DW UMa and the Irradiation Modulated Mass Transfer Model for Superhumps

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ABSTRACT

The light curves of the permanent superhumerker DW UMa are analyzed in order to determine the amplitudes of its superhumps, $A_{SH}$, and the amplitudes of the periodic light variations with the beat period – the irradiation amplitudes, $A_{irr}$. The resulting values of $A_{SH}$ and $A_{irr}$, together with other values from the literature, turn out to be correlated thereby confirming the irradiation modulated mass transfer model for superhumps.

Key words: accretion, accretion disks, binaries: cataclysmic variables, stars: individual: DW UMa

1. Introduction

Superhumps are periodic light variations with periods slightly longer than the orbital period observed in dwarf novae during their superoutbursts and also in some cataclysmic variables with stationary accretion – the so-called permanent superhumpers (Warner 2003, and references therein). They have been discovered during the 1972 superoutburst of the dwarf nova VW Hyi (Vogt 1974, Warner 1975), but first observed (although unrecognized as such at that time) ten years earlier in AM CVn (Smak 1967). One of the permanent superhumpers is the nova-like, eclipsing system DW UMa.

There are two, competing models for superhumps: the tidal-resonance (TR) model and the irradiation modulated mass transfer (IMMT) model. The TR model (reviewed in Section 2) fails to explain many important facts. The IMMT model (Section 3) appears to be very promising and the aim of the present paper is to test one of its crucial ingredients. The light curves of DW UMa are analyzed in Section 4 and the test is presented in Section 5.
2. The Tidal-Resonance Model for Superhumps

The tidal-resonance (TR) model, first proposed by Whitehurst (1988) and Hirose and Osaki (1990), explains superhumps as being due to tidal effects in the outer parts of accretion disks, leading via the 3:1 resonance to the formation of an eccentric outer ring undergoing apsidal motion and periodic dissipation of the kinetic energy of disk’s elements. This model and, in particular, the results of numerous 2D and 3D SPH simulations (cf. Pearson 2006, Smith et al. 2007 and references therein) reproduce (although not without problems) the observed superhump periods; this suggests that the basic "clock" which defines the superhump periods may indeed be related to the apsidal motion.

On the other hand, however, the TR model fails to explain many other important facts (cf. Smak 2010). In particular:

1. The 3:1 resonance, which is the crucial ingredient of this model, can occur only in systems with mass ratios \( q < q_{\text{crit}} = 0.25 \). This condition is not fulfilled by longer period CV’s, including the dwarf nova U Gem and the growing number of permanent superhumpers (one of them is DW UMa with \( q = 0.39 \pm 0.12 \); Araujo-Betancor et al. 2003).

2. The numerical 2D and 3D SPH simulations produce "superhumps" with amplitudes which – compared to the observed amplitudes – are about 10 times too small (Smak 2009a).

In spite of that the TR model continues to be commonly accepted...

3. The Irradiation Modulated Mass Transfer Model for Superhumps

From the analysis of eclipses observed in Z Cha (Smak 2007,2009b, based on light curves collected by Warner and O'Donoghue 1988) it was found that (1) the standard hot spot can be detected only during eclipses which occur away from superhump maximum; (2) during eclipses which occur closer to the superhump maximum it is replaced by the "hot line" or "hot strip" resulting from stream overflow; and (3) the superhump light source is located along the stream trajectory.

Further clue came from the analysis of the superoutburst light curves of several dwarf novae: it was found (Smak 2009c) that in the case of deeply eclipsing systems \( i > 82^\circ \) the observed brightness of the disk (excluding eclipses and superhumps) is modulated with phase of the beat period, related to the orbital and superhump periods by

\[
\frac{1}{P_b} = \frac{1}{P_{\text{orb}}} - \frac{1}{P_{\text{SH}}}.
\]

The updated version of the original amplitude vs. inclination diagram is shown here in Fig.1.

The presence of such modulations was interpreted as being due to a non-axisymmetric structure of the outer parts of the disk, involving azimuthal dependence of
Fig. 1. The modulation amplitude as a function of inclination. Data are taken from Smak(2009c, Table 2, and 2013, Table 1). Non-eclipsing systems with unknown inclinations are plotted between $i = 50^\circ$ and $60^\circ$. Marked above are values of $z/r = \cos i$.

