Curious Variables Experiment (CURVE).
CCD photometry of active dwarf nova DI UMa

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ABSTRACT

Context. We report an analysis of photometric behaviour of DI UMa – an extremely active dwarf nova. The observational campaign (carried out in 2007) covers five superoutbursts and four normal outbursts.

Aims. We examined principal parameters of the system in order to understand peculiarities of DI UMa, and other most active cataclysmic variables.

Methods. Based on precise photometric measurements, temporal light curve behaviour, O–C analysis and power spectrum analysis, we investigated physical parameters of the system.

Results. We found that the period of the supercycle is now equal to 31.45±0.3 days. Observations during superoutbursts give the period of superhumps equal to $P_{\text{sh}} = 0.055318\text{(11) days (79.66 ± 0.02 min)}$. During quiescence, light curve reveals modulation with a period $P_{\text{orb}} = 0.054579\text{(6) days (78.59 ± 0.01 min)}$, which we interpret as the orbital period of the binary system. The values obtained allowed us to determine fractional period excess equal to $1.35\% ± 0.02\%$, which is surprisingly small compared to the usual value for dwarf novae (2%-5%). Detailed O–C analysis has been performed for two superoutbursts with the best coverage. In both cases, we detected an increase of the superhump period with a mean rate of $P/P_{\text{sh}} = 4.4(1.0) \times 10^{-5}$.

Conclusions. Based on these measurements we confirm that DI UMa is probably a period bouncer – an old system which reached the period minimum long time ago, its secondary became a degenerate brown dwarf and the whole system evolves now toward longer periods. DI UMa is thus extremely interesting because we know only one more active ER UMa star with similar characteristics (IX Dra).

Key words. Stars: individual: DI UMa – binaries: close – dwarf novae – novae, cataclysmic variables

1. Introduction

The ER UMa type stars (Kato and Kunjaya [1995] still remain the most intriguing systems among all cataclysmic variables. Those objects, belonging to SU UMa-type dwarf novae, reveal various types of behaviour, such as normal outburst, superoutburst and superhumps. Smak [1984] solved the problem of the origin of normal outbursts in dwarf novae in terms of termal instability in accretion disc. Later, Whitehurst [1988] and Osaki [1989] proposed the model which discribed superoutburst phenomena in those stars (for a review see Osaki [2005]). The period between two consecutive superoutbursts (also called the supercycle period) in ER UMa type objects is about few tens of days. Until now, the shortest known supercycle for this class of stars is $P_{\text{sup}} = 19.07\text{ days}$ – a value for RZ LMi (Robertson et al. [1995] Olech et al. [2008]).

DI UMa is precisely a member of ER UMa class. The history of observations of DI UMa starts in 1959, when Hoffmeister [1959] discovered a rapidly varying star, which was later designated as DI UMa. Further spectroscopical studies identified this object as a cataclysmic variable (Bond [1978] Szkody & Howell [1992]. Kato, Nogami & Baba [1990] determined the period of the supercycle as 25 days. Soon after, Fried et al. [1999] found that superoutbursts have recurrence time of 30–45 days, and the superhump period and the orbital period are equal to 0.05529(5) and 0.054564(1) days, respectively. Hence, they obtained the superhump period excess of $1.3\%$, turned out to be one the lowest for known CVs. Although a small deviation from regularity in the occurrence of superoutburst is admissible, this prominent change of supercycle length remains problematic from the standard thermal–tidal instability model point of view. This fact, in addition to very low period excess, which is rather appropriate for quiet WZ Sge stars, both with global properties and parameters characterizing this system, have encourged us to take a closer look at the behaviour of DI UMa.

2. Observations and data reduction

Observations were carried out between January 15 and June 25 in 2007. Two telescopes have been used to collect the data. The first one is a 0.6-m Cassegrain telescope of Warsaw University Observatory, located in Ostrowik station. It is equipped with a Tektronix TK512CB back-illuminated CCD camera. The image scale was 0′′.76/pixel providing a 6′×6′ field of view (Udalski and Pych [1992]).
The second one is a f/3.8 0.3-m Newton telescope located at Jaczek Pala's amateur observatory in Słupsk, equipped with a SBIG ST-2K dual CCD camera.

