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The Dwarf Nova MN Dra: Periodic Processes at Various Phases of the Supercycle

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Abstract—We analyze photometry of the dwarf nova MN Dra carried out using various instruments at four observatories on 18 nights between May 20 and June 28, 2009. The observations cover a variety of activity states of the system: a superoutburst, three normal outbursts, and quiescence. Analysis of the system's light curve during the superoutburst decline reveals positive superhumps that recur, on average, with a period of 0.105 days and are due to the direct apsidal precession of the accretion disk. These are observed until the end of the superoutburst, but their period decreases at a rate of -24.5×10^{-5} of the period per period. Both the positive-superhump period and its derivative are in good agreement with estimates made during previous superoutbursts. At the brightness minimum and in normal outbursts, MN Dra displays brightness variations with a period of 0.096 days, whose amplitude is much larger during the brightness minimum (0.8^m–1.5^m) than during normal outbursts (0.1^m–0.2^m). We suggest that these brightness variations could be negative superhumps due to nodal precession of the oblique accretion disk.

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1. INTRODUCTION

The dwarf nova MN Dra was first discovered as a variable star by S.A. Antipin from the Moscow plate collection, and was originally designated Var73 Dra. To determine the nature of the variable (presumed to be a dwarf nova), it was observed at the Crimean Laboratory of the Sternberg Astronomical Institute in 2001. These observations confirmed the star to be a dwarf nova, of the SU UMa type.

Dwarf novae are a subclass of cataclysmic variables whose systems consist of a late-type star that loses matter through its inner Lagrange point to a non-magnetic, white-dwarf degenerate companion, first forming an accretion disk around it. SU UMa stars are the shortest-period systems among cataclysmic variables, with orbital periods in the range $\sim$ 80–180 min. This range also covers the so-called "gap" between two and three hours in the observed orbital-period distribution for cataclysmic variables. However, several recently discovered cataclysmic variables, including some dwarf novae, have periods in this gap. The most common explanation of the "gap" is a strong decrease in the mass-loss rate from the donor star, so that it shrinks within the Roche lobe, leading to a cessation of the outbursts. SU UMa stars also differ from other cataclysmic variables with longer periods in that they exhibit two kinds of outbursts:

(1) long-duration outbursts with amplitudes of 2^m–6^m that last approximately two or three weeks;

(2) fainter and shorter (3–5 days) outbursts.

The first type of outbursts are called superoutbursts and the second type, normal (or ordinary) outbursts. Short-period brightness variations, or superhumps, are observed during superoutbursts, whose periods are usually several percent longer than the orbital period. The superhumps have been successfully explained in the theory of tidal and thermal instability [1]. They are due to the precession of the accretion disk generated by gravitational perturbations of the secondary. These perturbations are most effective if particles in the accretion disk moving in eccentric orbits enter the 3 : 1 resonance with the orbital motion. The period of the superhumps is due to the beating between the precession period, P_{prec}, and the orbital period, P_{orb} [2]:

$$1/P_{sh} = 1/P_{orb} - 1/P_{prec}.$$

Such precession is sometimes called direct "apsidal" precession, to emphasize that it moves the apsidal line, and such superhumps are called "*positive superhumps*," because their periods always exceed those of the orbital brightness variations. Along with positive superhumps, a small number of cataclysmic variables (15) exhibit short-term brightness variations with periods shorter than the orbital period, called "*negative superhumps*." It is believed that these may be due to "classical," retrograde precession of a accretion disk that is inclined to the orbital plane [3, 4]. The simultaneous presence of positive and negative superhumps has been firmly observed for only three systems [5–7] and was suspected for three more systems [8–10]. The remaining 12 systems include stars with shorter periods, i.e., AM CVn stars, as well as stars with longer periods: nova-like stars and even X-ray novae [4, 11–17].

Antipin and Pavlenko [18] found that the period of MN Dra lies in the "gap." In their follow-up observations of the dwarf nova during two superoutbursts in 2002, Nogami et al. [19] confirmed that the period was in the "gap" and refined the mean superhump period (0.104885(93) days). During the course of a superoutburst in 2002 that had good observation coverage, the superhump period decreased at a rate of $-1.7(2) \times 10^{-3}$ of the period per period. This is an order of magnitude higher than the highest rate of change of a superhump period detected for another dwarf novae. Nogami et al. [19] also found variations with a similar period (0.10424(3) days) during the brightness minimum, and suggested that it could be related to continuously present superhumps in this binary, rather than to the orbital period. Another unique feature found for the object was the unusually short interval between subsequent superoutbursts (about 60 days), with the superhump period being long for an SU UMa star [19, 20]. Kato et al. [20] specially noted that the possibility that MN Dra has permanent superhumps—as was found for systems with short supercycles, ER UMa stars [21, 22]—required confirmation. This and the fact that the orbital period of MN Dra remained unknown were the motivation for our detailed study of the system's behavior at all phases of its outburst activity.

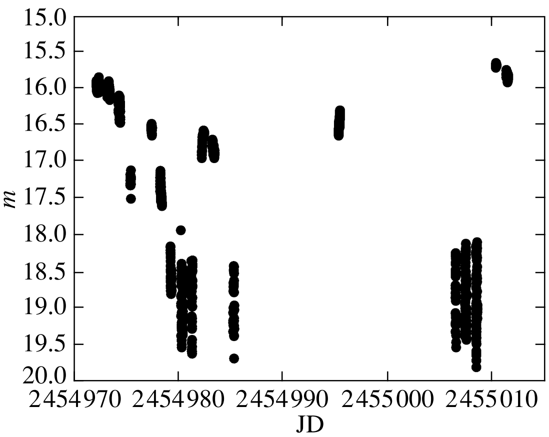

Fig. 1. Outburst light curve of MN Dra showing the system's brightness variations during our observations between May 20 and June 28, 2009.