Regardless of this interpretation it was obvious that the periodically variable irradiation of the observer with the beat period implies the periodically variable irradiation of the secondary with the superhump period. Taking this into account we will refer to the light variations with $P_b$ – as the irradiation light curve and to its amplitude – as the irradiation amplitude.

The evidence described above led to the irradiation modulated mass transfer (IMMT) model for superhumps (Smak 2009c). It consists of the following essential points:

1. The irradiation of the secondary component is modulated with $P_{SH}$.
2. Periodically variable irradiation of the secondary results in periodic variations of the mass transfer rate.
3. The periodically variable dissipation of the kinetic energy of the stream is observed in the form of superhumps.
4. Around superhump maximum the stream overflows the surface of the disk and – unlike in the case of the "standard" hot spot – its energy is dissipated along its trajectory above (and below) the disk.

The IMMT model is based on purely observational evidence. The only exception is point (2), which remains hypothetical. The problem of how the rate of the mass outflow from the secondary can be controlled by its irradiation is quite complex due primarily to the fact that the vicinity of the inner Lagrangian point L1
remains in the shadow cast by the disk. Results of preliminary model calculations (Osaki and Meyer 2003, Smak 2004, Viallet and Hameury 2007) were inconclusive and even controversial. The most recent results by Cambier (2015) are much more promising, but it is clear that further work is needed before this problem can be solved. In this situation the only alternative is to look for direct observational evidence supporting this point. This will be done in the next two Sections.

4. **DW UMa**

4.1. *DW UMa as Permanent Superhumper*

DW UMa is an eclipsing, nova-like, permanent superhumper. In addition to the positive and negative superhumps (Patterson et al. 2002, Boyd et al. 2017 and references therein) it shows spectroscopic peculiarities characteristic for the SW Sex stars (Thorstensen et al. 1991, Dhillon et al. 2013, and references therein) and occasionally displays the so-called low states (Honeycutt et al. 1993, Stanishev et al. 2004).

The most recent paper by Boyd et al. (2017) presented results of a large photometric program covering several seasons. Two of those results are of particular interest in the context of the present paper: (1) The superhump and irradiation amplitudes are variable. (2) The results from 2014 and 2015, when both amplitudes were determined, suggest that they are correlated. Such a correlation would provide the crucial test for the IMMT model (see Section 3). It is therefore of the utmost importance to confirm its existence.

4.2. *The Data*

Results by Boyd et al. (2017) show that the superhump period and the superhump and irradiation amplitudes are variable. Taking this into account it was decided to analyze light curves covering relatively short intervals of time. Three such data sets could be recovered from the literature.

1997. The data used in our analysis come from visual (V) light curves observed by Bíró (2000) during five consecutive nights of February 16 – February 20, 1997. The data points were read from his Fig.3 at equal intervals \(\Delta\phi_{\text{orb}} = 0.05\), excluding points with \(\phi_{\text{orb}} < 0.2\) and \(\phi_{\text{orb}} > 0.8\), and converted to magnitudes. The periodogram of those data showed two significant signals: at the orbital frequency (which was removed prior to further analysis) and at \(f_{\text{SH}} = 6.76 \pm 0.14\) c/d, corresponding to \(P_{\text{SH}} = 0.148 \pm 0.003\) d.
2002. Visual (V) light curves, observed by Stanishev et al. (2004) on five nights between January 11 and February 17, 2002, were used with data points being read from their Fig.1 at equal intervals \( \Delta t = 0.005 \text{d} \), excluding points with \( \phi_{\text{orb}} < 0.2 \) and \( \phi_{\text{orb}} > 0.8 \).

2003. "Unfiltered" light curves, observed by Stanishev et al. (2004) on five nights between March 6 and March 22, 2003, were used with data points being obtained in the same way as for 2002.

