Superhumps and their Evolution during Superoutbursts

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ABSTRACT

Light curves of superhumps and their evolution during superoutbursts are analyzed by decomposing them into their Fourier components, including the fundamental mode and the first three overtones. The amplitudes of the fundamental mode are found to decrease significantly during superoutburst while those of the overtones remain practically constant. The phases of maxima of the fundamental mode increase systematically during superoutburst while those of the overtones systematically decrease. The combination of the two effects is responsible for the characteristic evolution of superhump light curves: the appearance and growth of the secondary humps and the spurious phase jumps in the (O-C) diagrams.

Two interpretations are possible. Either that instead of just one superhump period $P_{sh}$ there are four periods $P_k$ which resemble – but are significantly different from – the fundamental mode and the first three overtones of $P_{sh}$. Or – more likely – that those time-dependent phase shifts are genuine.

Key words: binaries: cataclysmic variables, stars: dwarf novae

1. Introduction

Superhumps are periodic light variations, with periods which are slightly longer than the orbital periods, observed (1) almost always in dwarf novae during their superoutbursts (cf. Kato et al. 2009, 2010, 2012), (2) occasionally in dwarf novae at quiescence and during normal outbursts (e.g. Patterson et al. 1995, Still et al. 2010), and (3) in the so-called permanent superhumpers – the nova-like cataclysmic binaries with stationary accretion (cf. Patterson 1999).

During the last 40 years since their discovery (Vogt 1974, Warner 1975) the superhumps – particularly those observed during superoutbursts – were subject to many investigations. Most of them have concentrated primarily or even exclusively on the superhump periods. Fortunately there are also papers presenting full description of superhumps, including their light curves and showing the evolution of their shapes during superoutbursts. Generally the superhump amplitudes decrease during superoutburst (cf. Smak 2010 and references therein) and their shapes vary...
considerably (e.g. Patterson et al. 1995 and other references below). Those variations usually involve the appearance and growth of secondary humps which may – occasionally – replace the main maximum producing thereby a spurious phase shift in the (O-C) diagram; this is what happens in the case of the so-called late superhumps (cf. Udalski 1990, Patterson et al. 1995, 1998).

The aim of the present paper is to study the evolution of superhumps during the superoutbursts by decomposing their light curves into their Fourier components. This was done earlier by several authors, usually in order to prewhiten the observed curves (e.g. Olech et al. 2004a, 2004b, Otulakowska-Hypka 2013), but without paying attention to the results. And the results turn out to be important and revealing.

2. The Data and their Analysis

We begin by describing the superhump light curves used in our analysis. They are listed in Table 1.

Table 1
The Superhump Light Curves

| Star     | Superoutburst | Source of light curves                  |
|----------|---------------|-----------------------------------------|
| TT Boo   | June 2004     | Olech et al. (2004b), Fig.3              |
| GZ Cnc   | March 2010    | Kato et al (2010), Fig.9                 |
| PU CMa   | November 2009 | Kato et al (2010), Fig.4                 |
| GX Cas   | October 2010  | Kato et al (2012), Fig.7                 |
| HT Cas   | November 2010 | AAVSO International Database             |
| IX Dra   | September 2003| Olech et al (2004a), Fig.7               |
| IX Dra   | October 2010  | Otulakowska-Hypka et al. (2013), Fig.10  |
| XZ Eri   | January 2003  | Uemura et al. (2004), Fig.4              |
| V344 Lyr | August 2009   | Wood et al. (2011), Fig.18               |
| ER UMa   | January 1995  | Kato et al. (2003), Fig.4                |
| KS UMa   | February 2003 | Olech et al. (2003), Fig.6               |

**TT Boo.** The superhump period variations were quite complex (see Fig.5 in Olech et al. 2004b) and the average daily superhump light curves (their Fig.3) show secondary humps appearing after JD 2453169.
GZ Cnc. The daily average superhump light curves clearly show a secondary hump which appeared already on the second night and grew in amplitude which on JD 2455275 became higher than that of the original maximum. The phases from Fig.9 of Kato et al. (2010) are corrected here by Δφ = 0.25 thereby making φ = 0 correspond to maximum.

PU UMa. The light curves show a secondary hump starting with JD 2455162.

GX Cas. The average daily superhump light curves are corrected for variable period. They show secondary hump starting with JD 2455502.

HT Cas. Bąkowska et al. (2014ab) and Kato et al. (2012) presented results describing the November 2010 superoutburst of this star but without any information on the evolution of the shapes of superoutburst light curves. The data used here were taken from the AAVSO International Database and analyzed in 1-day intervals. They clearly show the development of a secondary hump.

IX Dra (2003). The secondary hump was present already on the second night (JD 2452904). Three days later its amplitude was equal to, and on the last two nights (JD 2452908 and 909) was higher than that of the primary maximum. The modulation of the light curve was so strong that the Authors (Olech et al. 2004a) used minima to determine the period and phases; consequently φ = 0 corresponds to minimum.

