Curious Variables Experiment (CURVE).
RZ LMi - the most active SU UMa star.

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Abstract

We report extensive photometry of the frequently outbursting dwarf nova RZ Leo Minoris. During two seasons of observations we detected 12 superoutbursts and 7 normal outbursts. The $V$ magnitude of the star varied in range from 16.5 to 13.9 mag. The superoutbursts occur quite regularly flashing every 19.07(4) days and lasting slightly over 10 days. The average interval between two successive normal outbursts is 4.027(3) days. The mean superhump period observed during the superoutbursts is $P_{sh} = 0.059396(4)$ days (85.530±0.006 min). The period of the superhumps was constant except for one superoutburst when it increased with a rate of $\dot{P}/P_{sh} = 7.6(1.9) \cdot 10^{-5}$. Our observations indicate that RZ LMi goes into long intervals of showing permanent superhumps which are observed both in superoutbursts and quiescence. This may indicate that decoupling of thermal and tidal instabilities play important role in ER UMa systems. No periodic light variations which can be connected with orbital period of the binary were seen, thus the mass ratio and evolutionary status of RZ LMi are still unknown.

Key words: Stars: individual: RZ LMi – binaries: close – novae, cataclysmic variables

1 Introduction

Dwarf novae are believed to be unmagnetized close binary systems containing white dwarf primary and low mass main sequence secondary. The secondary fills its Roche lobe and looses the material through the inner Lagrangian point. This matter forms an accretion disc around the white dwarf.

One of the most intriguing classes of dwarf novae are SU UMa stars which have short orbital periods (less than 2.5 hours) and show two types of outbursts: normal outbursts and superoutbursts.
Superoutbursts are typically about one magnitude brighter than normal outbursts, occur about ten times less frequently and display characteristic tooth-shape light modulations i.e. so called superhumps (see Warner 1995 for review).

The behavior of SU UMa stars in now quite well understood within the frame of the thermal-tidal instability model (see Osaki 1996 for review). Superhumps occur at a period slightly longer than the orbital period of the binary system. They are most probably the result of accretion disk precession caused by gravitational perturbations from the secondary. These perturbations are most effective when disk particles moving in eccentric orbits enter the 3:1 resonance. Then the superhump period is simply the beat period between orbital and precession rate periods. Although in the last decades significant progress has been made in explaining the behaviour of dwarf novae light curves, some physical processes ongoing in these systems are still not fully understood (see for example Smak 2000, Schreiber and Lasota 2007).

In the beginning of 90ties of XX century, SU UMa stars were believed to be quite uniform group of variables with common properties. These objects went into superoutburst every year or so and between two successive superoutbursts showed \( \sim 10 \) ordinary outbursts. However, there were some exceptions like WZ Sge, which show infrequent and large amplitude superoutburst followed by the period of quiescence with no single eruption lasting even 30 years.

In 1995 astronomical community was alerted about the presence of stars characterized by complete opposite behavior. First, Misslet and Shafter (1995) reported observations of PG 0943+521 (later called ER UMa), which allowed to detect superhumps with period of 0.0656 days and include this object into the SU UMa group of variables. The most intriguing feature of the long term light curve of ER UMa was very short interval between two successive superoutbursts (so called supercycle) reaching only 44 days. This value was about three times shorter than shortest previously known supercycles. This work was quickly followed by paper of Robertson et al. (1995), who confirmed all findings of Misslet and Shafter (1995) and precisely determined the value of supercycle of ER UMa to be equal to 42.95 days. Moreover, they found two more objects with similar properties - V1159 Ori with supercycle of 44.5 days and RZ LMi with supercycle as short as 18.87 days! In the same year Nogami et al. (1995) published paper which confirmed extremely short supercycle of RZ LMi and showing that it belongs to SU UMa variables exhibiting clear superhumps with period of 0.05946 days.

One year later the number of these unusual variables increased to four objects. Kato et al. (1996) reported the discovery that DI UMa has a supercycle of 25 days and shows clear superhumps with period of 0.0555 days.

The fifth ER UMa-type variable - IX Dra - was discovered by Ishioka et al. (2001). Their observations revealed a supercycle length of 53 days and an interval between normal outbursts of 3-4 days. Olech et al. (2004) determined precisely both superhump and orbital periods of the binary and estimated the supercycle length to 54 days.

