau" phase. Inspite of the lack of AAVSO estimates at the beginning of this outburst we can determine its start time rather accurately from the ASAS3 data base (Pojmanski 2001): there is a first positive observation in JD 2 452 087.9 ($V = 11.83$) while, on a frame obtained 24 hour earlier, WX Cet was below the threshold of about magnitude 14. The superoutburst of December 2004 was rather completely covered (Fig. 1, bottom). According to the AAVSO records, it had started at JD 2 453 346, 3 days before our observations. The plateau phase lasted till JD 2 453 359, a total of 13 days. Strong superhumps had already developed before our first run, and they were present during the entire plateau phase. In JD 24 453 368 we can observe an echo outburst of short duration, which was declining one day later with a rate of $2\overset{\mathrm{m}}{.}7$ d^{-1}. In spite of this interruption, late superhumps were present at least until JD 2 453 372, another 13 days after the rapid decline from the plateau.

Table 2. Times of superhump maxima measured during the July 2001 and Dec. 2004 superoutbursts (HJD–2 400 000). Also given are the mean amplitudes A averaged over one night.

T_max	E	A	T_max	E	A
52 093.8639	0	0.15	53 351.6224	34	
52 093.9232	1		53 352.5732	50	0.13
52 094.8726	17	0.14	53 353.5290	66	0.12
52 094.9322	18		53 353.5922	67	
52 095.8252	33	0.14	53 354.5497	83	0.12
52 095.8856	34		53 355.6190	101	0.16
52 095.9450	35		53 356.5688	117	0.12
52 096.8400	50	0.11	53 356.6294	118	
52 096.8996	51		53 358.5811	151	0.11
52 097.8549	67		53 358.6395	152	
52 099.8245	100	0.19	53 359.5877	168	0.13
52 099.8836	101		53 360.5963	185	0.24
52 099.9439	102		53 361.5361	201	0.42
			53 361.5937	202	
53 349.6016	0	0.19	53 365.6255	270	0.39
53 349.6606	1		53 366.5701	286	0.35
53 350.5529	16	0.14	53 369.5958	337	
53 350.6104	17		53 371.6158	371	0.42:
53 351.5620	33	0.14	53 372.6151	388	0.27

5.2. Superhump phenomenology

Table 2 contains the times of superhump maxima during both eruptions (July 2001 and December 2004). They were determined by a polynomial fit around the light-curve maxima. Only those observing runs, which cover at least one entire orbital period, were used for this. In addition, the mean nightly amplitude of the superhump variability after subtraction of longer-term trends (if present) is listed.

The superhump maxima observed during the July 2001 outburst lead to the ephemeris

$$\begin{array}{llll} \mathrm{HJD} & 2\,45\,2093.8638 + 0.05928\,E + 49 \times 10^{-7} E^2, & & (2) \\ \pm & .0004 \quad .00004 \qquad 7 & & \end{array}$$

with standard deviation $\sigma = 0\overset{\mathrm{d}}{.}0004$ and valid in the range E = 0–67, i.e., during the first 4 days of our observations (Fig. 2, top). The later observations at E = 100–102 cannot be included with the parabolic fit, but they are compatible with a constant period $P\mathrm{s} \approx 0\overset{\mathrm{d}}{.}0596$. From Table 2 we see that the superhump amplitude has grown strongly after the end of the domain of the increasing period.

The superhump periodicities in December 2004 reveal a rather complex pattern. During the first 5 days (E = 0–83) of our observations, superhump maxima lead to:

$$\begin{array}{llll} \mathrm{HJD} & 2\,453\,349.6025 + 0.059215\,E + 48 \times 10^{-7} E^2 & & (3) \\ \pm & .0019 \quad .000014 \qquad 20 & & \end{array}$$

with $\sigma = 0\overset{\mathrm{d}}{.}0021$. Afterwards, the plateau phase is characterised by a constant superhump period:

$$\begin{array}{llll} \mathrm{HJD} & 2\,453\,349.6391 + 0.059222\,E & & (4) \\ \pm & .0029 \quad .000004 & & \end{array}$$

valid for E = 101–185, just till the rapid decline from the plateau (see Fig. 2, bottom). After decline we observe a significantly longer period for late superhumps:

$$\begin{array}{llll} \mathrm{HJD} & 2\,453\,349.6217 + 0.059270\,E, & & (5) \\ \pm & .0049 \quad .000004 & & \end{array}$$

