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High-speed photometry of SDSS J013701.06 − 091234.9

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ABSTRACT

We present high-speed photometry of the Sloan Digital Sky Survey cataclysmic variable SDSS J013701.06 − 091234.9 in quiescence and during its 2003 December superoutburst. The orbital modulation at 79.71 ± 0.01 min is double-humped; the superhump period is 81.702 ± 0.007 min. Towards the end of the outburst late superhumps with a period of 81.29 ± 0.01 min were observed. We argue that this is a system of very low mass transfer rate, and that it probably has a long outburst interval.

Key words: techniques: photometric – binaries: close – stars: dwarf novae – stars: individual: SDSS J013701.06 − 091234.9 – novae, cataclysmic variables.

1 INTRODUCTION

Cataclysmic variable stars (CVs) are identified in the Sloan Digital Sky Survey by spectroscopic classification of candidates selected on the basis of their colours (see Szkody et al. 2002). The discovery of SDSS J013701.06 − 091234.9 (hereafter abbreviated SDSS0137) is announced in the second CV release of the Sloan Digital Sky Survey (Szkody et al. 2003). The optical spectrum shows a blue continuum with broad absorption around narrow emission cores of Hβ and higher members of the Balmer series. There is also some indication of broad TiO absorption features characteristic of an M-dwarf primary (Szkody et al. 2003). These features indicate that it is a very low mass transfer rate ($\dot{M}$) system where the accretion disc is so faint that most of the luminosity of the system comes from the stars themselves.

Szkody et al. (2003) obtained 2 h of time-resolved spectroscopy and reported an orbital period (P_{orb}) of 84 min; the short P_{orb} is also consistent with a low $\dot{M}$. The presence of TiO absorption, together with our photometry, indicates that this spectrum was taken during the normal quiescent state, rather than, say, during a decline from outburst, where the hydrogen absorption may originate from the disc.

We observed SDSS0137 at a quiescent V magnitude near 18.6 on seven nights; the system then brightened by ∼6 mag and strong superhumps were seen. This qualifies SDSS0137 as an SU UMa-type dwarf nova [see e.g. Warner (1995a) for a review of SU UMa stars].

In Section 2 we present our observations in quiescence and outburst. These results are discussed in Section 3 and summarized in Section 4.

2 OBSERVATIONS

We obtained photometry of SDSS0137 at the Sutherland site of the South African Astronomical Observatory (SAAO) using the 1.0- and 1.9-m telescopes together with the University of Cape Town charge-coupled device (UCT CCD) [O'Donoghue (1995) gives a description of the UCT CCD photometer and its reduction software]. In addition, the SAAO CCD was used on three nights; unlike the UCT CCD, this is not a frame-transfer CCD and hence there are a few seconds of deadtime between integrations.

All the quiescent observations were made in white light; with the UCT CCD this gives photometry with an effective wavelength similar to Johnson V, but with a very broad bandpass. This, together with the non-standard flux distribution of a CV, means that it is not possible to transform the observations on to any standard photometric system. By observing hot subdwarf and white dwarf standards, we are able to give V magnitudes that are accurate to only ∼0.1 mag.

Most of the outburst observations were made with telescopes of the Center for Backyard Astrophysics (CBA) – see Harvey et al. (1995).

2.1 Quiescent light curves

SDSS0137 was observed in quiescence on seven nights spread over almost four months; Table 1 is a log of these observations. We find a double-humped orbital modulation, but no coherent signals on shorter time-scales. The light curves are shown in Fig. 1. Note that

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Table 1. Log of the observations in quiescence.

Run No.	Date (at the start of the night)	HJD of first obs. (245 2000+)	Length (h)	$t_{\rm int}$ (s)	Telescope	V (mag)
S7060	2003 August 27	879.54482	3.20	40	1.0-m	18.4*
S7063	2003 August 28	880.47545	4.74	40	1.0-m	18.4*
S7073	2003 August 30	882.51423	2.51	40	1.0-m	18.5*
S7088	2003 September 5	888.55917	2.57	40	1.0-m	18.5
S7144	2003 October 5	918.44016	1.74	30	1.9-m	18.6
S7168	2003 December 16	990.28114	2.32	60	1.0-m	18.5
S7172	2003 December 17	991.27868	2.27	60	1.0-m	18.6:

Notes: $t_{\rm int}$ is the integration time; ':' denotes an uncertain value; *taken with the SAAO CCD.