2. OBSERVATIONS

A superoutburst of MN Dra was noted in May 2009, initiating a campaign of observations during the development of the superoutburst, the minimum, and subsequent normal outbursts. Our photometry was performed in the Crimea, Russia, and Slovakia. We observed using a FLI 1011E (2.6-m ZTSh telescope of the Crimean Astrophysical Observatory, CrAO), Apogee 47p (60-cm telescope of the Sternberg Astronomical Institute's Crimean Laboratory), PIXELVISION (60-cm telescope at Peak Terskol), SBIG ST10 XME (50-cm telescope of the Tatranska Lomnica Observatory, Slovakia), and SBIG ST-7 (38-cm telescope, CrAO) CCD detectors. We applied (2×2) binning with all the observations except those with the 2.6-m CrAO telescope. Each observing series lasted from 2.5 to 4.5 hours. The combined total observation time for the star was about 72 hours on 18 nights. We observed in the red, in the Johnson R_J or Cousins R_C band or in integrated light (without a filter). For the unfiltered observations, the peak sensitivity of the applied CCD detectors was also in the red.

The comparison star was at the coordinates $20^h23^m35.358^s$, $+64°36'56.66''$ (J2000.0) according to the USNO-A2.0 catalog [23]. A log of our observations is presented in Table 1, whose columns contain (1) the observation date and time interval in Julian dates, (2) the telescope, observing site, and light detector, (3) the color system and exposure time, and (4) the object's state of outburst activity during the observations.

We reduced the observations in accordance with the aperture photometry technique using codes written by V.P. Goranskii (http://vgoray.front.ru/software) and the MAXIM DL4 package. The observational uncertainties (understood as the r.m.s.

Table 1. Log of observations

JD 2454000+	Telescope (site), CCD	Photometric band; exposure time	Star state
972.28–972.53	2.6-m ZTSh (CrAO, Ukraine), FLI 10001E	Integrated light; 10 s	Superoutburst plateau
973.26–973.54	2.6-m ZTSh (CrAO, Ukraine), FLI 10001E	Integrated light; 10 s	Superoutburst plateau
974.38–974.53	38-cm (CrAO, Ukraine), SBIG ST-7	Integrated light; 180 s	Superoutburst plateau
974.27–974.35	60-cm (INASAN Terskol Branch, Russia), PIXELVISION	Integrated light; 90 s	Superoutburst plateau
975.49–975.57	50-cm (Tatranska Lomnica, Slovakia), SBIG ST10 XME	V; 120 s	Superoutburst decline
977.50–977.56	50-cm (Tatranska Lomnica, Slovakia), SBIG ST10 XME	R_c; 120 s	Rebrightening, maximum
978.29–978.42	50-cm (Tatranska Lomnica, Slovakia), SBIG ST10 XME	R_c; 120 s	Rebrightening decline
978.39–978.51	60-cm (SAI Crimean laboratory, Ukraine), Apogee 47p	R_j; 240 s	Rebrightening decline
979.31–979.45	60-cm (SAI Crimean laboratory, Ukraine), Apogee 47p	R_j; 240 s	Rebrightening decline
980.32–980.51	60-cm (SAI Crimean laboratory, Ukraine), Apogee 47p	R_j; 240 s	Minimum
981.30–981.42	60-cm (SAI Crimean laboratory, Ukraine), Apogee 47p	R_j; 240 s	Minimum
982.29–982.53	60-cm (SAI Crimean laboratory, Ukraine), Apogee 47p	R_j; 240 s	Normal outburst
983.29–983.53	60-cm (SAI Crimean laboratory, Ukraine), Apogee 47p	R_j; 240 s	Normal outburst maximum
985.28–985.40	60-cm (SAI Crimean laboratory, Ukraine), Apogee 47p	R_j; 240 s	Minimum
995.32–995.44	2.6-m ZTSh (CrAO, Ukraine), FLI 10001E	Integrated light; 10 s	Normal outburst maximum
1006.42–1006.50	60-cm (INASAN Terskol Branch, Russia), PIXELVISION	Integrated light; 180 s	Minimum
1007.32–1007.50	60-cm (INASAN Terskol Branch, Russia), PIXELVISION	Integrated light; 180 s	Minimum
1008.38–1008.51	60-cm (INASAN Terskol Branch, Russia), PIXELVISION	Integrated light; 180 s	Minimum
1010.24–1010.34	60-cm (INASAN Terskol Branch, Russia), PIXELVISION	Integrated light; 180 s	Normal outburst maximum
1011.26–1011.47	60-cm (INASAN Terskol Branch, Russia), PIXELVISION	Integrated light; 180 s	Normal outburst maximum