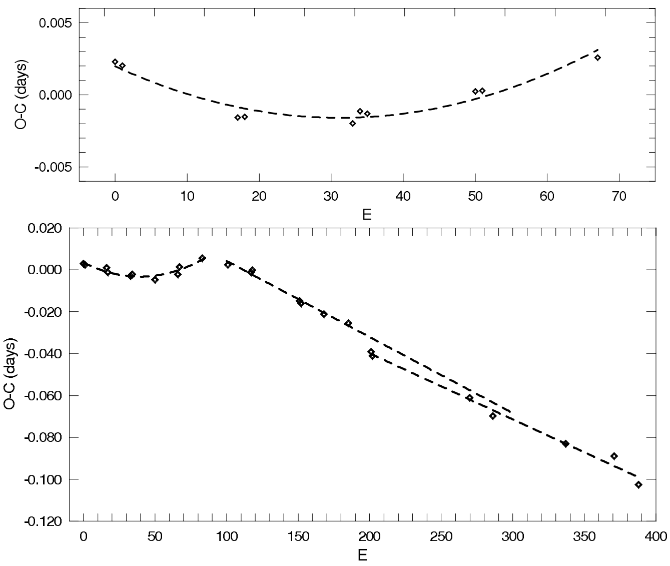

Fig. 2. O–C diagram of the superhump maxima during the July 2001 (*top panel*) and Dec. 2004 (*bottom panel*) superoutburst, based on assumed constant periods of 0.ᵈ059563 and 0.ᵈ059585, respectively. The dashed curves refer to Eq. (2) (*top*) and Eqs. (3–5) (*bottom*).

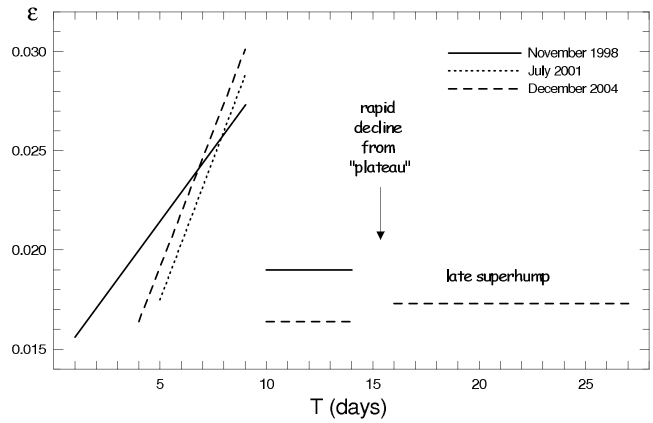

Fig. 3. Superhump period excess ϵ versus time during 3 superoutbursts of WX Cet. $T = 1$ refers to the first appearance of superhumps. For July 2001 and December 2004, the first observation ($E = 0$ in Table 2) refers to day 5 and 4, respectively; note the strong increase of ϵ during the first 9 days of each outburst.

which is valid for $E = 201$–388. For the corresponding O–C diagrams see Fig. 2 (bottom). The transition between the domain of changing and constant period ($E \approx 100$) is characterised again by a small rise in the superhump amplitude (see Table 2), but without significant phase shift. In contrast, there is a phase shift of $-0.14P_s$ during the rapid decline ($E \approx 185$).

The two superoutbursts covered by our observations reveal the same kind of behaviour: superhumps are present with an increasing period during the first days of the outburst, with identical $\dot{P}_s/P_s \approx 1.6 \times 10^{-4}$ in July 2001 and in December 2004. This value, however, is about twice that of Kato et al. (2001) from November 1998. As a possible reason for this, we have to remember that we have missed the first few days of both outbursts, implying that our time basis for the phase of increasing period is shorter: 4 days in July 2001 and 5 days in December 2004, as compared to 8 days in the observations of Kato et al. (2001). This, of course, implies larger uncertainties in the determination of $\dot{P}_s$.

Figure 3 shows the superhump period excess as a function of time during the three well-observed superoutbursts of WX Cet. In all three cases, we have a strong increase of ϵ during the first 9 days of a superoutburst, from $\epsilon \approx 0.016$ to $\epsilon \approx 0.028$ on average. This period derivative is one of the largest values ever observed in superhumping CVs (see Uemura et al. 2005). At day 10, however, a lower value $\epsilon = 0.018$ is recovered and remains constant through decline from plateau and even in the "late superhump stage" after decline (at least up to day 27).