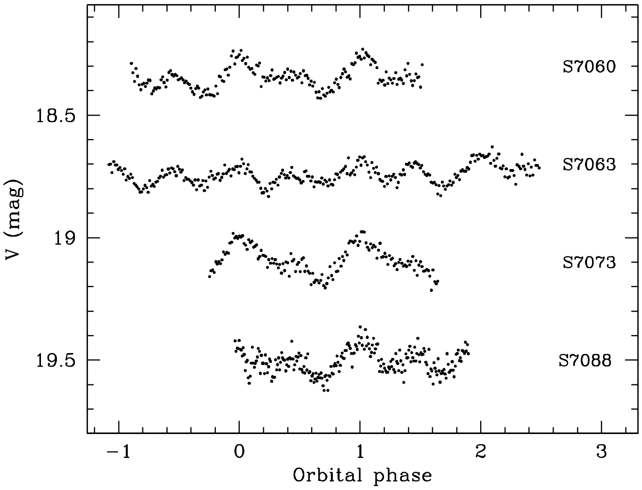

Figure 1. The first four of the light curves of SDSS0137 in quiescence, phased using equation (1). Runs S7063, S7073 and S7088 are shifted along the horizontal axis by 17, 53 and 169 cycles and down by 0.35, 0.60 and 1.00 mag respectively for display purposes.

the relative strength of the fundamental and first harmonic changes from night to night, in run S7073, e.g. the first harmonic is only barely present.

The lower scatter on the first three nights is caused in part by the fact that the SAAO CCD (used on these nights) gives a much larger field of view, and hence includes a larger number of comparison stars, than the UCT CCD, resulting in higher quality differential photometry. However, at least some of the scatter in run S7088 is caused by intrinsic flickering. The quantum efficiency of the UCT CCD peaks at $\lambda \sim 600$ nm, but is still 25 per cent at $\lambda \sim 350$ nm (O'Donoghue 1995), whereas the SAAO CCD has very poor blue and ultraviolet (but high red and near-infrared) sensitivity; see fig. 17 of Woudt & Warner (2002). Therefore the UCT CCD observations are more receptive of short-wavelength flickering.

Fig. 2 is a Fourier transform of the first four runs; the fundamental and first harmonic give an unambiguous $P_{\rm orb} = 79.71 \pm 0.01$ min. The ephemeris for the times of maximum is

$$\mathrm{HJD_{max}} = 245\,2879.594 + 0.055\,351(\pm 7)E. \qquad (1)$$

Fig. 3 shows the average light curve obtained by folding runs S7060, S7063, S7073 and S7088 on this ephemeris after removing a linear trend from each of the light curves individually.

2.2 Outburst observations

In a system with $\dot{M}$ as low as indicated by the the spectroscopic appearance of SDSS0137, one would expect to see only fairly infrequent dwarf nova outbursts. Nevertheless, after leaving SDSS0137 at $V = 18.6$ mag on 2003 December 17, we were lucky enough to find it at $V = 12.5$ mag four nights later. Table 2 is a log of the observations during the outburst. This is the first recorded outburst.

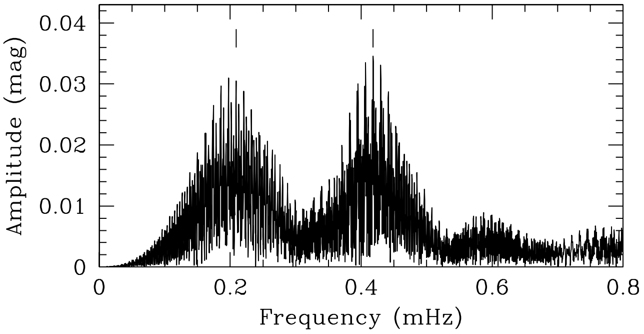

Figure 2. The Fourier transform of runs S7060, S7063, S7073 and S7088 combined. There is only one choice of alias that gives the correct fundamental and first harmonic relation; these peaks are marked by vertical bars at 0.2091 mHz (79.71 min) and 0.4183 mHz (39.85 min).

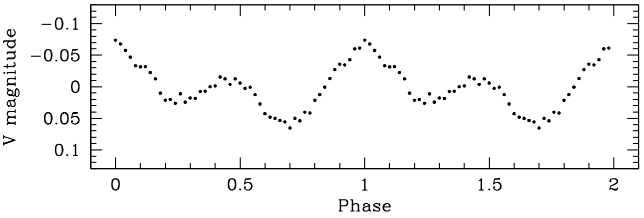

Figure 3. The mean quiescent light curve of SDSS0137 (plotted twice) using the first four runs folded on the ephemeris given in equation (1).

Smooth superhumps (with a peak-to-peak range of 0.27 mag) were present on December 21 already, implying that this was a superoutburst, that therefore SDSS0137 is an SU UMa-type dwarf nova, and that the start of outburst was probably two or three days earlier.