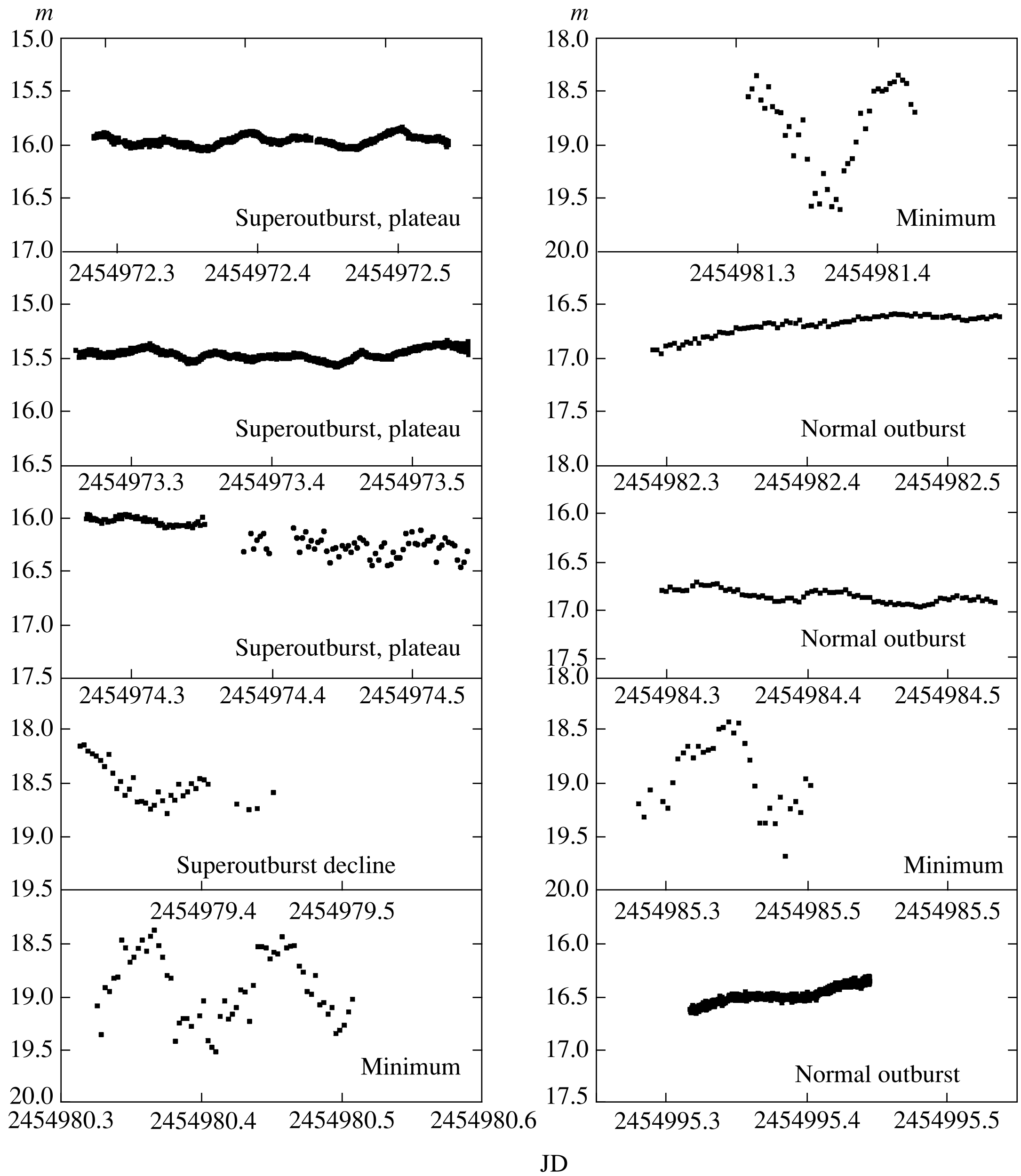

Fig. 2. Sample light curves of MN Dra acquired on May 20–June 12, 2009. The diagrams are plotted to the same scale.

deviation) depend on the telescope used, the color system, the object's brightness, and the weather conditions during the observations. We calculated this uncertainty from the brightness differences of several check stars relative to the comparison star. For the brightest state of the object, the uncertainties were 0.007^m–0.03^m; at the brightness minimum, they were 0.05^m–0.1^m. Observations acquired with different equipment and in different color systems were reduced to the Johnson system using specially determined corrections. This was possible thanks to the partial overlapping in time of our observations at the different observatories.

3. OUTBURST LIGHT CURVE OF MN Dra

A light curve displaying the behavior of MN Dra between May 20 and June 28, 2009 is shown in Fig. 1. The system experienced considerable variations during the interval covered by our observations: an outburst occurred, followed with rebrightening and a subsequent brightness minimum (for 2 days), then a normal outburst. When the observations were resumed after a 10-day gap due to poor weather, we found that MN Dra had entered its next normal outburst. Ten days later, the system's brightness decreased to its minimum level, followed by a normal outburst that was the third in a sequence. Comparing

