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The orbital and superhump periods of the dwarf nova HS 0417+7445 in Camelopardalis

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Abstract

We present the 2005–2010 outburst history of the SU UMa-type dwarf HS 0417+7445, along with a detailed analysis of extensive time-series photometry obtained in March 2008 during the second recorded superoutburst of the system. The mean outburst interval is 197 ± 59 d, with a median of 193 d. The March 2008 superoutburst was preceded by a precursor outburst, had an amplitude of 4.2 magnitudes, and the whole event lasted about 16 days. No superhumps were detected during the decline from the precursor outburst, and our data suggests instead that orbital humps were present during that phase. Early superhumps detected during the rise to the superoutburst maximum exhibited an unusually large fractional period excess of $\epsilon = 0.137$ ($P_{\text{sh}} = 0.0856(88)$ d). Following the maximum, a linear decline in brightness followed, lasting at least 6 days. During this decline, a stable superhump period of $P_{\text{sh}} = 0.07824(2)$ d was measured. Superimposed on the superhumps were orbital humps, which allowed us to accurately measure the orbital period of HS 0417+7445, $P_{\text{orb}} = 0.07531(8)$ d, which was previously only poorly estimated. The fractional superhump period excess during the main phase of the outburst was $\epsilon = 0.037$, which is typical for SU UMa dwarf novae with similar orbital period. Our observations are consistent with the predictions of the thermal-tidal instability model for the onset of superoutbursts, but a larger number of superoutbursts with extensive time-series photometry during the early phases of the outburst would be needed to reach a definite conclusion on the cause of superoutbursts.

Keywords: stars: dwarf novae, cataclysmic variables, accretion disks

1. Introduction

In cataclysmic variables (CVs) a white dwarf primary accretes material from a secondary star via Roche lobe overflow. The secondary is usually a late-type main-sequence star (Warner, 1995). In the absence of a significant white dwarf magnetic field, material from the secondary is processed through an accretion disc before settling on the surface of the white dwarf. In CVs with low to intermediate mass transfer rates, dwarf nova outbursts with amplitudes of 2–8 mag and durations of days to weeks are observed. The outbursts are thought to be caused by a thermal instability in the accretion disc associated with partial ionisation of hydrogen (Meyer and Meyer-Hofmeister, 1981; Smak, 1982; Cannizzo et al., 1982), and such time-dependent models for accretion disc evolution have been applied to a variety of astrophysical environments, e.g. AGN (Burderi et al., 1998) or young stellar objects (Bell and Lin, 1994). Dwarf novae of the SU UMa family occasionally exhibit superoutbursts which last several times longer than normal outbursts and may be up to a magnitude brighter. During a superoutburst the light curve of a SU UMa system is characterised by superhumps. These are modulations in the light curve which are a few percent longer than the orbital period. They are thought to arise from the interaction of the secondary star orbit with a slowly precessing eccentric accretion disc. The eccentricity of the disc arises because a 3:1 resonance occurs between the secondary star orbit and the motion of matter in the outer accretion disc. The actual trigger of the superoutbursts is still debated (Osaki and Meyer, 2003; Schreiber et al., 2004).

HS 0417+7445 (hereafter HS 0417), also known as 1RXS J042332+745300, was independently identified as a CV by Wu et al. (2001) in the course of follow-up spectroscopy of objects from ROSAT Bright Source Catalogue (Voges et al., 1999), and by Aungwerojwit et al. (2006) because of the presence of strong Balmer emission lines in its optical spectrum in the Hamburg Quasar Survey (HQS, Hagen et al. 1995). HS 0417 showed large amplitude variability on the HQS spectroscopic plates, between $B \simeq 18.0$ and $B \simeq 13.7$, suggesting a dwarf nova classification of the object. Further observations of HS 0417 by Aungwerojwit et al. (2006) between December 2000 and January 2005 showed the object near to a mean magnitude of ~ 17.5 , except during

January 2001 when the system was found in outburst near $B \simeq 13.5$. Photometry during this outburst revealed superhumps that identify HS 0417 as a SU UMa type dwarf nova. Two possible superhump periods were identified, $P_{\text{sh}} = 108.3$ or 111.2 min (0.0752 or 0.0772 d). Analysis of the quiescent data revealed a double-humped light curve with two possible values of the orbital period, $P_{\text{orb}} \simeq 105.1$ or 109.9 min (0.0723 or 0.0763 d). Brief descriptions of two superoutbursts in 2008 and 2010 were given by Kato et al. (2009, 2010).