The outburst light curves are shown in Fig. 4 (a few noisy runs are omitted). Linear trends were removed from most of these light curves. Combining all the data from the first eight nights of the outburst gives the Fourier transform displayed in Fig. 5. The superhump period ($P_{\rm sh}$) is 81.702 ± 0.007 min; the first and second harmonic are also clearly detected. The light curves in Fig. 4 are phased using this period.

By the ninth night the superhumps were becoming noticeably phase-shifted; another four nights later they had shifted by ~0.5 cycle and could be classified as late superhumps (e.g. Vogt 1983). The observed minus calculated (O−C) diagram (Fig. 6) shows the

Table 2. Log of the outburst observations.

HJD of first obs. (245 2000+)	Length (h)	t_{int} (s)	Telescope	*V* (mag)
995.29032	2.10	5	1.00-m	
995.57788	4.93	2	1.30-m	12.4
996.02674	3.48	15	0.25-m	
996.27143	0.96	6	1.00-m	
996.63321	2.70	5	1.30-m	12.6
997.01334	3.97	15	0.25-m	
997.29209	3.76	28	0.36-m	
997.46431	3.62	80	0.25-m	12.7
998.00842	4.16	15	0.25-m	12.8
999.01274	3.81	30	0.25-m	12.8
1000.08011	2.21	30	0.25-m	
1000.61812	1.75	45	0.36-m	13.0:
1001.45554	3.90	80	0.25-m	
1001.56973	2.33	60	0.36-m	13.0:
1002.29981	3.21	28	0.36-m	
1002.45077	3.57	80	0.25-m	
1002.56369	4.24	5	1.30-m	13.1
1003.27273	1.93	6	1.00-m	13.1
1004.25491	2.60	28	0.36-m	13.2
1006.23953	0.88	60	0.41-m	
1007.08293	1.63	30	0.25-m	13.5
1008.01126	3.03	30	0.25-m	13.6
1011.01927	3.13	30	0.25-m	
1011.30694	0.87	28	0.36-m	13.9
1012.01266	2.87	60	0.25-m	14.7

Notes: t_{int} is the integration time; the magnitudes are nightly averages; ':' denotes an uncertain value; most observations were in white light.

transition from superhumps to late superhumps; there is no cycle count ambiguity in this diagram.

Fig. 7 shows the observations on HJD = 245 3008 and one of the HJD = 245 3002 light curves plotted on the same intensity scale. The amplitude and position of the late superhump maximum indicate that it did not develop out of anything visible in the superhump profile. Rather, the structure in the superhump is its own repetitive profile.

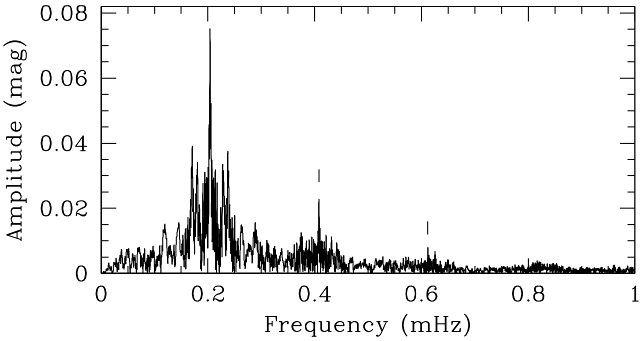

Figure 5. The Fourier transform of the first eight nights of the outburst. Vertical bars at 40.854 and 27.231 min mark the first and second harmonic.

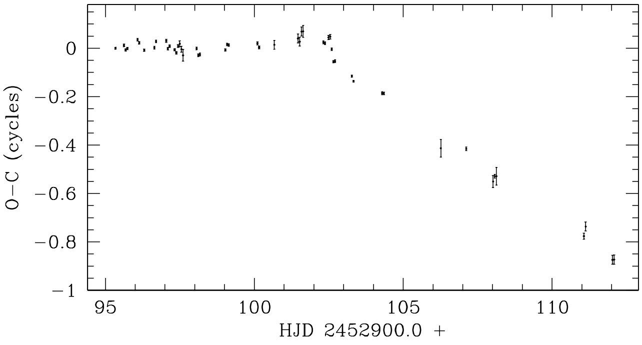

Figure 6. O−C diagram computed by comparing the observed times of maximum with the times calculated from a sine function with a period of 81.702 min. This is consistent with a constant period up until HJD 245 3003; after that the phase starts changing.

Fig. 8 is a Fourier transform of all the data taken after HJD = 245 3004; it gives a late superhump period of 81.29 ± 0.01 min.