The basic properties of five known up-today members of ER UMa group are summarized in Table 1.

It is clear that ER UMa stars consist a group of variables with common properties such as extremely short supercycles, small amplitudes of eruptions and relatively long superoutbursts lasting even longer than half of the supercycle. However, the period excess \( \varepsilon \) defined as \( P_{sh}/P_{orb} - 1 \), which is connected with mass ratio by the following relation:

\[
\varepsilon \approx \frac{0.23q}{1 + 0.27q}
\]
Table 1: Basic properties of ER UMa variables. $P_{\text{orb}}$ and $P_{\text{sh}}$ denote orbital and superhump periods, $\epsilon$ is a period excess, $T_s$ and $T_n$ are supercycle and cycle periods, $T_{\text{sup}}$ is duration of the superoutburst, $A_{\text{sup}}$ and $A_n$ are amplitudes of superoutburst and normal outburst.

| Star       | $P_{\text{orb}}$ [days] | $P_{\text{sh}}$ [days] | $\epsilon$ [%] | $T_s$ [days] | $T_n$ [days] | $T_{\text{sup}}$ [days] | $A_{\text{sup}}$ [mag] | $A_n$ [mag] | Ref     |
|------------|--------------------------|-------------------------|-----------------|--------------|--------------|--------------------------|------------------------|-------------|---------|
| RZ LMi     | ?                        | 0.05946                 | ?               | 18.9         | 3.8          | 11                       | 2.5                    | 2.0         | (1,2)   |
| DI UMa     | 0.054564                 | 0.0555                  | 1.72            | 25.0         | 5.0          | 12                       | 2.9                    | 2.1         | (3,4)   |
| ER UMa     | 0.06366                  | 0.065552                | 2.97            | 43.0         | 4.4          | 23                       | 2.6                    | 2.2         | (2,5,6) |
| V1159 Ori  | 0.062178                 | 0.064284                | 2.11            | 44.6-53.3    | 4.0          | 16                       | 2.2                    | 1.4         | (2,6,7,8)|
| IX Dra     | 0.06646                  | 0.066968                | 0.76            | 54.0         | 3.1          | 16                       | 2.2                    | 1.7         | (9,10)  |

1. Nogami et al. (1995), 2. Robertson et al. (1995), 3. Kato et al. (1996), 4. Thorstensen et al. (2002)
5. Kato et al. (2003), 6. Thorstensen et al. (1995), 7. Kato (2001), 8. Patterson et al. (1995)
9. Ishioka et al. (2001), 10. Olech et al. (2004)

suggests different evolutionary status of the particular members of ER UMa stars. For example, ER UMa and V1159 Ori seem to have normal secondaries and evolve towards the shorter orbital periods. On the other hand, DI UMa and IX Dra are much more evolved objects with sub-stellar secondaries (possibly degenerate brown dwarfs) and evolve towards the longer orbital periods (Patterson 2001, Olech et al. 2004). The question why DI UMa and IX Dra are so active, while WZ Sge stars having similar period excesses have longest supercycles, is still open.

2 RZ Leo Minoris

The variability of RZ LMi was discovered by Lipovetskij and Stepanjan (1981). Spectra obtained by Green et al. (1982) suggested that the star is dwarf nova with broad hydrogen and helium emission lines and with clear variability in $B$ filter in the range from 16.8 to 14.4 mag. Another spectrum obtained by Szkody and Howell (1992) showed H$\beta$ and H$\gamma$ absorption features and H$\alpha$ absorption with emission core, which indicated the presence of an accretion disk at high mass-transfer rate. RZ LMi was also included as a cataclysmic variable candidate in Palomar-Green Survey (Green et al. 1986) and designated as PG 0948+344.

Long term CCD photometry spanning over 2.5 years of almost continuous observations was presented by Robertson et al. (1995). The light curve in $V$ was characterized by long eruptions repeating quite regularly every 18.87 days and short eruptions occurring every 3.8 days. The brightness of the star varied from 17.0 to 14.2 mag.

Photometry made by Nogami et al. (1995) confirmed extremely short supercycle of RZ LMi and allowed to precisely determine the superhump period as equal to 0.05946(4) days.