6. Discussion

In the previous sections we present new results of WX Cet ranging from analysis of the long-term light curve and the outburst amplitudes to the evolution of the superhump signal during outburst. Now we want to relate the results of our detailed analysis of WX Cet to the properties of known SU UMa and WZ Sge systems and current theories of SU UMa superoutbursts and superhumps.

6.1. Superhumps

The observed period increase during the early stages of the outburst seems to be typical of short orbital period/low mass transfer systems like WZ Sge (Kato et al. 1998). On the other hand, we could not identify the so-called early superhumps first detected by Patterson et al. (1981) and probably also typical of WZ Sge systems (Nogami 2006). Meyer & Osaki (2002) suggested that early superhumps are caused by the disc reaching the 2:1 resonance radius, which can be located within the tidal truncation radius for systems with extreme mass ratios. However, neither the transition from early to ordinary superhumps nor the period changes of the latter are well understood. There is currently no theory available to consistently explain the variety of superhumps observed in SU UMa systems.

In any case, if superhumps are somehow caused by an eccentric disc we may relate the superhump period to the evolution of the accretion disc during outburst. In simple models, the superhump excess precession of the disc depends only on the mass ratio $q = M_2/M_1$ and the disc radius R_d/a:

$$\epsilon^{-1} = [0.37q/(1+q)^{1/2}]^{-1}(R_d/0.46a)^{-2.3} - 1, \quad (6)$$

(Patterson 2001). Since q and a are constant for a given binary, the remaining parameter is R_d, and variations of ϵ can be interpreted as radius variations. Adopting $q = 0.094$ (Patterson et al. 2005), we estimate that the disc in WX Cet expands and increases its diameter by nearly 35% within the first 9 days of a superoutburst. Afterwards, it shrinks even more rapidly (within 1 or 2 days), recovering its normal size and maintaining it for the rest of the outburst and for the following "late superhump" state.

Clearly, although eccentric discs and tidal resonances currently represent the only idea to explain the superhump phenomenon, we should be aware that this theory is facing serious difficulties and is probably not the end of the story. For example, it is not easy to understand why the disc should shrink by ~25% within 1 or 2 days in the middle of the plateau phase, i.e., during the quasi stationary outburst state. According to the disc instability model, a rapid shrinkage of the disc is only expected once the cooling front starts at the outer edge of the disc. This should then cause the instantaneous decline from outburst in the visual light curve. Equation (6) predicts a drastic shrinkage of the disc while the visual magnitude remains constant, which clearly contradicts the disc instability model. In this sense, the values given above

Table 3. Assumed binary parameter of WX Ceti and model parameter. In the EMT scenario $f_{\rm ill}$ defines the strength of enhanced mass transfer and $\langle R_{\rm out}\rangle$ the mean outer radius which is assumed to be given by the average of r_1, r_2, and $r_{\rm max}$ in Table 1 of Paczynsky (1977). We arbitrarily assumed a rather low value of the viscosity parameter during quiescence (α_c) to reproduce the long lasting low-states.

$P_{\rm orb}$/h	1.4
$T_{\rm sec}$	2750 K
$M_{\rm wd}/M_\odot$	1.0
$M_{\rm sec}/M_\odot$	0.1
$R_{\rm wd}/10^8$ cm	5.6
$i/^\circ$	60
d/pc	100
$\alpha_{\rm c}$	0.008
$\alpha_{\rm h}$	0.12
$\langle R_{\rm out}\rangle/10^{10}$cm	2.1
$f_{\rm ill}$	0.15

for the evolution of the outer radius of the disc during outburst have to be taken as a highly uncertain interpretation.

6.2. The long-term light curve

The first and often ignored fact we want to mention here is that WX Cet apparently shows not only superoutbursts, but also short normal outbursts. Of course, for some normal outbursts our identification is based on only one or very few measurements and our interpretation therefore is of a somewhat speculative nature. However, there are at least two obvious normal outbursts at HJD = 2 450 697 and HJD = 2 447 864.