All the outburst light curves were searched for rapid quasi-coherent oscillations, but with no success.

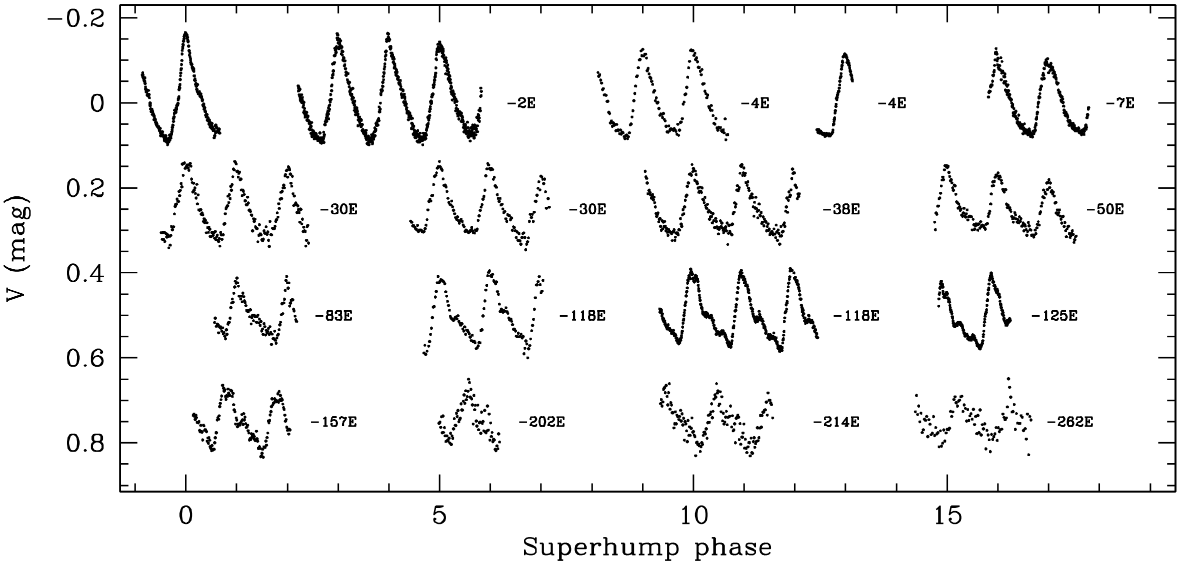

Figure 4. The outburst light curves after linear trends were removed from some of them; most of these light curves were binned to improve signal-to-noise ratio. The observations are phased according to the superhump period of 81.702 min. Individual runs are shifted along the horizontal axis by the number of cycles indicated, and arbitrarily displaced vertically. A few of the lower quality runs are not shown.

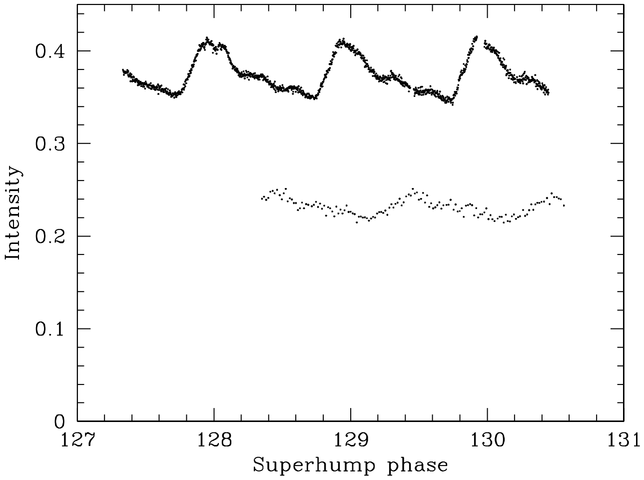

Figure 7. Superhump and late superhump profiles plotted in intensity units. There is no vertical displacement between the two light curves; they are phased using the superhump period and the time of the first observed superhump maximum. The bottom light curve is transposed along the horizontal axis by 95 superhump cycles.

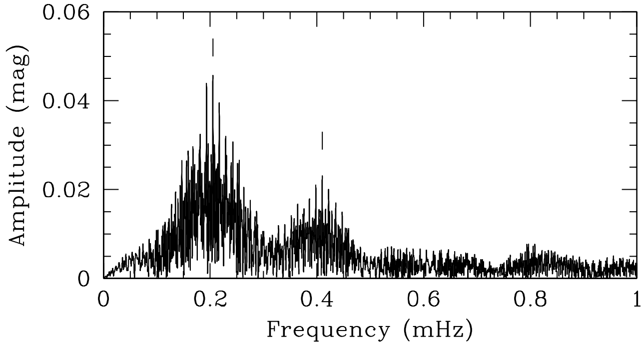

Figure 8. The Fourier transform of all observations of the late superhump. Peaks corresponding to the fundamental and first harmonic are marked.