Here we report a detailed analysis of time-series photometry obtained in 2008 during the second superoutburst of HS 0417, from which we determine accurate orbital and superhump periods. We also discuss the possible mechanisms triggering superoutbursts, and how pre-cursor outbursts, such as detected in our data, can help to distinguish between the competing models.

2. Observations

We detected HS 0417 in outburst on 2008 March 3.977 at a filterless magnitude of 14.5C. Time resolved photometry was conducted during the course of the outburst according to the observation log shown in Table 1. Raw images were dark-subtracted and flat fielded before being measured using differential aperture photometry relative to comparison stars with V -band photometry given by Henden (2010). We will generally refer to dates in the truncated form $\text{JD} = \text{JD} - 2454000$. From the overall light curve of the superoutburst shown in Fig. 1 it is apparent that the superoutburst was preceded by a precursor outburst. Detailed views of the individual light curves are shown in Fig. 2.

3. Analysis & Results

3.1. Outburst history

Examination of the AAVSO International Database (Henden, 2010), supplemented with data from the authors, reveals at least 11 outbursts of HS 0417 between April 2005 and October 2010 (Table 2). Two of the outbursts are definitely superoutbursts as superhumps were recorded: the one in March 2008 outburst discussed in this paper and the 2010 Sep discussed by Kato et al. (2010). In both cases the outburst lasted about 16 days.

The April 2005 outburst lasted ~ 8 days and the star showed a rapid decline with no superhumps confirming this to be a normal outburst. Similarly, the absence of superhumps during the October 2007 outbursts suggests it too

Table 1: Log of the observations.

Date 2007 (UT)	Start time (JD-2454000)	Duration (h)	Filter	Observer
Mar 4	530.304	4.8	C	JS
Mar 4	530.363	5.3	V	IM
Mar 5	531.337	0.5	C	BS
Mar 6	531.558	7.0	C	SB
Mar 6	532.247	10.0	V	PD
Mar 7	532.546	7.5	C	SB
Mar 7	533.237	5.8	V	PD
Mar 7	533.302	4.1	V	IM
Mar 7	533.398	3.2	C	JS
Mar 7	533.441	4.6	C	BS
Mar 8	533.707	1.0	V	IM
Mar 8	534.295	4.4	C	JS
Mar 8	534.370	5.0	C	IM
Mar 9	535.292	2.2	C	JS
Mar 9	535.304	0.4	C	IM
Mar 9	535.337	6.7	C	BS
Mar 10	536.369	2.1	C	JS
Mar 11	536.506	7.9	C	SB
Mar 12	538.463	1.7	C	IM
Mar 13	538.511	6.6	C	SB
Mar 16	542.319	3.3	C	IM
Mar 17	543.325	4.0	C	IM
Mar 18	543.512	7.3	C	SB

Notes on the equipment used for the observations. JS: 0.28 m SCT plus Starlight Xpress SXV-M7; SB: 0.4 m reflector plus SBIG ST-8XME; PD: 0.265 m reflector plus Meade DSI Pro; IM: 0.35 m SCT plus Starlight Xpress SXVF-H16; BS: 0.28 SCT plus Starlight Xpress MX716.

was a normal outburst. Whilst we are not aware of any time series photometry conducted during the other outbursts, their short outburst duration (less than 6 to 8 days) suggests they too were normal outburst.

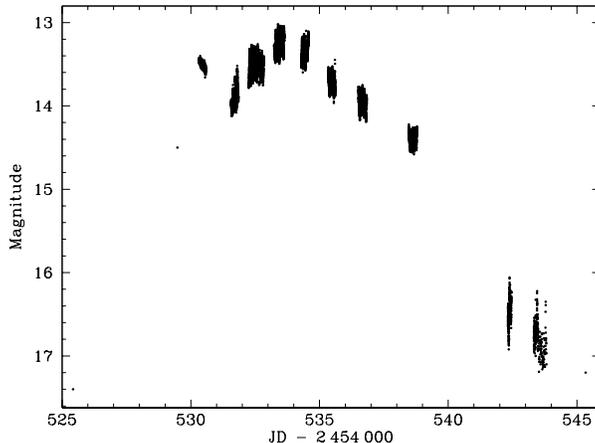


Figure 1: Light curve of HS 0417 during the 2008 March outburst.