Another interesting and peculiar feature of WX Ceti is the increase of the superoutburst cycle length from about 500 d (HJD $\sim$ 2 430 000) to 1000 d (HJD $\sim$ 2 453 000). It seems that simultaneously the maximum magnitude of the superoutbursts decreases although we should take into account that the early data used to compile the sequence of superoutburst magnitudes shown in Table 1 is based on the analysis of photographic plates and the determined magnitudes are perhaps somewhat uncertain. Only since HJD = 2 447 682 do most superoutbursts have $\gtrsim$10 individual data points covering both the final rise and the plateau quite well. Analysing only these data we find that the superoutburst length and maximum magnitude are usually $W \sim$ 15 days and $V \sim$ 11.5 with the only exception being the particular bright and long superoutburst with $W \sim$ 20 days and $V \lesssim$ 10.8 respectively at HJD = 2 447 682 d. In short, the data compiled in Sect. 2 is probably incomplete concerning normal outbursts, and some early measurements are probably rather uncertain, but, nevertheless, the information available indicates a correlation between superoutburst cycle length, maximum brightness, and length of the superoutbursts.

6.3. Model calculations

As mentioned in the introduction, dwarf nova outbursts are in general successfully explained within the disc instability model, while explaining superoutbursts of SU UMa stars requires an additional and uncertain ingredient. Enhanced mass transfer and tidal instabilities (see, e.g., Lasota (2001) for an excellent review) are currently discussed. Analysing the observations of VW Hyi in detail, Schreiber et al. (2004) have shown that the EMT model is more sensitive to variations of the mean mass transfer rates and therefore probably the more promising scenario.

We want to investigate whether variations of the mass transfer rate can in principal explain the correlations observed in the long term light curve of WX Cet. We performed a numerical test using the EMT model assuming a gradual decrease of the mean mass transfer rate over the course of several decades. The disc instability code we use has been written by Hameury et al. (1998) and improved by Buat-Ménard et al. (2001). To account for the assumed enhanced mass transfer during outburst, we follow Hameury et al. (2000) and Schreiber et al. (2004) and relate the mass transfer rate to the mass accretion rate using the following prescription:

$$\dot{M}_{\rm tr} = \max\,(\dot{M}_{\rm tr0}, f_{\rm ill}\langle\dot{M}_{\rm acc}\rangle), \qquad (7)$$

with

$$\langle\dot{M}_{\rm acc}\rangle = \int_{-\infty}^{t_0} \dot{M}_{\rm acc}\,{\rm e}^{(-t_0-t)/\Delta t}{\rm d}t, \qquad (8)$$

where $f_{\rm ill}$ is the efficiency of the mass tranfer enhancement and we used Δt = 2 d (see also Buat-Ménard & Hameury 2002). We assume the mean mass transfer rate to decrease from 2×10^{16} g s^{-1} to 0.5×10^{16} g s^{-1} over the course of 7000 days, to analyse the effect of a strongly decreasing mass transfer rate on the predicted light curve. The mass ratio of WX Cet and an upper limit for the secondary mass have been estimated by Mennickent (1994) to be $q \sim 10$ and $M_{\rm sec} \lesssim 0.17$. Although these estimates are quite uncertain, we assume binary parameters consistent with these values. The model parameters we assume are typical of disc instability calculations with the exception of a rather small value for the viscosity parameter in the low state ($\alpha_{\rm c}$ = 0.008), which is needed to reproduce the observed long quiescence periods. Adjusting $\alpha_{\rm c}$ to describe the observations is apparently arbitrary and very probably not a proper description of the physical difference between SU UMa stars with short and long quiescence periods. However, the conclusions of this section are not affected by this assumption because the general effects of a decreasing mean mass transfer rate are independent of the exact value of $\alpha_{\rm c}$. Our focus is to see whether a decreasing mass transfer rate can in principle explain the observed long-term behaviour of WX Ceti. The entire set of model parameters is given in Table 4.

Figure 4 shows snapshots of the resulting simulated light curve and the evolution of the mass transfer rate. In the EMT model the disc has to reach a critical mass to trigger a superoutburst. For a high mass transfer rate, the model predicts only very long superoutbursts ($W \sim$ 30 d) with a very short quiescence time ($\lesssim$200 days, see top panel of Fig. 4). With decreasing mass transfer rate, the quiescence time increases and the superoutbursts become shorter ($W \sim$ 15 d, middle panel of Fig. 4). For very low mean mass transfer rates, normal outbursts appear and the supercycle length becomes longer than 1000 days (bottom panel of Fig. 4).