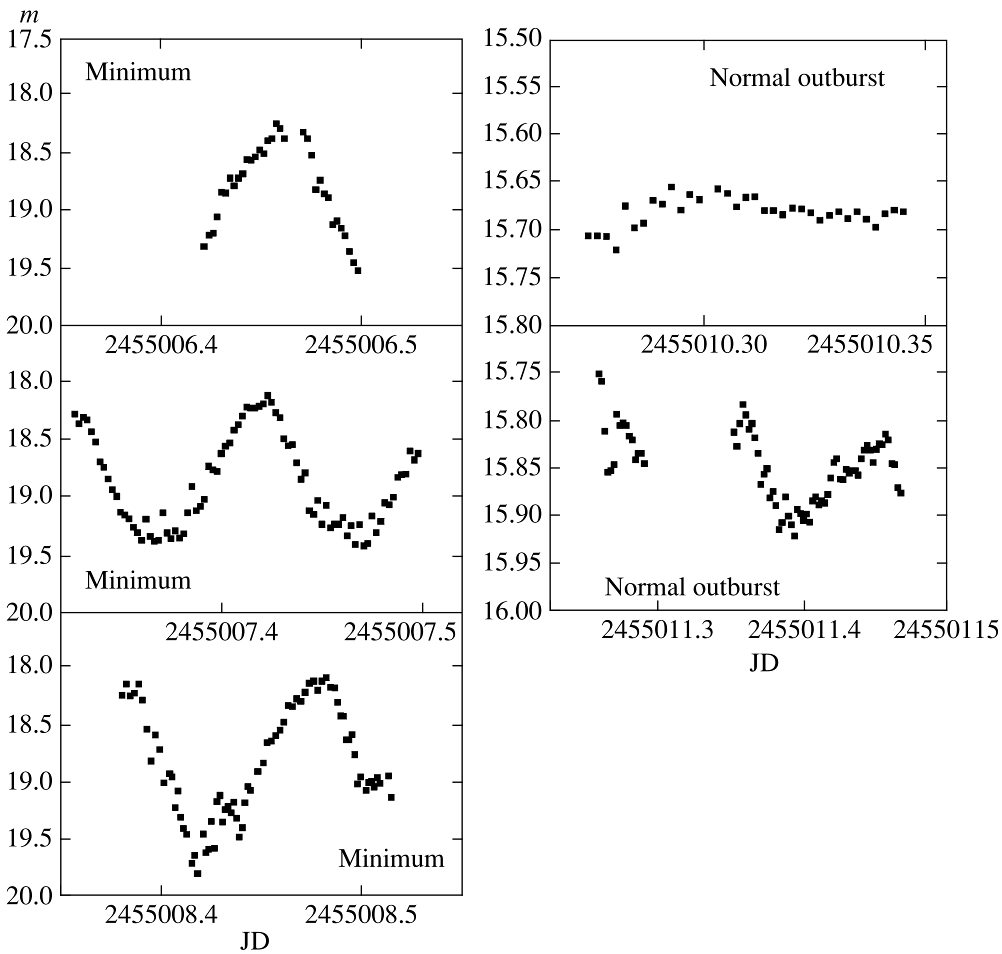

Fig. 3. Light curves of *MN* Dra acquired between June 23 and 28, 2009. The scale is different for the brightness minimum and the outburst.

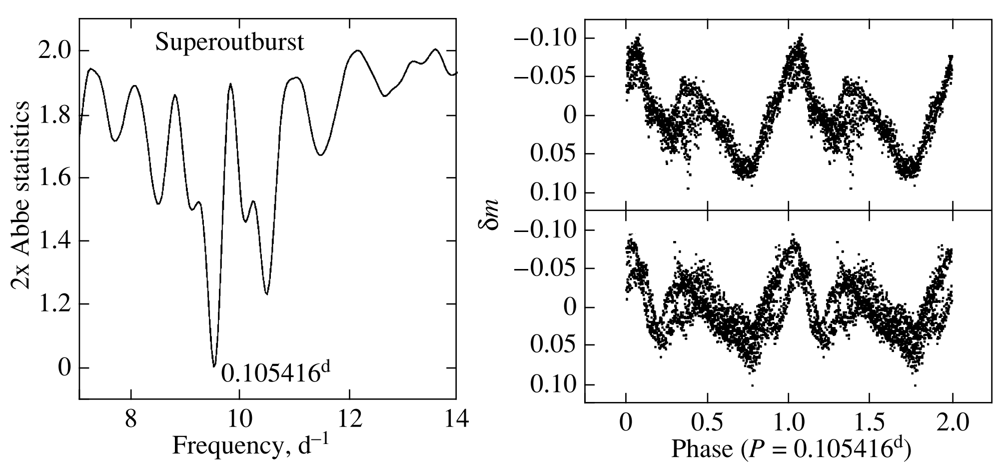

Fig. 4. Left: periodogram for two nights of observations during the superoutburst. Right: phased light curves plotted for each of the two nights with the 0.105416-day period: JD 2454972 (top) and JD 2454973 (bottom).