Observations of DI UMa reported in this paper cover 36 nights and include 3093 measurements. The average exposure time was about 150 sec. Although we have not used an autoguider, images of stars remain unshifted and PSF profiles seem undistorted.

For the observational data processing we used the IRAF package. Next, the profile photometry was obtained using the DAOphotII package (Stetson 1987). A standard way of reduction was performed for the Ostrowik data. Unfortunately, amateur observations from Słupsk were obtained without flat field calibration images, so only simplified reduction was possible. This measurements have poorer accuracy but they were good enough to be included in the analysis.

Observations were carried out without filters for two reasons. First, due to the lack of an autoguider system, we wished to keep exposures short in order to minimize guiding errors. Second, because our main goal was an analysis of the temporal behaviour of the light curve, the use of filters could cause the object to become too faint to be observed in quiescence. Relative unfiltered magnitudes of DI UMa were determined as the difference between the magnitude of the star and the magnitude of a nearby comparison star.

Table 1: Observational journal for the DI UMa campaign.

| Date in 2007 | Start [HJD] (2454000+) | End [HJD] (2454000+) | Dur (hr) | No. of points | $< V >$ (mag) |
|-------------|------------------------|----------------------|----------|---------------|--------------|
| Jan 15      | 116.30818              | 116.64998            | 3.80     | 101           | 14.84        |
| Mar 07      | 167.33473              | 167.56941            | 2.56     | 97            | 16.23        |
| Mar 13      | 173.49266              | 173.65707            | 3.95     | 117           | 15.26        |
| Mar 26      | 186.33092              | 186.64037            | 2.43     | 99            | 17.69        |
| Mar 27      | 187.32042              | 187.52248            | 4.76     | 89            | 16.95        |
| Mar 28      | 188.39363              | 188.55087            | 5.07     | 106           | 15.71        |
| Mar 30      | 190.35526              | 190.46698            | 2.73     | 48            | 17.51        |
| Mar 31      | 191.36005              | 191.38821            | 0.68     | 9             | 17.69        |
| Apr 04      | 195.30920              | 195.31517            | 0.14     | 7             | 17.41        |
| Apr 05      | 196.33060              | 196.35222            | 0.52     | 24            | 15.73        |
| Apr 10      | 202.31427              | 202.34950            | 0.85     | 26            | 17.65        |
| Apr 12      | 203.34770              | 203.46420            | 2.80     | 79            | 17.46        |
| Apr 13      | 204.34525              | 204.47620            | 3.14     | 96            | 15.98        |
| Apr 14      | 205.36642              | 205.52808            | 3.88     | 115           | 14.70        |
| Apr 15      | 206.27831              | 206.47507            | 4.72     | 172           | 14.67        |
| Apr 16      | 207.28708              | 207.58366            | 7.12     | 523           | 14.82        |
| Apr 17      | 208.27757              | 208.40331            | 3.02     | 102           | 14.87        |
| Apr 19      | 209.34435              | 209.53969            | 4.69     | 123           | 14.93        |
| Apr 20      | 211.35228              | 211.46001            | 2.59     | 60            | 15.06        |
| Apr 21      | 212.28355              | 212.37567            | 2.21     | 61            | 15.21        |
| Apr 23      | 214.37639              | 214.46617            | 2.15     | 58            | 15.52        |
| Apr 25      | 216.28540              | 216.52020            | 5.64     | 176           | 17.15        |
| Apr 26      | 217.32268              | 217.45414            | 2.94     | 38            | 17.40        |
| Apr 29      | 220.39641              | 220.51590            | 2.87     | 22            | 16.08        |
| May 15      | 237.44159              | 237.51015            | 1.65     | 42            | 14.77        |
| May 17      | 238.37388              | 238.49019            | 3.66     | 139           | 14.83        |
| May 18      | 239.33408              | 239.51366            | 4.31     | 136           | 14.94        |
| May 20      | 241.36450              | 241.40883            | 1.06     | 24            | 15.11        |
| May 21      | 242.36734              | 242.46793            | 2.41     | 63            | 15.22        |
| May 22      | 243.38513              | 243.47040            | 2.05     | 52            | 15.30        |
| May 23      | 244.37801              | 244.48001            | 2.43     | 63            | 15.30        |
| May 24      | 245.34680              | 245.49097            | 3.46     | 66            | 15.61        |
| May 25      | 246.33298              | 246.43703            | 2.50     | 26            | 16.66        |
| Jun 12      | 264.35449              | 264.36172            | 0.17     | 4             | 17.95        |
| Jun 19      | 271.37112              | 271.46188            | 2.18     | 53            | 14.72        |
| Jun 20      | 272.34845              | 272.41129            | 2.35     | 48            | 14.74        |