The extreme properties of RZ LMi, its relatively high brightness, lack of precise photometry in minimum light, unknown orbital period and determination of the superhump period basing on the data from only one superoutburst encouraged us to include this object into the list of variables regularly monitored within the Curious Variables Experiment (Olech et al. 2003, 2006).
| Date          | No. of frames | Start 2453000 s | End 2453000 s | Length [hr] |
|---------------|---------------|-----------------|---------------|-------------|
| 2004 Apr 01/02| 50            | 130.00000       | 130.50000     | 0.50000     |
| 2004 Apr 02/03| 51            | 130.50000       | 131.00000     | 0.50000     |
| 2004 Apr 03/04| 52            | 131.00000       | 131.50000     | 0.50000     |
| 2004 Apr 04/05| 53            | 131.50000       | 132.00000     | 0.50000     |
| 2004 Apr 05/06| 54            | 132.00000       | 132.50000     | 0.50000     |
| 2004 Apr 06/07| 55            | 132.50000       | 133.00000     | 0.50000     |
| 2004 Apr 07/08| 56            | 133.00000       | 133.50000     | 0.50000     |
| 2004 Apr 08/09| 57            | 133.50000       | 134.00000     | 0.50000     |
| 2004 Apr 09/10| 58            | 134.00000       | 134.50000     | 0.50000     |
| 2004 Apr 10/11| 59            | 134.50000       | 135.00000     | 0.50000     |
| 2004 Apr 11/12| 60            | 135.00000       | 135.50000     | 0.50000     |
| 2004 Apr 12/13| 61            | 135.50000       | 136.00000     | 0.50000     |
| 2004 Apr 13/14| 62            | 136.00000       | 136.50000     | 0.50000     |
| 2004 Apr 14/15| 63            | 136.50000       | 137.00000     | 0.50000     |
| 2004 Apr 15/16| 64            | 137.00000       | 137.50000     | 0.50000     |
| 2004 Apr 16/17| 65            | 137.50000       | 138.00000     | 0.50000     |
| 2004 Apr 17/18| 66            | 138.00000       | 138.50000     | 0.50000     |
| 2004 Apr 18/19| 67            | 138.50000       | 139.00000     | 0.50000     |
| 2004 Apr 19/20| 68            | 139.00000       | 139.50000     | 0.50000     |
| 2004 Apr 20/21| 69            | 139.50000       | 140.00000     | 0.50000     |
| 2004 Apr 21/22| 70            | 140.00000       | 140.50000     | 0.50000     |
| 2004 Apr 22/23| 71            | 140.50000       | 141.00000     | 0.50000     |
| 2004 Apr 23/24| 72            | 141.00000       | 141.50000     | 0.50000     |
| 2004 Apr 24/25| 73            | 141.50000       | 142.00000     | 0.50000     |
| 2004 Apr 25/26| 74            | 142.00000       | 142.50000     | 0.50000     |
| 2004 Apr 26/27| 75            | 142.50000       | 143.00000     | 0.50000     |
| 2004 Apr 27/28| 76            | 143.00000       | 143.50000     | 0.50000     |
| 2004 Apr 28/29| 77            | 143.50000       | 144.00000     | 0.50000     |
| 2004 Apr 29/30| 78            | 144.00000       | 144.50000     | 0.50000     |

**TOTAL:** 655
3 Observations and Data Reduction

Observations of RZ LMi reported in present paper were obtained during 46 nights between January 22, 2004 and May 28, 2005 at the Ostrowik station of the Warsaw University Observatory and at CBA Concord at the San Francisco suburb of Concord, approximately 50 km from East of the City. The Ostrowik data were collected using the 60-cm Cassegrain telescope equipped with a Tektronics TK512CB back-illuminated CCD camera. The scale of the camera was 0.76′/pixel providing a 6.5′ × 6.5′ field of view. The full description of the telescope and camera was given by Udalski and Pych (1992).

The Ostrowik data reductions were performed using a standard procedure based on the IRAF\footnote{IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the National Science Foundation.} package and profile photometry was derived using the DAOphotII package (Stetson 1987).

The CBA data were collected using an f/4.5 73-cm reflector operated at prime focus on an English cradle mount. Images were collected with a Genesis G16 camera using a KAF1602e chip giving a field of view of 14.3′ × 9.5′. Images were reduced using AIP4WIN software (Berry & Burnell 2000).

In both sites we monitored the star in “white light” in order to be able to observe it with good precision also at minimum light of around 17 mag.