Of course, due to assumptions and serious simplifications, simulated light curves always look different than observed ones, and this is also true for our numerical experiment and the observations of WX Ceti. However, our calculations show that the behaviour of WX Ceti can be explained by variations of the mass transfer rate. According to this scenario, WX Ceti was in a state with a rather high mass transfer rate producing long and rather frequent superoutbursts at HJD $\sim$ 2 429 400. With decreasing mass transfer rate, the supercycle length significantly increased, normal outbursts appeared, and the superoutbursts shortened.

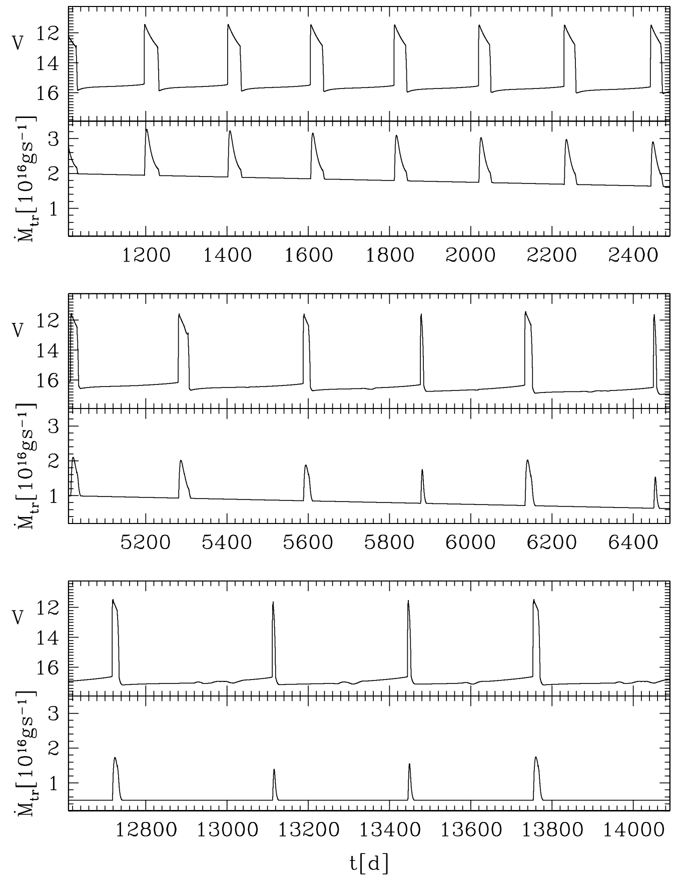

Fig. 4. The light curve and the mass transfer rate predicted by the EMT model for a dwarf nova system with the parameters given in Table 4 and assuming the mean mass transfer rate to continuously decrease from $\dot{M}_{\rm tr} = 2 \times 10^{16}$ g/s to $\dot{M}_{\rm tr} = 0.5 \times 10^{16}$ g/s. For the high mass transfer rate the model predicts only superoutbursts (top panel). With decreasing mass transfer rate, small outbursts appear, superoutbursts become shorter, and the supercycle length significantly increases (middle and bottom panel).

6.4. WX Ceti, WZ Sge, and SU UMa stars

The main properties of WZ Sge star have recently been summarised by Imada & Monard (2006) and by Nogami (2006). According to these authors, WZ Sge stars are characterised by (1) very long recurrence cycles (years to decades), (2) large outburst amplitudes over $6^{\rm m}$, (3) long outburst durations (40–100 d), (4) the occurrence of echo outbursts (short eruptions just after decline), (5) no normal outbursts between successive superoutbursts, (6) small superhump period excess ($\leq$1%), and (7) early superhumps, i.e., double-peaked humps during the first days of a superoutburst, with a periodicity of almost the same as the orbital period. In Fig. 5 we show the amplitude distribution of all SU UMa and WZ Sge type stars listed in the final edition of the Catalog and Atlas of Cataclysmic Variables by Downes et al. (2005), supplemented by a few additional stars from the cvcat file (Kube et al. 2003). Only stars with definite maximum and minimum magnitudes were used, neglecting those with lower amplitude limits. From the histogram it becomes clear that there is a large overlap in the amplitude distribution, revealing catalogued SU UMa as well as WZ Sge stars in the amplitude range between $5^{\rm m}$ and $8^{\rm m}$, which implies that (2) is not a very distinctive criterion. Indeed, the above authors mention that, strictly applying the above criteria for WZ Sge stars, especially (6) and (7), only four stars qualify for this subclass: EG Cnc, AL Com, WZ Sge, and HV Vir. The presence of many more so-called WZ Sge stars in Fig. 5 reflects the uncertainty in distinguishing WZ Sge and SU UMa stars in present-day catalogues. WX Cet violates several of the above criteria, in particular (3), (5), (6), and (7), but it fullfills others. Therefore, we prefer to call WX Cet an ordinary SU UMa star with a long outburst cycle, and leave the problem of the WZ Sge classification to future studies, which should also consider, in addition to phenomenological criteria, the understanding of the underlying physics.