4.3. The superhump and irradiation amplitudes

The superhump and irradiation amplitudes, \( A_{\text{SH}} \) and \( A_{\text{irr}} \), are determined simultaneously – via the least squares solution – by fitting

\[
m = \langle m \rangle + \frac{dm}{dt} \Delta t - A_{\text{SH}} \cos(\phi_{\text{sh}} - \phi_{\text{SH}}^{\text{max}}) - A_{\text{irr}} \cos(\phi_{\text{irr}} - \phi_{\text{irr}}^{\text{max}}),
\]

(2)

to individual points. The results are listed in Table 1. Listed in that table are also the superhump and irradiation amplitudes taken from Boyd and Gaensicke (2009) and from Boyd et al. (2017, Table 3).

| Year | JD 2400000+ | \( A_{\text{SH}} \) | \( A_{\text{irr}} \) |
|------|------------|-----------------|-----------------|
| 1997 | 50496-500  | 0.030 ± 0.011   | 0.025 ± 0.012   |
| 2002 | 52286-323  | 0.058 ± 0.013   | 0.079 ± 0.019   |
| 2003 | 52703-721  | 0.070 ± 0.013   | 0.086 ± 0.012   |
| 2008 | 54570-600  | 0.055 ± 0.010   | 0.060 ± 0.010   |
| 2014 | 56728-768  | 0.049 ± 0.002   | 0.043 ± 0.002   |
| 2015 | 57020-110  | 0.063 ± 0.003   | 0.062 ± 0.003   |

Notes to Table 1: (1) This paper; data from Bíró (2000). (2) This paper; data from Stanishev et al. (2004). (3) Boyd and Gaensicke (2009). (4) Boyd et al. (2017).

The superhump amplitudes determined for 2002 and 2003 require some comments. In the case of 2002 our value \( A_{\text{SH}} = 0.058 \pm 0.013 \), based on light curves
between JD 2452286-323, is larger than $A_{SH} = 0.048$ obtained by Stanishev et al. (2004) from light curves between JD 2452286-389, and $A_{SH} = 0.045 \pm 0.004$ obtained by Boyd et al. (2017) from light curves between JD 2452311-332. On the other hand, however, the amplitude determined from the three nights between JD 2452373-389 (Stanishev et al. 2004, Fig.1) is lower: $A_{SH} = 0.035 \pm 0.013$ (regretfully, the coverage in $\phi_{irr}$ was insufficient for simultaneous determination of $A_{irr}$). This shows that during the 2002 season the superhump amplitude was simply decreasing. In the case of 2003 our value $A_{SH} = 0.070 \pm 0.013$, based on light curves between JD 2452703-721, is larger than $A_{SH} = 0.040$ obtained by Stanishev et al. (2004) from light curves between JD 2452703-793. Our determination, based on the same interval, gave similar value: $A_{SH} = 0.036 \pm 0.016$.

4.4. The Light Curves

The superhump and irradiation light curves are then obtained as

$$\Delta m_{SH} = m - \left[ <m> + \frac{dm}{dt} \Delta t - A_{irr} \cos(\phi_{irr} - \phi_{max}) \right],$$

with a similar expression for $\Delta m_{irr}$. They are shown in Fig.2.

![Fig. 2. Superhump (left) and irradiation (right) light curves of DW UMa in 1997, 2002, and 2003. Normal points are shown with error bars representing the scatter of individual points.](image-url)
5. The Crucial Test for the IMMT Model

The superhump amplitudes and the irradiation amplitudes from Table 1 are compared in Fig.3. They are correlated. The formal fit to the points gives

\[ A_{SH} = (0.34 \pm 0.07) A_{irr}^{(0.62 \pm 0.07)}. \]  \hspace{1cm} (4)

![Fig. 3. The dependence of superhump amplitudes on irradiation amplitudes. Data points and their errors are taken from Table 1. Symbols in red represent the two original points from Boyd et al. (2017). Green line represents Eq.4.](image)

To conclude: the superhump amplitude does indeed depend on the irradiation amplitude thereby confirming the last element of the IMMT model which still required such a confirmation. It can only by hoped that further such tests involving either DW UMa or other permanent superhumpers will strengthen this conclusion.

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