Dwarf novae are known to exhibit quasi-period outbursts. In the case of HS 0417, the mean outburst interval between the 11 outbursts was 197 ± 59 d and the median interval was 193 d. Although observational coverage of HS 0417 has been good since the 2005 outburst, there are nevertheless 43 gaps in the data of more than 6 d during which further outbursts might have been missed. We note that the normal outbursts of HS 0417 have a rather long duration compared to other SU UMa dwarf novae. Close monitoring of this object should continue to improve the statistics of the outburst frequency and duration.

3.2. The March 2008 superoutburst

Figure 1 shows the overall light curve of the outburst, from its discovery at 14.5C on JD 529. Photometry conducted the next night (JD 530) showed that the star had brightened to ~ 13.4 C, but that it was fading at an average rate of 0.50 mag d^{-1} . By contrast, the following night (JD 531) the star, although considerably fainter at ~ 14.1 C, was re-brightening rapidly at 0.91 mag d^{-1} . Superhumps were plainly visible at this point, suggesting this to be the start of the superoutburst. It appears that the activity on JD 529 to 530 represented a normal outburst which was the precursor, perhaps even the trigger, for the superoutburst (see Sect. 4). At its brightest on JD 533 the star reached magnitude 13.2 (averaged over the superhumps). An approximately linear decline followed between maximum on JD 533 and JD 538 at 0.14 mag d^{-1} , which is typical of a dwarf nova in decline from a superout-

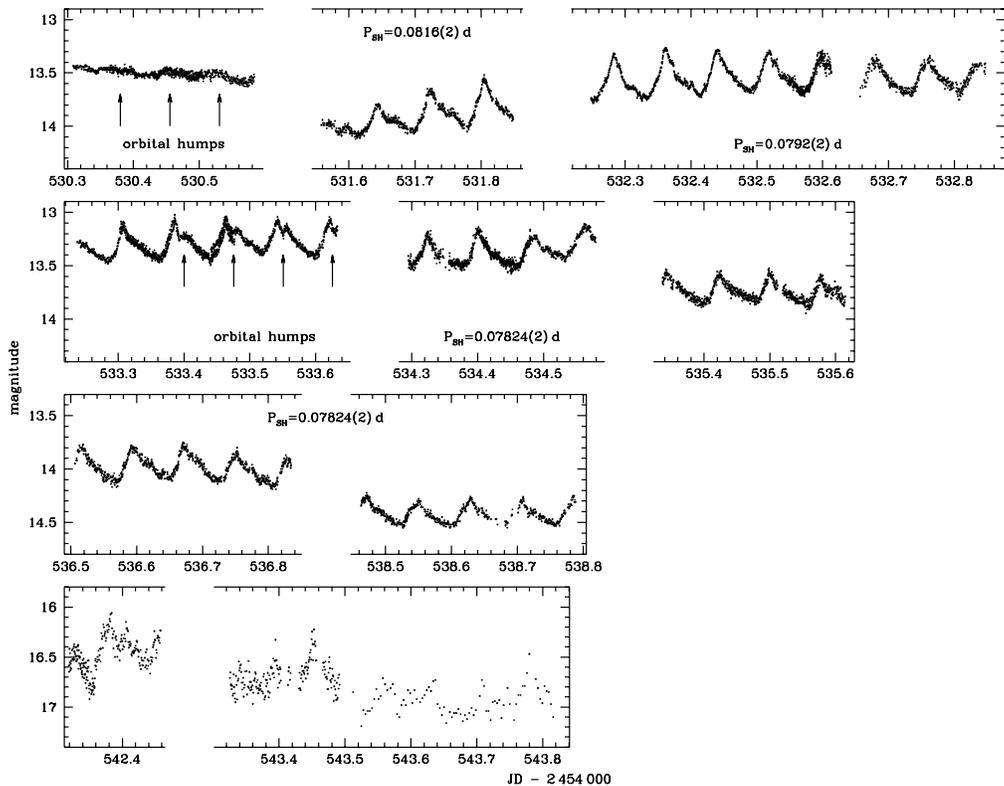


Figure 2: Detailed light curves of HS 0417 during the 2008 March outburst. All panels have the same scale in the time and magnitude axes to facilitate like-for-like comparison of the superhumps and orbital humps. Arrows indicate the occurrence of orbital humps. The evolution of the superhump period throughout the outburst is indicated.

burst. There was then a 4 d gap in the record until JD 542 when the star was at 16.5C; hence it is not possible to conclude whether there was a gradual or a sudden fade in the intervening period. Finally the star was found at magnitude 17.2C, close to its quiescence magnitude of 17.4C, on JD 545 approximately 16 days after the outburst was first detected. Thus the overall outburst amplitude was 4.2 magnitudes.