IX Dra (2010). The secondary hump appeared on the third night (JD 2455480). Around JD 2455802 the phase of the primary maximum showed a jump by Δφ ≈ 0.15 (see Fig.13 in Otulakowska-Hypka et al. 2013). The phases are corrected here by Δφ ≈0.05/day in order to make φ_{max} ≈ 0 during the first four nights.

XZ Eri. The secondary hump was present starting with JD 2452670.

V344 Lyr. The Authors (Wood et al. 2011) determined the average superhump light curves in 5-day intervals with φ = 0 corresponding to minimum.

ER UMa. The secondary humps were present starting with the first night. Around JD 2449747 the phase of the primary maximum showed a jump by Δφ ≈ 0.5 (see Fig.1 in Kato et al. 2003).

KS UMa. Clear secondary humps did not appear until around JD2452690.

Nearly all periodograms of superhumps which can be found in the literature are limited to the region of the fundamental mode and only seldom include the region of the first overtone. The only exception was the analysis of V344 Lyr by Wood et al. (2011, Fig.10), their discrete Fourier Transform extending up to the fifth overtone and showing significant power up to the third overtone. Consequently the light curves described above were decomposed into their fundamental mode and the first three overtones

\[ m = \langle m \rangle - \sum_{k=0}^{3} 2\pi (k+1) A_k \cos(\phi - \phi_{max}^k), \]  

where \( k = 0 \) corresponds to the fundamental mode, while \( k = 1, 2, 3 \) – to the overtones. At this point the presence of higher overtones, with much smaller but non-
negligible amplitudes, cannot be excluded. Therefore whenever a reference is made in the text to "three overtones" or "four periods" the reader will be expected to add "or more?".

The analysis was limited to the superhump light curves observed during the main part – plateau – of a given superoutburst. Results are presented and discussed in the next two sections.

3. The Amplitudes

The behavior of amplitudes during superoutbursts is shown in Fig.1. Three sets of parameters are determined for each star: the average amplitude $<A_k>$, the maximum amplitude $A_{k,\text{max}}$ and the rate of decline $dA_k/dt$.

The amplitudes of the overtones are much smaller than those of the fundamental mode which is illustrated by the following sets of values: $<A_k> = 0.062, 0.029, 0.012, 0.008$ and $A_{k,\text{max}} = 0.086, 0.034, 0.014, 0.008$ for, respectively, $k=1,2,3,4$. It appears that the amplitudes of overtones higher than $k=3$ would be negligible.

The amplitudes of the fundamental mode systematically decrease with time at the average rate $dA_0/dt = -0.0066 \pm 0.0013$ mag/day. Those of the overtones either decrease slightly, remain practically constant, or even slightly increase (e.g. the 1-st overtone in KS UMa), the average rates being: $dA_1/dt = -0.0012 \pm 0.0007$, $dA_2/dt = -0.0004 \pm 0.0003$ and $dA_3/dt = 0.0000 \pm 0.0003$ mag/day.

The obvious consequence is that at the beginning of the superoutburst the superhump light curves are dominated by the fundamental mode. As the amplitude of the fundamental mode decreases and becomes comparable to those of the overtones, their contributions to the superhump light curve become significant.

4. The Phases of Maximum

4.1. Results

The behavior of phases of maxima during superoutburst is shown in Fig.2. In all cases the phase of maximum of the fundamental mode increases with time while in practically all cases those of maxima of the overtones decrease.

The values of $d\phi_{\text{max}}^k/dt$ were determined for all individual cases and the lines with slopes corresponding to those values are shown in Fig.2. Their average values are: $<d\phi_{\text{max}}^0/dt> = +0.018 \pm 0.006$, $<d\phi_{\text{max}}^1/dt> = -0.009 \pm 0.002$, $<d\phi_{\text{max}}^2/dt> = -0.017 \pm 0.006$, and $<d\phi_{\text{max}}^3/dt> = -0.024 \pm 0.005$. The differences between those values for $k=1,2,3$ are significant only at the 1$\sigma$ level but not at the 3$\sigma$ level. This could suggest that they are practically identical. Comparison of individual values of $d\phi_{\text{max}}^k/dt$ (Fig.3) shows, however that this is not the case.
Fig. 1. Evolution of amplitudes – of the fundamental mode and the first three overtones – during superoutburst. Errors (not shown) are comparable or only slightly larger than the size of the symbols.

4.2. Phase Shifts versus Four Periods

There are two possible interpretations of the ”phase diagrams” shown in Fig.2. The first is that we are dealing with time-dependent, genuine phase shifts (see Section 5).