A full journal of our CCD observations of RZ LMi is given in Table 2. In total, we monitored the star for 165.5 hours and obtained 5552 exposures.

Relative unfiltered magnitudes of RZ LMi were determined as the difference between the magnitude of the variable and the intensity averaged magnitude of two nearby comparison stars. The magnitudes and colors of our comparison stars were taken from Henden and Honeycutt (1995). Transformation to Johnson \( V \) magnitudes was done using \( BVR \) photometry of the field of variable obtained on 2004 Apr 21.

The accuracy of our measurements varied between 0.004 and 0.119 mag depending on the brightness of the object and atmospheric conditions. The median value of the photometric errors was 0.012 mag.

4 General light curve

The global light curve spanning whole period of our observations is shown in Fig. 1. In total we detected 12 long eruptions and 7 short outbursts. The superoutburst are labeled by corresponding roman numbers. In quiescence the star fades to \( V \approx 16.5 \) mag and during the highest phase of superoutburst reaches 13.9 mag giving the full amplitude of variability equal to \( A \approx 2.6 \) mag. It is only slightly larger than the value of 2.5 mag determined by Robertson et al. (1995). During the brightest normal outburst the star reaches 14.4 mag.

First, from global light curve we selected only nights during which the star was in superoutburst (it means that we detected clear superhumps). Then we computed ANOVA statistics with two harmonic Fourier series (Schwarzenberg-Czerny 1996). The resulting periodogram, for the frequency range \( 0 \div 0.15 \) c/d, is shown in Fig. 2. The dominant peak is detected at frequency \( f_0 = 0.05245(10) \) c/d, which corresponds to the period of 19.07(4) days. This value is interpreted as supercycle length i.e. mean interval between two successive superoutbursts. It is in quite good agreement with value of 18.87 obtained by Robertson et al. (1995).

Next, we fitted analytical light curve to the superoutburst number V (solid line in Fig. 1), which has very good coverage, and repeated it every 19.07 days. The stability of the supercycle period
is very interesting. The analytical light curve has no problems with hitting precisely superoutbursts numbers I, II, III, VI and VII in 2004 and even superoutbursts numbers XXIV and XXVI occurring one year later.

Figure 1: The general photometric behavior of RZ LMi during our campaign. Dots and open circles correspond to our and AAVSO observations. The solid line fitted to eruption no. V is repeated every 19 days.

Figure 2: The ANOVA spectrum of RZ LMi global light curve after removing the data from quiescence and normal outbursts.

Additionally, Fig. 3 shows the light curve consisting of only superoutburst data and phased with period 19.07 days. One can clearly see that superoutburst lasts slightly over half of the supercycle i.e. over 10 days. It consists of: initial rise, which takes about 1.3 days, plateau phase with linear decrease
of brightness at rate of 0.063 mag/day and lasting 7.5 days and final decline which takes about 1.5 days.

Figure 3: The light curve of RZ LMi in superoutbursts obtained by folding the general light curve with supercycle period of 19.07 days.

Figure 4: The ANOVA spectrum of RZ LMi global light curve after removing the data from superoutbursts.

Figure 5: The light curve of RZ LMi in normal outbursts and quiescence obtained by folding the general light curve with cycle period of 4.027 days.
Now we can make opposite operation i.e. remove from the light curve all superoutbursts and leave intervals when star is in quiescence and goes into normal outbursts. Again, for the resulting light curve, we computed the ANOVA statistics and showed the result in Fig. 4. The dominant peak has a double structure with maxima at frequencies $f_1 = 0.2483(2)$ and $f_2 = 0.2509$ c/d. The phased light curve looks better for the first frequency, and we choose it as correct value. The corresponding period of 4.027(3) days is interpreted as normal cycle i.e. interval between two successive normal outbursts. The light curve phased with this period is shown in Fig. 5.

Normal outburst lasts 2.8 days and consists of quick initial rise lasting only half a day, narrow maximum and slower decline. Taking into account the fact that every supercycle we observe two normal outbursts, RZ LMi is in the quiescence only for 3 days in each supercycle.

5 Superhumps

The superhumps of RZ LMi were observed on several occasions. Fig. 6 shows data from three consecutive nights of superoutburst no. II which occurred in February 2004. Periodic, tooth-shape light variations with amplitude of 0.1-0.2 mag are clearly visible.