3.3. Superhump periods

The light curves obtained during the 2008 March superoutburst of HS 0417 are shown in detail in Fig. 2, where we used the same scale for both time and magnitude for ease of comparison. Modulations in the light curve were

detected throughout the outburst, however, as we shall see, their period appeared to be different during different stages of the outburst. Hence we analysed different phases of the outburst light curve in turn.

Superhumps were first detected during the rise to superoutburst on JD 531, when they were increasing in peak-to-peak amplitude from 0.3 to 0.4 mag (Fig. 2).

We searched for periodic signals in our time resolved photometry using Scargle’s (1982) method as optimised by Horne and Baliunas (1986), and found $P_{\text{sh}} = 0.0856(88)$ d. The following day, JD 532, the superhumps were of the same amplitude, but the superhump period was slightly shorter at 0.0792(22) d.

During the interval covering the outburst maximum on JD 533 and the linear decline to JD 538 the superhump amplitude gradually diminished from 0.4 to 0.3 magnitudes. In order to study the superhump behaviour during this period, we first extracted the times of each resolvable superhump maximum from the individual light curves according to the method of Kwee and van Woerden (1956). Times of 26 superhump maxima were found and these were then used to assign superhump cycle numbers which best fitted the assumption of a constant superhump period. We found that the maxima fitted well a constant superhump period $P_{\text{sh}} = 0.07824(2)$ d (112.67 min) having the following ephemeris:

$$\text{JD}(\text{max}) = 2454533.30893 + 0.07824(2) \times E \quad (1)$$

The superhump cycle number, the measured times of superhump maximum and the O–C (Observed-Calculated) residuals relative to the above superhump maximum ephemeris are shown in Fig. 3.

As an independent approach for the measurement of P_{sh} , we carried out a Scargle period analysis of all the data from JD 533 to 538, after subtracting the mean and linear trend from the light curves. The power spectrum in Fig. 4 has its highest peak at a period of 0.07822(2) d, plus its one cycle/day aliases, which we interpret as the signal from the superhumps. The superhump period error estimate is derived using the method described by Schwarzenberg-Czerny (1991). A phase diagram of the data folded on this period is shown in the top panel of Fig. 5 which illustrates that both the superhump period as well as the morphology of the superhump variation remain very stable throughout JD 533 to 538. While the values of P_{sh} from the two methods are in close agreement, it is not unusual for O–C analysis

Table 2: Recorded outbursts of HS 0417. Given are the UT date and Julian date of the outburst, the time interval between two consecutive outbursts, the peak magnitude, and the outburst duration. .

Date (UT)	JD-2450000	Interval (d)	m_{\max}	Duration (d)
2005 Apr 10	3470.6		13.6	~ 8
2006 Feb 15	3782.4	311.8	15.6	< 8
2006 Sep 12	3991.4	209.0	14.6	~ 7
2007 Mar 7	4167.4	176.0	14.8	< 7
2007 Oct 17	4390.6	223.2	14.7	< 7
2008 Mar 3	4529.5	138.9	13.2	~ 16
2008 Aug 14	4693.4	163.9	15.7	< 6
2009 Feb 25	4888.3	194.9	15.9	< 8
2009 Jun 11	4993.7	105.4	14.5	< 7
2009 Dec 18	5184.3	190.6	14.4	< 7
2010 Sep 2	5441.6	257.3	13.5	~ 16

to give a more accurate method of tracking periodic waves in dwarf novae as it is less troubled by changes in amplitude and peak shape than period analysis techniques (Patterson et al., 2002). Thus in view of the consistency of the O-C analysis, we take our value of P_{sh} from that analysis.

Superhumps were still in evidence on JD 542 (Fig. 2) and the measurement of a single time of superhump maximum showed it to be broadly consistent with the above superhump ephemeris. However by JD 543 the superhumps were much less coherent and there was considerable scatter in the data. Under these circumstances it was not possible to measure superhump maximum timings.