3 DISCUSSION

It has often been noted that the standard model of CV evolution predicts the existence of a large number of short-period, low-$\dot{M}$ CVs, but that only very few such systems are known (e.g. Kolb 2002). Low-$\dot{M}$ CVs are intrinsically faint, but many are being discovered in surveys that reach faint limits, such as the Sloan Digital Sky Survey.

The orbital modulation of SDSS0137 is very similar to the double hump in WZ Sge (e.g. Patterson 1980). Three more examples of CVs with double-humped orbital modulations are WX Cet (Rogoziecki & Schwarzenberg-Czerny 2001), SDSS J161033.64 − 010223.3 (Woudt & Warner 2004) and HS 2331+3905 (Araujo-Betancor et al. 2004). WZ Sge and WX Cet are both low-$\dot{M}$ dwarf novae of long outburst interval; no outburst has yet been observed in SDSS J161033.64 − 010223.3.

The double-humped modulation in WZ Sge (and the other systems like it) has not been convincingly modelled, but is probably caused by the bright-spot. An early explanation was that the bright-spot has a large scaleheight and is thus visible above the inner accretion disc when it is on the far side of the disc (Krzeminski & Smak 1971; Robinson, Nather & Patterson 1978). Since then, it has been demonstrated that the disc in WZ Sge is optically thin (Skidmore et al. 2000; Mason et al. 2000) so that the bright-spot can be seen through it.

The second hump in SDSS0137 has lower amplitude during run S7073 than in any of our other runs. This has also been observed in WZ Sge (Krzeminski & Smak 1971); in WX Cet the second hump is sometimes not detected at all (Rogoziecki & Schwarzenberg-Czerny 2001). A possible explanation for this is that the optical thickness of the disc can temporarily increase so that the spot is (at least partially) obscured when it is on the side of the disc facing away from the observer (Krzeminski & Smak 1971). However, in the case of our run S7073, an increase in optical depth of the disc cannot have been caused by an increase in $\dot{M}$ through the disc, since the system was 0.10 mag fainter than in run S7063 and 0.14 mag fainter than in run S7060. Although there are a few features in the spectrum that may be attributed to the secondary, it does not contribute a large fraction of the total flux, therefore it seems very unlikely that the orbital modulation contains a substantial amount of ellipsoidal variation from the secondary.

Normal superhumps are thought to be caused by tidal stresses acting on an eccentric disc (e.g. Whitehurst 1988). Repetitive structure in superhump profiles similar to what can be seen in Fig. 7, and in more of the light curves in Fig. 4, has been observed in VW Hyi as well (Schoembs & Vogt 1980; Warner 1985). The fractional period excess of the superhump is $\epsilon = (P_{\rm sh} - P_{\rm orb})/P_{\rm orb} = 0.0250 \pm 0.0001$.

The interval between supermaximum and the first appearance of superhumps is less than 4 d. This indicates that the outburst interval in SDSS0137 is probably years at most, rather than decades (Warner 1995b).

A variation in bright-spot brightness, resulting from the varying depth in the white dwarf potential well at which the stream impacts the disc, was initially proposed as a model for superhumps (Vogt 1982), but has since been used to explain late superhumps (e.g. Whitehurst 1988; Murray 1996; Rolfe, Haswell & Patterson 2001) (but see also Hessman et al. 1992). Hellier (2001) proposes an alteration to the tidal thermal instability (Osaki 1989), namely that the tidal and thermal instabilities are uncoupled. The tidal eccentricity can persist after the disc has come down from the thermal high state at the end of the outburst. The viscous dissipation – caused by tidal stresses – which results in superhumps then decreases because the disc viscosity is now much lower. At this point the late superhumps should become detectable above the superoutburst light. It is therefore perhaps surprising that the late superhump cannot be seen in the HJD = 245 3002 light curves.

There are two other systems for which the transition from superhumps to late superhumps has been carefully tracked: V1159 Ori (Patterson et al. 1995) and IY UMa (Patterson et al. 2000). In both these examples O−C increases during the transition, in contrast to what is shown in Fig. 6.

4 SUMMARY

We classify the CV SDSS0137 as an SU UMa-type dwarf nova and report an orbital period of 79.71 min and a superhump period of 81.702 min. SDSS0137 has a double-humped orbital modulation, which is compatible with the very low $\dot{M}$ indicated by the spectral appearance. Late superhumps developed ∼11 d after the start of the outburst.

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