![Superhumps of RZ LMi from three consecutive nights of February 2004.](image)

Additionally, Fig. 7 shows global light curve of superoutburst no. V, which has the best observational coverage. The observing runs, due to the geometric conditions, are not as long as in February, but the star was observed on almost every night of the superoutburst. We were able to see the initial rise (Apr 13), the birth of superhumps before the maximum brightness (Apr 14), full amplitude variations which occurred one night later, slow evolution towards smaller amplitudes occurring during next five days of plateau phase and trace of superhumps during final decline.
5.1 ANOVA analysis

The data from each night containing superhumps were fitted with straight line or parabola. In purpose of detrending, this analytic curve was subtracted from real light curve. As a result we obtained a set of data with average brightness equal to zero and consisting only short term modulations.

For these sets we computed ANOVA statistics and showed corresponding periodograms in Fig. 8. Additionally, the frequencies and periods determined using these periodograms are summarized in Table 3.

The main frequencies detected in each superoutburst are consistent within the errors with each other and power spectrum computed for all superoutbursts returns the mean frequency $f_{sh} = 16.8363 \pm$
Table 3: Frequencies and periods of superhumps found in the periodograms computed for detrended data of six superoutbursts.

| Superoutburst | Date               | $f_{sh}$ [c/d] | $P_{sh}$ [d]   |
|---------------|--------------------|----------------|----------------|
| No. I         | 2004, Jan 29 - Feb 01 | $16.8 \pm 0.1$ | 0.0595(4)      |
| No. II        | 2004, Feb 19 - Feb 24 | $16.824 \pm 0.020$ | 0.05944(7)    |
| No. III       | 2004, Mar 10 - Mar 13 | $16.831 \pm 0.025$ | 0.05941(9)    |
| No. V         | 2004, Apr 14 - Apr 21 | $16.823 \pm 0.010$ | 0.05944(4)    |
| No. VI        | 2004, May 04 - May 12 | $16.828 \pm 0.020$ | 0.05942(7)    |
| No. XXIV      | 2005, Apr 05 - Apr 18 | $16.836 \pm 0.025$ | 0.05940(9)    |
| Mean          | 2004 - 2005         | $16.8363 \pm 0.001$ | 0.059396(4)   |

0.001, which corresponds to the period of $P_{sh} = 0.059396(4)$ days (85.530 ± 0.006 min), confirming that RZ LMi is one of the shortest period SU UMa, and particularly ER UMa, stars.

Figure 8: ANOVA power spectra for superhumps observed in six superoutbursts of RZ LMi and composite spectrum obtained from all data from supermaxima.
Table 4: Cycle number $E$, $O - C$ values and times of maxima for superhumps observed in six superoutbursts. Note that the first three superoutbursts have common $E$ numbering.