3. Global light curve

Figure 1 presents the photometric behaviour of DI UMa during this campaign. The shape of the light curve corresponds to the standard picture of active dwarf novae (Olech et al. 2001). Kato and Kunjaya (1995) Robertson et al. (1995). Frequent superoutbursts reach $V \approx 14.5$ magnitude at the maximum and fade to $V \approx 17.8$ at quiescence, so the amplitude of the superoutburst reaches $A_{\text{max}} \approx 3.3$ mag. Between very prominent superoutbursts we can find normal outbursts, reaching $\approx 15.4$ mag with an amplitude of $\approx 2.4$ mag.

Commonly accepted point of view, concerning behaviour of dwarf novae light curve, especially excess of brightness during superoutbursts (in comparison to normal outburst brightnesses), as well as its duration time and profiles are in agreement with our observations. This allowed us to undoubtedly separate measurements collected in different phases of activity. Base on that, from the global light curve we have selected only those nights during which the star was in superoutbursts (marked by open circles). Then, for the resulting light curve, we have computed the power spectrum using the ZUA code of Schwarzzenberg-Czerny (1990).

The power spectrum was computed for a range of 0 - 0.2 c/d, thus the frequencies which we found represent the longest periods that could be seen in the light curve and reflect the variability related to superoutbursts. The resulting periodogram is shown in Figure 2. Two prominent peaks can be observed. The highest peak at frequency of 0.316 c/d corresponds to the period of the superoutburst cycle, which according to our measurements is 31.45 days. This value is significantly different from previous estimates made by Kato et al. (1996) and agrees with the range measured by Fried et al. (1999). Because, our light curve span on 6 consecutive superoutbursts the observational coverage is richer than in earlier measurements and allowed us to achieve higher accuracies of period determinations.

As one can see from Figure 1 the profiles of superoutbursts are fitted with solid lines. Those lines were obtained based on points belonging to superoutburst IV having best observational coverage. Average superoutburst profile was approximated by an analytical fit using Bezier curves.

Table 1. Observational journal for the DI UMa campaign.
Fig. 1. Global light curve of DI UMa during the 2007 campaign. Dots, plus signs and circles indicate different periods of DI UMa activity. Those symbols represents quiescent state, normal outbursts and superoutbursts stage, respectively. Such division is used for further analysis (as in the text). Solid line shows a fit of the superoutburst profile no. IV, which is repeated every 31.45 days backward and forward.

Fig. 2. Power spectrum of DI UMa light curve after removal of the data from quiescence and normal outbursts. The peak corresponding to the supercycle period is marked by an arrow.

Profile obtained in this way was shifted backward and forward accordingly to the determined earlier supercycle period of 31.45 days. This line serves only as a check and

Fig. 3. Light curve of DI UMa in superoutbursts obtained by folding the general light curve with a supercycle period of 31.45 days.
demonstrator tool and is not used in later analysis, as for example in detrending procedure described in paragraph 4.1. During the observing season, the stability of the supercycle was quite high and the analytical light curve fits observations very well.

Figure 3 presents the phased light curve folded with the supercycle period of $P_{\text{orb}} = 31.45$ days. As one can see, the shape of the superoutburst is typical. First, the brightness of the star rose rapidly from the 17.8 mag during quiescent level to a peak magnitude of around 14.5 mag. This increase phase lasting $\sim 2$ days. After that, a plateau, with slowly decreasing trend at a rate of 0.8 mag/day and lasting $\sim 9.4$ days was observed. At the end of the plateau, the star reached $\sim 15.7$ mag, then much steeper decline took place, and the final decline lasted $\sim 4.1$ days. Based on this figure, we conclude that on the average the whole superoutburst lasts around $\approx 17.7$ days. In total, we have five certain detections of the superoutburst and one more (no. II) added as a prediction.