Aungwerojwit et al. (2006) gave two possible superhump periods, derived from a short observing run during the first observed superoutburst of HS 0417, 0.0752 d and 0.0772 d, with a slight preference for the longer period. Our value of $P_{\text{sh}} = 0.07822(2)$ d determined from a much larger data set confirms their choice, and supersedes their less accurate superhump period. Our value of P_{sh} also agrees with the results independently obtained by Kato et al. (2009) and Kato et al. (2010) for the 2008 and 2010 superoutbursts.

3.4. *Orbital humps and the orbital period*

Close examination of the superhump profiles reveals secondary humps in some cases and occasionally these appear as distinct secondary peaks. This was particularly obvious during JD 533 as indicated by the arrows in Fig. 2. It was evident that the secondary humps appeared to move with respect to the underlying superhump, suggesting they had a slightly shorter period. One possible explanation is that the secondary humps represent an orbital hump, which if true would allow the orbital period to be determined. To explore this possibility further we measured the times of maximum of nine such secondary humps, according to the Kwee and van Woerden method. As with the previous superhump period analysis, we again assigned orbit numbers which best fitted the assumption of a constant orbital period. We found that the maxima fitted well a constant orbital period $P_{\text{orb}} = 0.07531(8)$ d (108.45 min), with a orbital hump ephemeris thus:

$$\text{JD}(\text{max}) = 2454533.40296 + 0.07531(8) \times E \quad (2)$$

The orbit number, the measured times of orbital hump maximum and the O–C residuals relative to the above orbital hump maximum ephemeris are shown in the bottom panel of Fig. 3.

As an independent test on our measurement of P_{orb} from the timing of the orbital hump maxima, we pre-whitened the data from JD 533 to 538 with $P_{\text{sh}} = 0.07822$ d, the (constant) superhump period prevailing during this interval (Sect. 3.3). The Scargle periodogram calculated from the pre-whitened data has two major peaks at 0.07581(51) d and 0.0819(58) d. These appear to be aliases as further pre-whitening with either one of these signals causes both to disappear from the power spectrum. We suggest that the shorter-period signal is due to the orbital hump and hence represents the orbital period. We reject the longer-period signal as being due to the orbital hump as it would imply $P_{\text{orb}} > P_{\text{sh}}$, which would be very unusual for an SU UMa type dwarf nova. The values of P_{orb} derived from the two methods are consistent with each other, given their errors, however we prefer the value given by the linear orbital hump ephemeris for the reasons given Sect. 3.3.

Aungwerojwit et al. (2006) determined two possible orbital periods of HS 0417 from a number of photometric time series obtained in quiescence, 0.730 d and 0.0763 d, with some preference for the longer period. Their data suffered from severe fine-structured aliases due to the sparse sampling of the photometry. Our orbital period, $P_{\text{orb}} = 0.07531(8)$ d agrees broadly with the

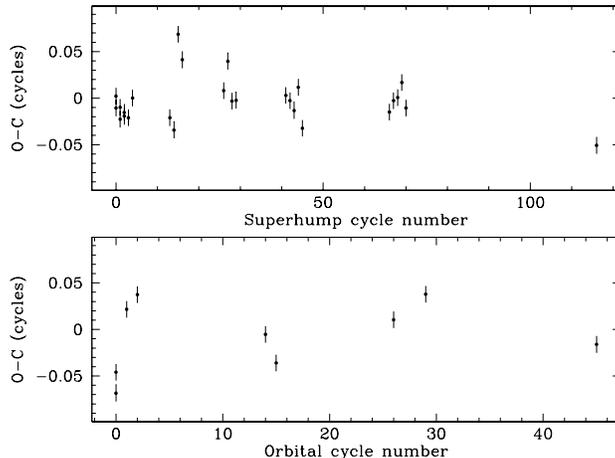


Figure 3: Top panel: Observed minus computed (O–C) times for the superhump maxima measured from the light curves in Fig. 2. Bottom panel: O–C times of the orbital hump maxima.

preferred value of Aungwerojwit et al. (2006). While we feel confident about our orbital period determination based on the detection of orbital humps superimposed on the superhumps, a spectroscopic confirmation of P_{orb} would be desirable.