| $E$ | $HJD_{\text{max}} - 2453000$ | Error | $O - C$ | $E$ | $HJD_{\text{max}} - 2453000$ | Error | $O - C$ |
|-----|-------------------------------|-------|---------|-----|-------------------------------|-------|---------|
| 0   | 34.6080                       | 0.0040| 0.0069  | 0   | 110.3440                      | 0.0030| 0.0316  |
| 1   | 34.6640                       | 0.0050| -0.0504 | 1   | 110.4033                      | 0.0020| 0.0302  |
| 13  | 35.3820                       | 0.0020| 0.0362  | 2   | 110.4610                      | 0.0025| 0.0018  |
| 14  | 35.4372                       | 0.0025| -0.0346 | 16  | 111.2905                      | 0.0025| -0.0303 |
| 348 | 55.2830                       | 0.0035| 0.0422  | 17  | 111.3505                      | 0.0027| -0.0199 |
| 349 | 55.3418                       | 0.0025| 0.0320  | 34  | 112.3573                      | 0.0025| -0.0665 |
| 350 | 55.3992                       | 0.0030| -0.0018 | 35  | 112.4147                      | 0.0035| -0.0999 |
| 351 | 55.4592                       | 0.0020| 0.0082  | 69  | 114.4360                      | 0.0025| -0.0633 |
| 352 | 55.5198                       | 0.0025| 0.0284  | 84  | 115.3290                      | 0.0030| -0.0262 |
| 353 | 55.5745                       | 0.0020| -0.0508 | 85  | 115.3895                      | 0.0025| -0.0074 |
| 354 | 55.6390                       | 0.0030| 0.0349  | 101 | 116.3390                      | 0.0030| 0.0188  |
| 365 | 56.2900                       | 0.0030| -0.0664 | 102 | 116.4010                      | 0.0030| 0.0252  |
| 366 | 56.3500                       | 0.0023| 0.0036  | 117 | 117.2958                      | 0.0025| 0.0927  |
| 367 | 56.4065                       | 0.0025| -0.0453 | 118 | 117.3545                      | 0.0030| 0.0812  |
| 368 | 56.4680                       | 0.0030| -0.0100 | 119 | 117.4155                      | 0.0030| 0.1083  |
| 369 | 56.5300                       | 0.0025| 0.0337  | 337 | 130.3560                      | 0.0020| 0.0129  |
| 370 | 56.5870                       | 0.0030| -0.0068 | 338 | 130.4170                      | 0.0030| 0.0401  |
| 371 | 56.6465                       | 0.0025| -0.0052 | 354 | 131.3630                      | 0.0020| -0.0303 |
| 382 | 57.3000                       | 0.0030| -0.0044 | 355 | 131.4207                      | 0.0030| -0.0587 |
| 383 | 57.3600                       | 0.0030| 0.0056  | 0   | 473.7042                      | 0.0020| -0.0049 |
| 384 | 57.4200                       | 0.0025| 0.0156  | 1   | 473.7638                      | 0.0020| -0.0018 |
| 436 | 60.5060                       | 0.0035| -0.0358 | 2   | 473.8230                      | 0.0015| -0.0054 |
| 438 | 60.6235                       | 0.0035| -0.0579 | 10  | 474.3040                      | 0.0035| 0.0900  |
| 455 | 61.6340                       | 0.0035| -0.0475 | 11  | 474.3630                      | 0.0030| 0.0830  |
| 702 | 76.3160                       | 0.0035| 0.1038  | 12  | 474.4220                      | 0.0030| 0.0760  |
| 705 | 76.4910                       | 0.0035| 0.0497  | 33  | 475.6640                      | 0.0025| -0.0207 |
| 706 | 76.5450                       | 0.0020| -0.0413 | 34  | 475.7228                      | 0.0015| -0.0311 |
| 719 | 77.3210                       | 0.0025| 0.0216  | 35  | 475.7825                      | 0.0025| -0.0263 |
| 720 | 77.3830                       | 0.0030| 0.0653  | 36  | 475.8440                      | 0.0020| 0.0088  |
| 721 | 77.4410                       | 0.0025| 0.0417  | 50  | 476.6750                      | 0.0025| -0.0052 |
| 722 | 77.4965                       | 0.0030| -0.0241 | 51  | 476.7325                      | 0.0030| -0.0374 |
| 737 | 78.3905                       | 0.0030| 0.0252  | 52  | 476.9724                      | 0.0027| -0.0293 |
| 738 | 78.4485                       | 0.0020| 0.0016  | 53  | 476.8515                      | 0.0022| -0.0346 |
| 739 | 78.5032                       | 0.0023| -0.0776 | 84  | 478.6983                      | 0.0030| 0.0478  |
|     |                               |       |         | 85  | 478.7580                      | 0.0030| 0.0525  |
|     |                               |       |         | 86  | 478.8160                      | 0.0030| 0.0287  |
5.2 The $O - C$ analysis

In the light curve of RZ LMi from all superoutbursts we detected 70 maxima of superhumps. Their times are listed in Table 4 together with the errors, cycle number $E$ and $O - C$ values computed according to the ephemeris which will be described further.

The $O - C$ values from first three superoutbursts shows no signs of significant trend indicating that the period of superhumps was roughly constant.

There are observational evidences that ER UMa stars shows ordinary superhumps also in quiescence indicating that in these systems the disk is elliptical and tidally unstable all the time. It might suggest that the star should remember the phase of the superhumps from one superoutburst to another. The $O - C$ data from our superoutbursts number I, II and III seem to confirm this hypothesis. They can be fitted with common linear ephemeris in the form:

$$\text{HJD}_{\text{max}} = 2453034.6076(10) + 0.059405(2) \cdot E$$  \hspace{1cm} (2)

The corresponding $O - C$ diagram is shown in Fig. 9.