4. Superhumps

Figure 4 shows the light curves of DI UMa during individual nights of the superoutburst that occurred in April 2007 (marked by roman number IV in Figure 1). Data from twelve almost consecutive nights (gaps on Apr 19, Apr 22 and 24) are presented in this plot. One can clearly see a change of superhumps from orbital humps (April 12), steep initial rise with a trace of modulation (April 13), through fully developed tooth-shape common superhumps (April 14-21), to gradual disappearance and finally - transition to quiescence and orbital humps (April 25-26). At maximum light, the amplitude of clearly visible common superhumps reaches almost 0.3 mag.

4.1. Periodicity analysis

As one may see from previous figures, the light curves of DI UMa are characterized by an alternately changing trend from increasing to decreasing and so on. Thus, the magnitudes had to be transformed to a common $V$ system. Moreover, the fact that the data from quiescence to maximum of superoutbursts showed a variability in a range of about 3.3 mag, can have pernicious effect on period search. Taking this into account we prepared the data by subtracting the mean (and trend if necessary) from each night’s time series as follows:

The data from each night were fitted with a straight line or a parabola and this fit was subtracted from the actual light curve. This allowed us to detrend all nightly light curves and shift the data from the whole campaign to a common level. As a result, the data have average brightness equal to zero and consist of only short-term modulations with periods significantly shorter than one day. After such approach, we expect improvement of reliability of further period determination.

One can expect that the power spectrum based on all available data can be contaminated by several smaller peaks and aliases which are due to the presence of various periodicities in the light curve. Thus, based only on one periodogram which covers all available data, it is very hard to perform precise extraction of all frequencies present in the light curve. For that reason we decided to perform a more detailed frequency analysis.

4.1.1. Superoutburst data analysis

Let us look again at Figure 1. We separated all points into three kinds of data. Points marked by open circles are the measurements made during the superoutburst phase. These points, after the detrending process, were taken first for the analysis. The periodicity search was made using the ZUZA code (Schwarzenberg-Czerny 1976).

The lowest panel of Figure 4 presents the resulting periodogram. The most prominent peak correspond to the superhump period equal to $P_{\text{sh}} = 0.05504(5)$ days. This value is in agreement with the previous determination done by Fried et al. (1999).

We also decided to check the period stability of superhumps during successive superoutbursts. Figure 5 shows a comparison of periodograms obtained for different superoutbursts. As one can see, there is no sign of a significant superhump period change from one superoutburst to another. Nevertheless, periodograms for different superoutburst may be not conclusive due to insufficient available data used for their preparation. Especially, there is only one night for the superoutburst no. I and three nights for the superoutburst no. VI. For the same reason aliases can significantly distort the obtained spectrum.

The detrended light curve containing superhumps from all superoutbursts might be phased with one period and shows no significant traces of phase shift between superhumps from different superoutbursts. Such a light curve phased with a period $P = 0.05504$ days is presented in Figure 6.

Moreover, in order to check the stability of the phase of superhumps, we plotted phased light curves separately for each night. We chose the superoutburst no. IV as it had the best coverage. Figure 6 presents the result of this approach. Successively, light curves from April 14 to 23 are shown from top to bottom of the plot. During first four nights only a slight or no phase-shift was observed. Later on (around April 18) one can see the emergence of a secondary hump, but with no significant phase reversal, contrary to some ER UMa stars (for example see Kato et al. 2003). One can expect that a modulation connected with the orbital period, present in quiescent light curve, may also detected in superoutbursts as it was in the case of another active dwarf nova, IX Dra (Olech et al. 2004a). This idea encouraged us to search for frequencies correlated with orbital humps in the power spectrum. We decided to perform prewhitening of the detrended light curve of DI UMa from all superoutbursts. So first we removed from the light curve the modulation with a period corresponding to superhumps. Then we performed power spectrum analysis based on thus obtained data. As a result we acquired a noisy power spectrum with no significant peak, indicating that orbital modulation is absent during the superoutburst or its amplitude is below our detection limit.