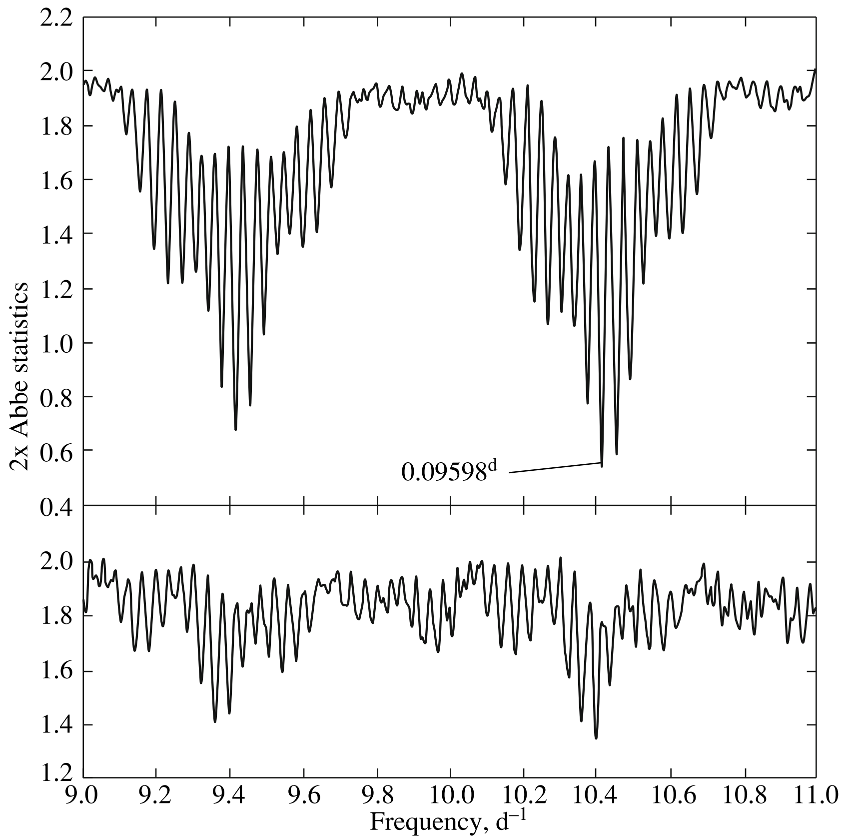

Fig. 5. Periodogram for observations during the brightness minimum. Top: periodogram for the raw data. Bottom: periodogram for the data after subtracting a wave with a 0.09598-day period.

our light curve to those obtained during the outbursts of 2001 and 2002, which lasted about 13 days each, we see that the beginning of the 2009 superoutburst was missed, and our observations of MN Dra cover only the second half of the superoutburst. From our observations, the mean amplitude of the ordinary outbursts is 2.5^m–3^m, in a good agreement with the findings of [18, 19] for earlier outbursts of MN Dra.

4. SHORT-TERM BRIGHTNESS VARIATIONS OF MN Dra

The longest one-night series of our observations of MN Dra are presented in Figs. 2 and 3. Short-term brightness variations with periods of about 2.3–2.5 hours are present in the light curves for each night, but with different amplitudes. The amplitude during the superoutburst and short outbursts varies within 0.1^m–0.15^m, whereas it is much larger in the minimum, 0.8^m–1.5^m. These variations during the superoutburst are obviously "positive" superhumps, while the nature of the brightness variations in the minimum and normal outbursts requires additional analysis. We will consider the brightness variations of MN Dra observed during and outside the superoutburst separately.

5. BRIGHTNESS VARIATIONS DURING THE SUPEROUTBURST

For our longest and most accurate series of observations (May 20 and 21), acquired during the superoutburst, we computed a Stellingwerf periodogram using the software package developed by Pelt [24, 25]. As a criterion, we have used the 2x Abbe Statistics (see for more details the "Mathematical statistics Tables," "Nauka," Moscow, 1983, p. 1983). The most significant peak indicates a period of 0.105416(44) days. Figure 4 displays the periodogram and the corresponding phase curves for this period. On both nights, the profile of the mean light curve displayed two well separated peaks, with the mean amplitudes for each of the observing series being 0.15^m and 0.1^m. Figure 4 clearly shows the fine structure of the superhumps, making it possible to distinguish differences between the profiles in adjacent cycles.

Note that the derived period does not characterize the mean superhump period, since we did not observe the initial stages of the superoutburst. However, it agrees well with estimates of the superhump period (0.104–0.10 days) made for various superoutbursts