![Figure 9: The $O - C$ diagram for superhumps maxima of RZ LMi detected during its superoutbursts number I, II and III. Black dots correspond to possible late superhumps described in Sect. 6.](image)

Moreover, the detrended light curve containing superhumps from all superoutbursts might be phased with one period and shows no traces of phase shifts between superhumps from different superoutburst. Such a light curve is plotted in Fig. 10.

![Figure 10: Detrended light curve of RZ LMi containing superhumps from all superoutbursts.](image)

Something strange happened to RZ LMi during superoutburst number IV. We detected then a clear eruption, which has properties of superoutburst i.e. is brighter that ordinary outburst and shows
Figure 10: The detrended light curve from data collected during all superoutbursts observed in 2004 folded on superhump period.

decline typical for plateau phase but during two nights of this bright state we have not detected any superhumps.

The superoutburst no. V occurred in right time but with slightly different behaviour of superhumps. Their maxima can be fitted with following linear ephemeris:

$$HJD_{\text{max}} = 2453110.3408(11) + 0.059414(15) \cdot E$$  \hspace{1cm} (3)

but from the $O-C$ values computed according to this ephemeris and shown in Table 4 and in Fig. 11 it is evident that the period of superhumps was quickly increasing. Thus the moments of maxima can be fitted with the following parabola:

$$HJD_{\text{max}} = 2453110.3436(13) + 0.059152(65) \cdot E + 2.27(55) \cdot 10^{-6} \cdot E$$  \hspace{1cm} (4)

indicating that the period was increasing with the rate of $\dot{P}/P_{\text{sh}} = 7.6(1.9) \cdot 10^{-5}$. Such a period derivative is typical for SU UMa stars with superhump periods of around 0.06 days (for example see Fig. 5 in Rutkowski et al. 2007).

![Figure 11](image1.png)

Figure 11: The $O-C$ diagram for superhumps maxima of RZ LMi detected during its superoutburst number V.

There are insufficient number of data to investigate possible period changes during superoutburst no. VI, thus the corresponding moments of maxima were fitted only with the linear ephemeris:
Figure 12: The $O-C$ diagram for superhumps maxima of RZ LMi detected during its superoutburst number XXIV.

$$HJD_{\text{max}} = 2453130.3566(17) + 0.05918(14) \cdot E$$

There was only one superoutburst with sufficient amount of data for $O-C$ analysis in 2005 season. It was superoutburst no. XXIV and its maxima can be fitted with the following linear ephemeris:

$$HJD_{\text{max}} = 2453473.7045(9) + 0.059416(21) \cdot E$$

However, the data collected in Table 4 and shown in Fig. 12 might suggest slight increasing trend with rate of $\dot{P}/P_{sh} = 4.5(2.5) \cdot 10^{-5}$. On the other hand, the error of this determination is large, and within $2\sigma$ it is consistent with constant value of period.

6 Quiescence and normal outbursts

As we wrote earlier RZ LMi is so active that it is difficult to find it in quiescence. However, on three occasions, we collected sufficient amount of data to make the analysis of behaviour of the star in minimum light and in ordinary outbursts.

Figure 13: Sample light curves of RZ LMi from quiescence.

The first interval of data comes from 2004, Mar 17-22 when we observed RZ LMi on four nights of minimum light and one night of the normal outburst. Sample light curves from these period are shown in Fig. 13 and display clear and periodic light variations of amplitude around 0.3-0.4 mag. Taking into account that these data were collected just after the final decline of superoutburst no. III, one can suspect that we observe so called late superhumps - the phenomenon occurring at the end
of superoutburst with period roughly equal to period of ordinary superhumps but with phase shift reaching up to 0.5 cycle. $O-C$ diagram from Fig. 9 shows the moments of the maxima observed on 2004 Mar 17 as black dots suggesting that they are shifted in phase by about 0.3 cycle i.e. significantly less than typical value of 0.5 cycle.

Figure 14: ANOVA power spectra for three long runs covering the quiescence and normal outbursts.