4.1.2. Quiescence data analysis

We now turn to the analysis of the data collected during quiescence (black dots in Fig. 1). We repeated the approach from section 4.1.1 and produced a periodogram using the ZUZA software. Figure 7 presents results of this procedure. One of the most prominent peaks present in power spectrum is located at frequency of $f_{\text{orb}} = 18.323 \pm 0.005$ c/d ($P_{\text{orb}} = 0.054576(15)$ days). From a statistical point of
Fig. 4. Nightly light curves of DI UMa from its April 2007 superoutburst. Consecutive nights are denoted by dates in top-left/right corner. Dots shows the data obtained in Warsaw University Observatory, whereas open circles denotes observations made in Shupsk Observatory.
view, it is possible that some other, lower, peak represents the true modulation present in the quiescent light curve of DI UMa. But we recall here the result of Fried et al. (1999) who photometrically obtained the orbital period of DI UMa as equal to $P_{\text{orb}} = 0.054564(1)$ days, which is in excellent agreement with our determination. Hence, we assume the value of $P_{\text{orb}} = 0.054576(15)$ days as the most probable for the orbital period of the binary. We phased our quiescence data based on this determination. The result of this procedure is shown in Fig. 9.

In addition, we have some points collected during normal outbursts, but due to an insufficient amount of measurements we cannot draw useful conclusions for them.

4.2. The O-C analysis

DI UMa often shows clear and periodic modulation in quiescence, with an amplitude reaching even 0.4 mag. For this modulation we determined 15 moments of maxima. A least-squares linear fit to these data gives the following ephemeris:

$$HJD_{\text{orb-max}} = 2454186.341(4) + 0.054580(7) \times E$$  \hspace{1cm} (1)

Fig. 5. Power spectra for superhumps observed during four superoutbursts of DI UMa. The numbers near the most prominent peaks represent the most probable value of superhump period.

Fig. 6. Detrended light curve from data collected during all observed superoutbursts in 2007 campaign, folded with superhump period of $P_{sh} = 0.05504$ days.

Fig. 7. Stability of superhumps phase during eight nights covering the April 2007 superoutburst, from April 14 (top to April 23 (bottom). Light curves are phased with superhump period $P_{sh} = 0.055014$ days.
which agrees within errors with the determination based on the power spectrum and described in the previous paragraph. The combination of both these measurements gives us our final value of the orbital period of the binary as equal to $P_{\text{orb}} = 0.054579(6)$ days (78.59 ± 0.01 min).

On the other hand, the light curve of DI UMa from superoutbursts contains 38 moments of maxima.

The observations from superoutbursts no. IV and V contain enough data to perform detailed analysis and draw valuable conclusions about the temporal evolution of the superhump period.

The maxima from superoutburst no. IV might be fitted with a common ephemeris in the form:

$$HJD_{\text{max}} = 2454205.3729(9) + 0.055320(12) \times E$$

The $O-C$ values computed according to this ephemeris are shown in the top panel of Figure 10. It is clear that they show a slightly increasing trend and thus we decided to fit the maxima with a quadratic ephemeris in the form:

$$HJD_{\text{max}} = 2454205.3761(12) + 0.055139(50) \times E + 1.23(33) \cdot 10^{-6} \times E^2$$

We would like to point out that the maxima denoted by negative cycle numbers come from the night of April 12/13, i.e. from the quick initial rise to the superoutburst, and were not included into above fits. They are shifted in phase by about half a cycle and might correspond not to ordinary superhumps but to some kind of early superhumps or even orbital humps. Especially light curve in April 13 resemble early superhumps shapes known from other studies, (Kato 2002, Maehara 2007). Osaki & Meyer (2002) proposed that early superhumps are caused by two-armed dissipation pattern on the accretion disc. During our observations the early superhumps have double-peaked profile and its amplitude was in the range of 0.05-0.07 mag. Unfortunately, since clear shape of early superhumps was visible only in April 13 the precise determination of its period is impossible. The crude estimate (read from graph) gives $P_{\text{esh}} \approx 0.0540$ days with high uncertainty about 1%. In light of previous observations of early superhumps (for example Patterson 2003), which suggest $P_{\text{esh}}$ is equal to around orbital period, we treat this value with caution.