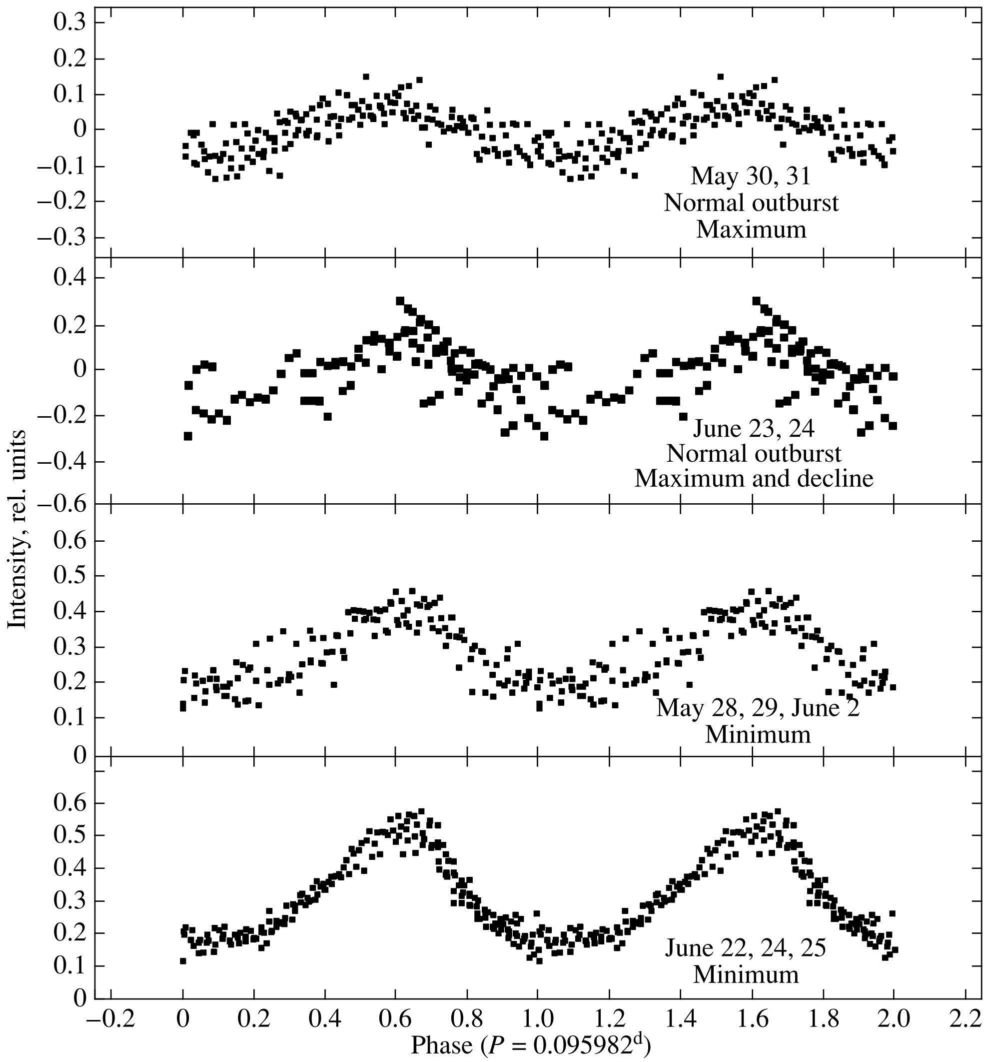

Fig. 6. Phase curves of the 0.095982-day period for different states of the outburst activity of *MN* Dra (see the text for details).

of this object that were observed either completely or partially [20].

6. BRIGHTNESS VARIATIONS OUTSIDE THE SUPEROUTBURSTS

As was already noted, the light curves at minimum revealed unusual behavior: a very large variation amplitude. To determine whether these variations were periodic and derive their period if they are, we performed a periodogram analysis for the data obtained during the minimum, after the end of the superoutburst (seven nights in total). The Stellingwerf periodogram is shown in the upper panel on the left side of Fig. 4. The strongest peak corresponds to a period of 0.09598(2) days. To check if this is the only signal or whether there are other close periods near the best period, we whitened the periodogram, i.e., plotted another periodogram for the data after subtracting a wave with a period of 0.09598(2) days from the initial observations. The result is presented in the bottom panel of Fig. 5. This periodogram reveals no significant frequencies, though the noise signal near the subtracted period (at 10.35–10.45 d^{-1}) is somewhat stronger than at the adjacent frequencies. This could be due to the fact that we subtracted the dominant period using the mean amplitude at minimum (as we saw from the individual light curves, the actual amplitude varied over a wide range), but may also reflect the presence of other, very weak, periodic signals. Verifying this latter possibility requires a considerable increase in the periodogram signal-to-noise ratio; this could be achieved with additional high-quality observations in the minimum with larger telescopes (recall that the object is as faint as 18^m–19.5^m at its minimum brightness).

To properly compare the amplitudes of the 0.096-day brightness variations at different stages of

Table 2. Epochs of brightness maxima

	HJD Max				
972.299 (0.001)	972.401 (0.001)	972.51 (0.001)	973.350 (0.001)	973.455 (0.001)	974.295 (0.002)
974.500 (0.002)	977.523 (0.003)	978.36 (0.001)	978.46 (0.003)	979.398 (0.004)	980.361 (0.005)
980.461 (0.003)	981.410 (0.005)	982.466 (0.005)	983.325 (0.002)	983.418 (0.005)	983.502 (0.005)
985.331 (0.005)	995.354 (0.001)	1006.465 (0.003)	1007.421 (0.002)	1008.480 (0.003)	

the outburst activity, taking into consideration that the difference between the mean brightnesses for the outburst maximum and minimum is about 3^m, we converted the data from the logarithmic magnitude scale (m) to a linear relative-intensity scale (I) according to the relation:

$$I = 10^{-0.4m} \times 10^7.$$

The observations were subdivided into four groups. One included observations during three nights at the minimum after the end of the superoutburst, two of which preceded the first subsequent normal (short) outburst, with the third night following it (Fig. 1). The second group consisted of observations on three nights in a sequence during the minimum, separated from the end of the superoutburst by three weeks (the “far” minimum). The third group included observations on two nights of the first normal outburst immediately after the superoutburst, and the fourth group two nights after the “far” minimum (Fig. 1). We computed the phases for these observations using the ephemeris

$$\text{HJD Min} = 2455006.4021 + 0.09598E. \quad (1)$$

The result is presented in Fig. 6. Not only the data in the minimum, but also the outburst data are fairly well reproduced with the elements for the 0.09598-day period. The variability amplitude was 0.15–0.20 in relative intensity units in both outbursts, 0.20 relative units in the minimum before the outburst, and 0.35 relative units in the later minimum.

It seems that the profile of the mean curves (Fig. 6) changed with time rather than with the system’s brightness level. It was symmetric for the first normal outburst, but asymmetric for the other normal outburst and for both minima, with the ascending branch steeper than the decline.

The same type of profile of negative superhumps was also noted for the dwarf novae V503 Cyg [5], BF Ara [7], SDSS J210014.12+004446.0 [26].

7. O–C DEVIATIONS

We determined the epochs of maxima for all the light curves, presented in Table 2. The uncertainties of the derived epochs of maxima are given in parantheses.