The second interpretation, based on an obvious analogy between the ”phase diagrams” and the traditional (O-C) diagrams, is that instead of just one superhump
Fig. 2. Evolution of the phases of maxima – of the fundamental mode and the first three overtones – during superoutburst. Errors (not shown) are comparable or only slightly larger than the size of the symbols. For special comments on IX Dra (2010) and ER UMa see Section 4.4.

period $P_{sh}$ there are four periods $P_k$. They resemble – but are significantly different from – the fundamental mode and the first three overtones of $P_{sh}$:

$$P_k = \frac{1}{k+1} \left[ P_{sh} + P_{sh}^2 \frac{d\phi_{max}^k}{dt} \right],$$

where $P_{sh}$ is the period used for calculating phases shown in Fig.2.
Fig. 3. Comparison of individual values of $d\phi_k^e/\,dt$ for $k = 1, 2, 3$. Typical errors are shown in the upper left corners.

One can also consider the corresponding periods of the fundamental mode

$$P_{k, fm} = (k + 1) \, P_k.$$  \hspace{1cm} (3)

The obvious question is: why those periods have not been detected earlier? The answer is simple. The peaks in the periodograms are generally too broad to distinguish between $f_k$ and $(k + 1) \times f_{sh}$, which differ only very slightly. It may be also worth to add that the periodograms, which can be found in the literature, nearly always cover only the region around $f_{sh}$ and do not extend to higher frequencies.

4.3. The Case of GZ Cnc and IX Dra (2003)

Those two examples illustrate how the presence and evolution of the secondary hump can produce spurious phase jumps in the (O-C) diagrams.

As already mentioned in Section 2 the modulation of the lightcurves in those two cases was very strong. The amplitude of the secondary hump grew considerably and eventually exceeded that of the primary maximum. In GZ Cnc this happened on JD 2455275 while in IX Dra – on JD 2452908 (one day earlier the two amplitudes were already equal).

Fig. 4 presents the (O-C) diagrams based on moments of maxima taken from –
respectively – Table 9 in Kato et al. (2010) and Fig.7 in Olech et al. (2004a). As could be expected they show spurious phase jumps by $\Delta \phi \sim 0.4P$ and $\sim 0.5P$.

### 4.4. The Case of IX Dra (2010) and ER UMa

Those two cases differ from the others and require additional comments. The (O-C) diagram of IX Dra (Otulakowska-Hypka et al. 2013, Fig.13) shows around JD 2455483 a phase jump by about $0.15P$. The phase diagram (Fig.2) shows that this was largely due to a phase jump in $\phi_{0_{\max}}^1$ (there was also a smaller phase jump in $\phi_{\max}^1$). After that event all four $\phi_{\max}^k$ followed the "standard" pattern.

The case of ER UMa was similar: The (O-C) diagram (Kato 2003, Fig.1) shows around JD 2449747-48 a phase jump by about $0.5-0.6P$. The phase diagram (Fig.2) shows a similar phase jump in $\phi_{0_{\max}}^0$ followed by the "standard" behavior of all four $\phi_{\max}^k$.

The nature of those genuine phase jumps of the fundamental mode component requires explanation.

### 5. Discussion

Results presented in this paper create problems which complicate our understanding of superhumps.

The first of them is related to the periods of superhumps. According to their commonly accepted interpretation they are related to the period of apsidal motion of the disk:

$$\frac{1}{P_{sh}} = \frac{1}{P_{orb}} - \frac{1}{P_{aps}}.$$  \hspace{1cm} (4)

Furthermore, it is commonly accepted that the period of disk’s apsidal motion is a function of its radius: $P_{aps} = f(r_d)$ (cf. Montgomery 2001, Murray 2000 and references therein).

Replacing $P_{sh}$ in Eq.(5) by four different periods $P_{k,aps}$ would imply four different apsidal motion periods $P_{k,aps}$ and four different disk radii $r_d, d'$. Obviously then the "four-period" interpretation must be abandoned in favor of "genuine phase shifts".

The commonly accepted tidal-resonance model (Whitehurst 1988, Hirose and Osaki 1990; see also Smith et al. 2007 and references therein), explains superhumps as being due to tidal dissipation effects in the outer parts of accretion disk undergoing apsidal motion. As discussed earlier (Smak 2010) this model fails to explain many important facts. Whether and how it could explain the time-dependent phase shifts is a question addressed to its adherents.

The irradiation modulated mass transfer model proposed on purely observational evidence by the present author (Smak 2009, 2013) explains superhumps as being due to periodically modulated dissipation of the kinetic energy of the stream.
Its essential ingredient is the non-axisymmetric structure of the outer parts of the disk involving the azimuthal dependence of their vertical thickness: $z/r = f(\alpha)$.

It is quite possible that the behavior of phases of maxima $\Phi_{\text{max}}^k$, seen in the phase diagrams, simply reflects the evolution of the disk outer structure and the shape of $f(\alpha)$ but – for the time being – this is only a speculation.

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