Having established a value of P_{orb} , we can now address the low-amplitude modulations seen during the decline from the precursor outburst on JD 530 (Fig. 1, 2) and ask whether they are associated with the orbital humps seen during the subsequent superoutburst. Orbital humps have been seen during the early stages of superoutbursts in a number of SU UMa systems (O’Donoghue, 2000), especially in the short orbital period dwarf novae WZ Sge (Patterson et al., 1981), AL Com (Kato et al., 1996) and HV Vir (Leibowitz et al., 1994), but also in normal SU UMa systems, e.g. V1040 Cen (also known as RX J1155.4-5641, Patterson et al. 2003). Since HS 0417 was fading rapidly during the photometry conducted on JD 530, we removed this linear trend from the data and then performed a Scargle period analysis on the data. The resulting power spectrum has a rather broad main peak at 0.0733(69) d, which is consistent with our value of P_{orb} determined above. A phase diagram with the data folded on this period is shown in the bottom panel of Fig. 5. We conclude that it is likely that the low-amplitude humps seen during the decline from the trigger outburst are orbital humps.

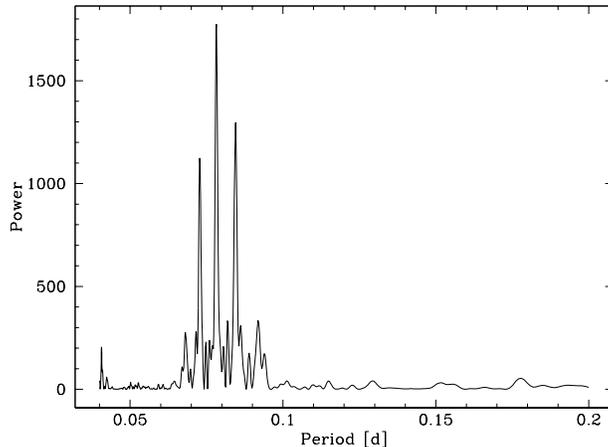


Figure 4: Power spectrum of all data from JD 533 to 538.

4. Discussion

Taking the measured values $P_{\text{orb}} = 0.07531(8)$ d and $P_{\text{sh}} = 0.07824(2)$ d allows the fractional superhump period excess $\epsilon = (P_{\text{sh}} - P_{\text{orb}})/P_{\text{orb}}$ to be calculated as 0.037. This value is consistent with the range of ϵ observed in other SU UMa dwarf novae with similar P_{orb} (Patterson et al., 2005). Measuring ϵ provides a way to estimate the mass ratio, $q = M_{\text{sec}}/M_{\text{wd}}$, of a CV, and following Patterson et al. (2005) we find $q \simeq 0.16$ for HS 0417.

The appearance of very long-period superhumps (0.0856(88) d) during the rise to the superoutburst maximum is unusual, as this phase is more often characterised by the appearance of orbital humps (O’Donoghue, 2000).

Our observations of this superoutburst of HS 0417 clearly documented the occurrence of a precursor outburst that was well-separated from the main superoutburst. From the published superoutburst light curves, it appears that precursor outbursts occur in some, but by no means all SU UMa dwarf novae, and no global study on the presence or absence of such events has been made so far. VW Hyi is probably the SU UMa dwarf nova with the best-documented long-term light curve, and precursor outbursts are seen during some, but not all superoutbursts (e.g. Vogt 1983 and references therein), which could be suggestive that the time lag between the precursor outburst and the superoutburst is variable, leading sometimes to a smooth transition from one to the other. Similarly, superoutbursts with and without precursor outburst have been observed in TV Cor (Uemura et al., 2005). A further

complication is that whether the precursor is seen clearly separated from the superoutburst can be a function of the observed wavelength. Pringle et al. (1987) presented a multi-wavelength study of VW Hyi where a distinct precursor outburst was observed in the ultraviolet, and possibly in X-rays, but not in the optical. Finally, precursor outbursts appear to occur in other disc-accreting systems as well, such as e.g. the black-hole binary XTE J1118+480 (Uemura et al., 2000; Kuulkers, 2001).

Generally it is agreed that superhumps are the observational manifestation of the precession of an eccentric accretion disc that extends to the 3:1 resonance radius (Whitehurst 1988, see Smith et al. (2007) for a comprehensive 3D simulation). However, the *cause* of superoutbursts is still debated. In the thermal-tidal instability model (TTIM, e.g. Osaki 1989), the accretion disc radius gradually grows throughout the superoutburst cycle, until the disc radius reaches the 3:1 resonance radius during a normal outburst, which triggers enhanced tidal dissipation in the disc and leads the system into the superoutburst. Hence, in the TTIM, the disc growth to the 3:1 radius triggers the superoutburst. In the competing enhanced mass transfer model (ETMT, e.g. Vogt 1983), a feedback mechanism exists between the accretion luminosity and the mass loss rate of the companion star. In the ETMT, increased mass loss triggered by a normal outburst results in the disc growing to the 3:1 radius, hence the onset of a superoutburst is a consequence of the feedback mechanism. The presence or absence of precursor outbursts holds significant diagnostic potential to differentiate between the two models. Schreiber et al. (2004) presented a series of models for both the TTIM and ETMT, and concluded that the variety of superoutbursts with and without precursor are better described by the ETMT model.