We computed the O–C deviations for two phase intervals of the supercycle:

(a) for the superoutburst, including the end of the slanted plateau and the decline;

(b) for other dates, including the short outburst and the minimum brightness state.

We calculated the O–C deviations for the first interval using the ephemeris:

$$\text{HJD Max} = 2454972.299 + 0.105416E_1, \quad (2)$$

and for the second interval using the ephemeris:

$$\text{HJD Max} = 2454979.398 + 0.095982E_2. \quad (3)$$

We can clearly see that the O–C deviations during the superoutburst decrease according to a parabolic law, corresponding to the superhump period varying at the rate $\dot{P} = -24.5 \times 10^{-5}$ of the period per period. Outside the superoutburst, the O–C values are distributed near zero, with the scatter being largest for E_2 cycle numbers between 0 and 170. In the E_2 cycle range between 260 and 330, the scatter of the O–C values is a factor of ten lower, and the behavior of the O–C residuals corresponds to a constant period of 0.096 days. The behavior of O–C during the last stage does not depend on whether it is the brightness minimum or maximum of a short outburst (Fig. 7).

8. ORBITAL PERIOD

To find the orbital period, we separately analyzed data acquired on three nights during the brightness minimum fairly far from the supermaximum, approximately in the middle of the supercycle (JD 2455006, JD 2455007, and JD 2455008). A periodogram of the raw data demonstrated the period $P = 0.096$ days to

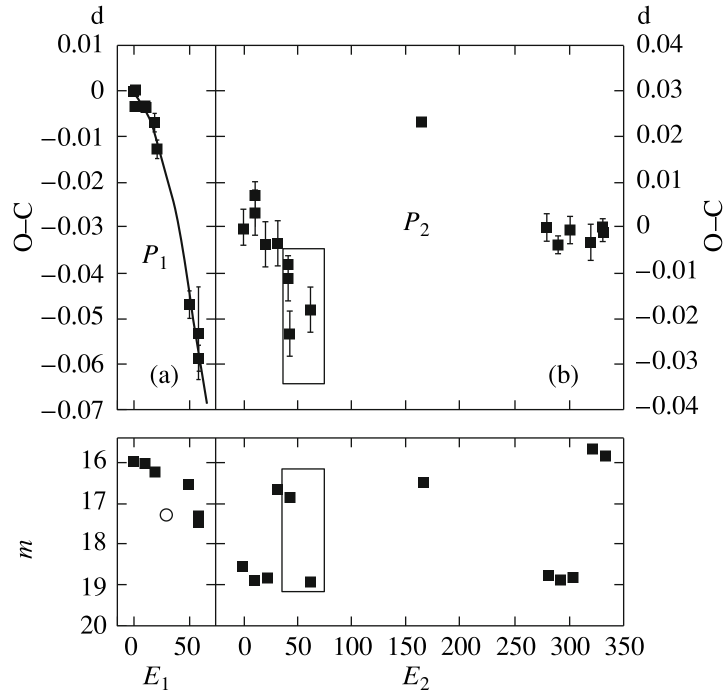

Fig. 7. Top: O−C residuals versus the cycle number E for the data (a) in and (b) after the superoutburst. The O−C residuals for the outburst are for the period P_1 and the ephemeris (1); those for later data are for the period P_2 and the ephemeris (2). The corresponding cycle numbers are designated E_1 and E_2. Bottom: mean light curve. The rectangles in both panels isolate the region of a rapid O−C change within 2 days.

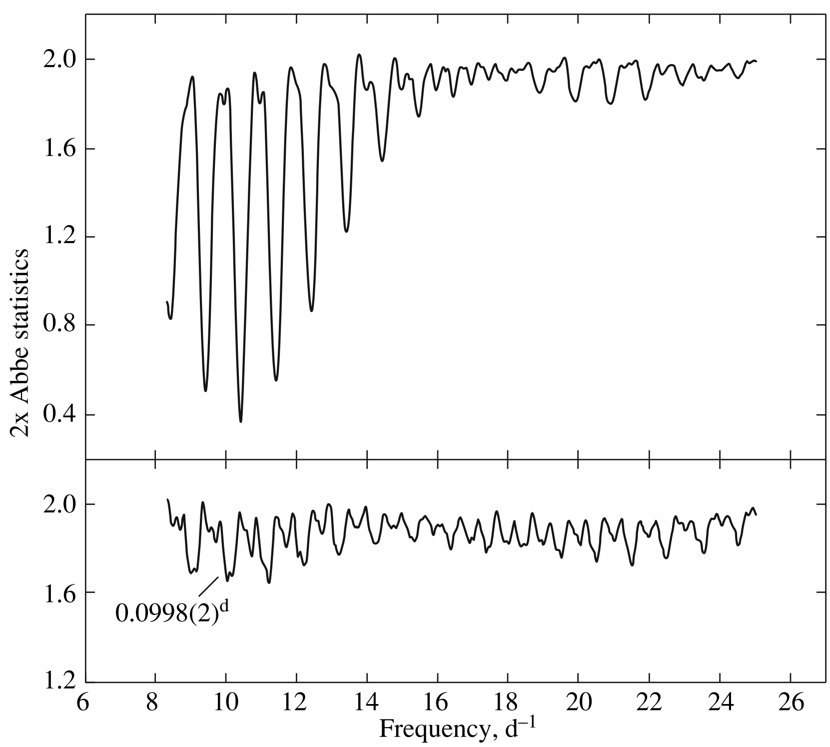

Fig. 8. Periodogram analysis for data acquired on three nights during the brightness minimum: JD 2455006, JD 2455007, and JD 2455008. Top: periodogram for the raw data. Bottom: periodogram for the data after subtracting a wave with a period of 0.09598 days.