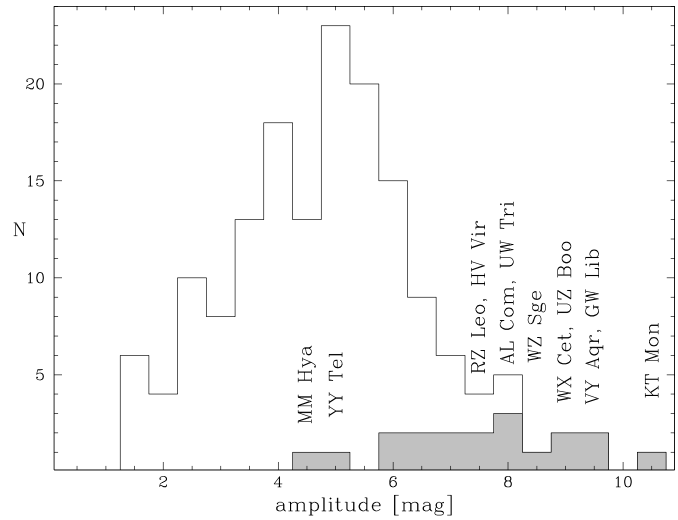

Fig. 5. Histogram of SU UMa dwarf novae based on the catalogue of Downes et al. (2005). The population of WZ Sge systems is shaded gray and some stars classified as WZ Sge systems are marked. Apparently, the amplitude of the outburst alone is not a good measure to distinguish between the two types of dwarf novae.

7. Conclusions

We have analysed the currently available observational information including some new photometric data of the SU UMa dwarf nova WX Cet and discussed our results in the context of present models for SU UMa stars. The results of this study can be summarised as follows:

1. WX Cet does not only show superoutbursts, but also short normal dwarf nova outbursts. In addition, it seems that the superoutburst cycle length increased during the past 70 years. This behaviour can be explained in the context of the disc instability model and the enhanced mass transfer scenario by assuming a decreasing mean mass transfer rate.
2. In quiescent state, WX Cet displays a typical hump light curve with an orbital period of 0.0582610 days. Occasionally, the hump has a double peak, possibly indicating a partial eclipse of the hot spot by the secondary
3. For the first 9 days of both superoutbursts that we observed, we determine a positive superhump period derivative of $\dot{P}_{\rm s}/P_{\rm s} \approx 1.6 \times 10^{-4}$, one of the largest values ever observed for SU UMa stars. During the remaining time of the superoutburst, as well as during the decline from the "plateau" phase, a constant superhump period of about 0.05922 days was observed. Late superhumps are present for at least 12 days after the decline from the "plateau", with a period of $0\overset{\rm d}{.}05927$. The transition between ordinary and late superhumps reveals a phase shift of only $-0.14P_{\rm s}$. According to current superhump models, the large period derivative might

be interpreted as an expanding disc, increasing its diameter by nearly 35% during the first 9 days of the superoutburst. However, in this picture the rapid change from the increasing superhump period to a significantly smaller value would indicate an unrealistic fast decrease of the disc's radius during the plateau phase of the outburst.

To progress with our understanding of SU UMa dwarf novae, WX Cet deserves special attention because of three features discussed in this work: the occurence of normal dwarf nova outbursts in a long-cycle dwarf nova, the indications for an increase of the cycle length during the past decades, and, in particular, the large superhump period derivative during the first stages of the superoutburst. It would be interesting to search for similar behaviour among other SU UMa stars, to elucidate hitherto unknown details in the physics of the erupting accretion disc, as well as the evolutionary status of WX Cet among the cataclysmic variables with the shortest orbital periods.

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