Substantially more information can be drawn from time-resolved photometry covering the very early stages of a superoutburst, but unfortunately very few such studies exist due to the time-critical nature of securing the necessary observations. Kato (1997) analysed observations obtained during the precursor outburst of the 1993 T Leo superoutburst, and concluded that superhumps were already present during the decline from the precursor. In contrast to this, no significant modulations were seen during the precursor outbursts of the 2003 superoutburst in GO Com (Imada et al., 2005) and during the precursor outburst of the 2004 superoutburst of TV Cor (Uemura et al., 2005). Our observations of HS 0417 clearly rule out the presence of superhumps during the decline of its 2008 superoutburst, and suggest that instead orbital humps were present during this phase. Superhumps with an unusually

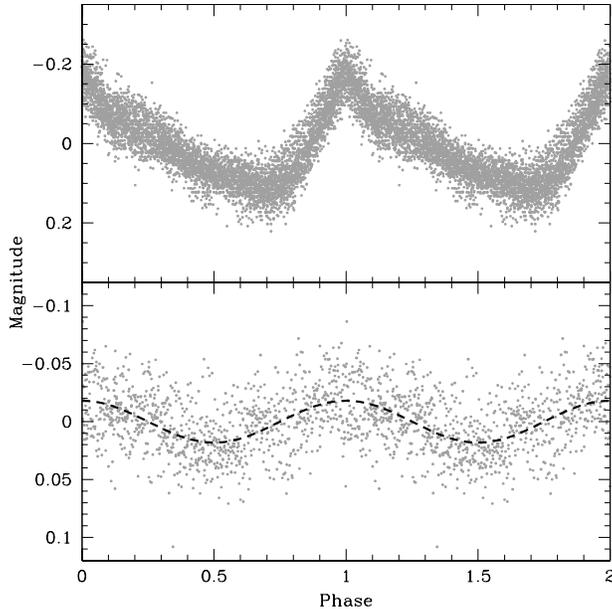


Figure 5: Top panel: all data from JD = 533 to 538 folded on the superhump period $P_{\text{sh}} = 0.07822$ d. Bottom panel: the data from JD = 530 folded on $P_{\text{orb}} = 0.07531$ d. The dashed line shows a sine-fit to the folded data.

large fractional period excess ($\epsilon = 0.137$) developed subsequently very early during the rise to the superoutburst maximum. The development of superhumps during the 2008 precursor outburst and subsequent superoutburst of HS 0417 is consistent with the predictions of the TTIM, where a normal outburst results in the growth of the accretion disc to the 3:1 resonance radius, triggering the superoutburst.

5. Conclusions

We have obtained extensive photometry of the second recorded superoutburst of the SU UMa dwarf nova HS 0417. The superoutburst was preceded by a precursor outburst. Time-series analysis of our data provides an accurate measurement of the superhump period, $P_{\text{sh}} = 0.07824(2)$ d, and a robust estimate of the orbital period, $P_{\text{orb}} = 0.07531(8)$ d. Combining both values gives a superhump period excess of $\epsilon = 0.037$, typical for SU UMa type dwarf novae in this orbital period range, and subsequently an estimated mass ratio $q = M_{\text{wd}}/M_{\text{sec}} \simeq 0.16$.

Our observations add to the small number of precursor outbursts that are well-documented in terms of time-resolved photometry. Our data rules out that superhumps were present during the decline from precursor outburst, and strongly suggests that the light curve of HS 0417 was instead modulated on the orbital period during that phase. Superhumps developed during the rise to the main superoutburst, but initially exhibited an unusually large period excess of $\epsilon = 0.137$ ($P_{\text{sh}} = 0.0856(88)$ d), but then settled into a regime of constant P_{sh} for at least six days.

Our observations demonstrated that the rapid response by a network of small telescopes can provide detailed insight into the still poorly known dynamics of the temporal evolution superoutbursts in compact binaries with extreme mass ratios, and we encourage a more systematic study of these events.

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