The maxima from superoutburst no. V can be fitted with a linear ephemeris of the form:

$$HJD_{\text{max}} = 2454237.46511(97) + 0.055313(22) \times E$$

Also in this case a slightly increasing trend of the superhump period was observed, thus the maxima could be fitted with a quadratic ephemeris, which is given in the following equation:

$$HJD_{\text{max}} = 2454237.4669(13) + 0.055183(68) \times E + 1.18(58) \cdot 10^{-6} \times E^2$$
The superhump periods from linear fits can be used together to compute our final mean value of the superhump period, which is $P_{\text{sh}} = 0.055318(11)$ days (79.66 ± 0.02 min).

It is worth to note that period derivatives obtained during both superoutbursts are consistent within errors and give a relatively low value of $\dot{P}/P_{\text{sh}} = 4.4(1.0) \times 10^{-5}$.

We would like to recall here the figure from Uemura et al. (2005), updated by Rutkowski et al. (2007), showing the relation between the period derivative and the superhump period. It is presented in Figure 11. The figure shows that DI UMa is placed in the group of small superhump period stars, which is presented in Figure 11. The figure shows that DI UMa is placed in the group of small superhump periods ($P_{\text{sh}}$) and exhibits low but positive $\dot{P}/P_{\text{sh}}$ value.

![Fig. 11. Relation between the superhump period and its derivative for known SU UMa stars.](image)

5. Conclusions

Our five-month observational campaign concerning of an active SU UMa-type star DI UMa resulted in the detection of five superoutbursts which repeat every 31.45 days. It is a much larger than the 25 days obtained by Kato, Nogami & Baba (1996) but falls within the range of 30–45 days observed by Fried et al. (1999).

Our observations indicate that DI UMa shows periodic light modulations both in quiescence and during superoutbursts. The first of these modulations, with $P_{\text{orb}} = 0.054579(6)$ days (78.59 ± 0.01 min), is interpreted as the orbital period of the system and the second, with $P_{\text{sh}} = 0.055318(11)$ days (79.66 ± 0.02 min), as the superhump period.

A very short orbital period and small period excess equal to only 1.35% ± 0.02% suggest that DI UMa is a so-called period bouncer, i.e. an old system which reached its period minimum long time ago, its secondary became a degenerated brown dwarf and the whole system now evolves toward longer periods (Patterson 2001). DI UMa is thus unique because we know only one more active ER UMa star with similar characteristics - namely IX Dra (Olech et al. 2004). Inspection of Figure 11 indicates that long period systems tend to show large negative values of $\dot{P}/P_{\text{sh}}$, whereas short period systems are characterized by small and positive period derivatives. This picture has a physical interpretation proposed by Osaki and Meyer (2003). In long period dwarf novae with high transfer rates, the 3:1 resonance radius in the accretion disc is close to the tidal truncation radius, thus eccentric waves in the disc may propagate only inwards, causing a decrease of the superhump period. In short period systems, showing lower accretion rates and more infrequent outbursts, the 3:1 radius is much smaller than the tidal truncation radius and enough matter is stored in the disc to cause the propagation of outward eccentric waves. In such systems the superhump period may increase.

Does DI UMa fit this scenario? It is a short-period but active dwarf nova, showing both frequent outbursts and superoutbursts, indicating a high mass transfer rate. It may mean that the disc contains enough matter to reach not only the 3:1 resonance radius, but also the region of the 2:1 resonance radius, as in the case of IX Dra - another active but old dwarf nova. There is thus a possibility of the ignition of propagating outward eccentric waves, which may cause an increase of the superhump period.

It is worth to recall that DI UMa is the second shortest period dwarf nova with determined period derivative. A shorter superhump period and its derivative were determined for VS 0329+1250 (Shafter et al. 2007).

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