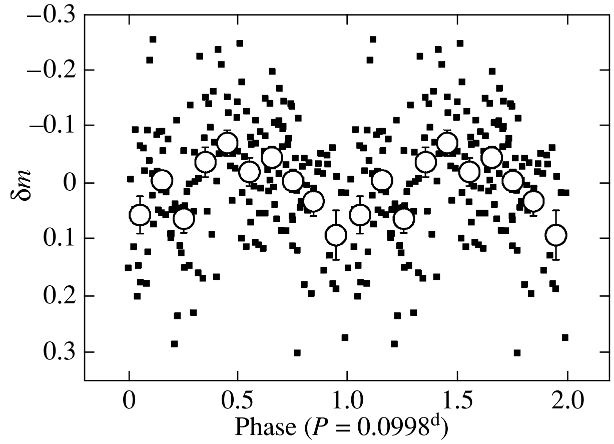

Fig. 9. Phased light curve for the 0.09982-day period (squares). The open circles with bars are the mean values with their rms errors for each of ten phase intervals of the period.

dominate at this phase of the outburst activity. After subtracting a periodic wave with this period, we again plotted the periodogram, which exhibited an appreciable peak indicating the presence of a weak signal at a period of 0.0998(2) days and the corresponding one-day-alias peaks (Fig. 8). The phased curve plotted for this period using the ephemeris

$$\text{HJD Max} = 2455006.4213 + 0.09982E, \quad (4)$$

is a single-peaked wave with a mean amplitude of 0.1^m, formally exceeding the rms uncertainty by a factor of 3.9 (Fig. 9).

Can this be the orbital period? If this is the case, we find for the combination of the orbital period, $P_{orb} = 0.0998$ days, and the mean positive-superhump period, $P_{sh} = 0.105$ days, that $\epsilon = (P_{sh} - P_{orb})/P_{orb} = 0.05$. This value is in excellent agreement with the empirical $\epsilon - P_{orb}$ relation (presented, for example, in [27]). Despite the satisfactory significance of the period and its consistency with the $\epsilon - P_{orb}$ criterion, further observations are needed to confirm the correctness of this hypothesis.

9. DISCUSSION

According to our observations, the period of the positive superhumps during the superoutburst of MN Dra in 2009 decreased at a rate of -24.5×10^{-5} of the period per period. This is a large negative derivative for a superhump period among known SU UMa stars. However, an even larger period derivative was reported for an earlier superoutburst in 2002: $-165.9(17.7) \times 10^{-5}$ [19]. Kato et al. [20] quote a lower value for MN Dra (-10^{-4}). Though our estimate of the rate of change of the superhump period is not based on a complete superoutburst, it agrees with the other determinations listed above.

After the 2009 superoutburst, the O–C residuals varied towards both negative and positive values, displaying the strongest variations during the brightness decline of the first normal outburst and during the second outburst.

Beginning with the minimum preceding the third outburst, the O–C residuals, and hence the period, were constant for five nights during the minimum brightness state and the outburst itself. What is the nature of the shorter constant period, $P_2 = 0.095982$ days? This is too short to be the orbital period. With the mean superhump period $P_{sh} = 0.104885$ days [19], the corresponding value $\epsilon = (P_{sh} - P_{orb})/P_{orb} = 0.093$ is far from the empirical $\epsilon - P_{orb}$ relation. On the other hand, it may be that the true period is not this P_2 period, but the less significant one-day alias, $P_x = 1/(1/P_2 - 1) = 0.10617$ days. However, it is considerably longer than the mean superhump period and is still much longer than the late period of the superhumps if we take into account their evolution. We believe that P_2 is the period of negative superhumps, due to the nodal precession of an accretion disk inclined to the orbital plane. From the behavior of the O–C residuals, we conclude that MN Dra exhibited a multi-periodic process with varying contributions of the individual periods in 2009, during the first half of its supercycle. In the superoutburst, the main contributor to the variations was the apsidal precession of the disk, resulting in the 0.105-day period. However, the period that dominated towards the end of the first half of the supercycle was the negative-superhump period, 0.096 days. Several periodic processes could simultaneously act immediately after the end of the superoutburst, during at least ~100 cycles, judging from the large scatter of the O–C residuals.

10. CONCLUSIONS

We have reported the results of our study of the behavior of the SU UMa dwarf nova MN Dra based on extensive photometry acquired in May–June 2009. Two kinds of brightness variations were present at different phases of the system's outburst activity.

1. Towards the end of the superoutburst, we revealed positive superhumps whose period (0.105 days) and period derivative (-24.5×10^{-5}) agree with earlier results for other superoutbursts.

2. During the quiescent (minimum) state and during normal outbursts of MN Dra, we detected brightness variations with a period of 0.096 days. We believe that these are negative superhumps due to nodal precession of an oblique accretion disk. Their amplitude is much larger in the brightness minimum (0.8^m–1.5^m) than during outbursts (0.1^m–0.2^m).

Our conclusions are important for studies of dwarf novae and for correct interpretation of observations of such systems.

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