To find a period of these variations, we first transformed our light curves to the intensity units, next we detrended them removing long scale behaviour. The resulting ANOVA periodogram is shown in upper panel of Fig. 14. The highest peak occurs at frequency $f_0 = 16.778 \pm 0.02$ c/d corresponding to the period of 0.05960(7) days. This is only 0.3% longer than mean superhump period and the two periods differ by the value which is about three times larger that the error of the period determination. It is also possible that true value of frequency appears as 1-day alias at $f_0 = 17.778 \pm 0.02$ c/d corresponding to the period of 0.05625(7) days which is significantly shorter than superhump period and might be also shorter than unknown orbital period of the system. In this case this period might be assumed as period of negative superhumps. However, it is known that negative superhump, orbital and positive superhump periods correlate with each other (Retter et al. 2002, Olech et al. 2007). This correlation indicates that the orbital period should be around 0.0574 days and superhump period excess $\epsilon$ should be as large as 3.5% i.e. about three times too high for star with such a superhump period.

Thus the final conclusion is that in quiescence RZ LMi showed modulations with period roughly equal to superhump period and indicating that in this interval the disc could be still eccentric and precessing.

Two other long intervals when the star was observed in quiescence occurred on 2005, Feb 07 - 11 and 2005, Mar 19 - Apr 06. From two lower periodograms shown in Fig. 14 it is clear that no periodic modulations were observed at that time.
7 Discussion

7.1 Evolutionary status of RZ LMi

From our Table 1 summarizing main properties of ER UMa stars, it is clear that these objects have many common properties but may be divided into two subgroups probably with different evolutionary status. Fig. 15, repeated after Patterson (1998, 2001) and Olech et al. (2004), shows correlation between period excess (i.e. mass ratio) and orbital period of the system. The solid line shows the evolutionary track of a dwarf nova with a white dwarf of mass $0.75 \, M_\odot$ and secondary component with effective radius 6% larger than that of single main sequence star. The nova evolves towards the shorter periods first due to the magnetic braking, next due to the emission of gravitational waves. After reaching the period minimum, the secondary becomes degenerate brown dwarf and system starts to increase its orbital period.

![Figure 15](image.jpg)

Figure 15: The relation between the period excess and orbital period of the system. The solid line corresponds to the evolutionary track of a binary with a white dwarf of $0.75 \, M_\odot$ and a secondary with effective radius 6% larger than in the case of an ordinary main sequence star. Calculations were made under the assumption that below the orbital period of two hours the angular momentum loss in only due to gravitational radiation. Triangles denote the positions of ER UMa and V1159 Ori.

It seems that DI UMa and IX Dra (both belonging to ER UMa stars) are such evolved period bouncers, which in fact should be similar to old and inactive WZ Sge stars (WZ Sge, AL Com and EG Cnc showed in the plot). On the other hand, ER UMa and V1159 Ori, shown as filled triangles, seem to be much younger objects still evolving towards shorter periods.

Where is the place of RZ LMi? It is difficult to answer this question without knowledge about the orbital period of the system. Our photometric data showed no other short term modulations than these corresponding to the ordinary superhumps. It would be very tempting to make the spectroscopic
observations of the star in quiescence. With minimum brightness of 16.5 mag it can be done with 2-3-meter class telescope.

7.2 Stability of the supercycle

The comprehensive analysis of the global light curve of RZ LMi made by Robertson et al. (1995) and based on almost three years observing period showed that supercycle of RZ LMi is not stable. Their $O-C$ diagram for supermaxima was characterized by clear decreasing trend with $\dot{P} = -1.7 \cdot 10^{-3}$. However graph shows also occasional jumps where particular superoutburst occur even 5 days before or after the predicted moment. If this decreasing trend would continue to the epoch of our observations the supercycle should be then around 18.5 days, which is in disagreement with determined value of 19.07 days.

Our global light curve spans only two seasons and has no enough data to construct reliable $O-C$ diagram for supermaxima. However, quick look at Fig. 1, could draw some valuable conclusions. In 2004 the 19-day periodicity is preserved through all superoutbursts except eruption number IV. In this case, we, in fact, are not certain whether we deal with superoutburst which occurred slightly before predicted moment or exceptionaly bright normal outburst lasting longer than usual. Vicinity of eruption number IV is also the time when disk could loose its eccentricity, expel the matter via this long outburst and rebuilt eccentricity again in superoutburst no. V.

Data from 2005 seem to confirm stability of 19-day supercycle. The superoutburst no. XXIV, which has the best observational coverage, occurs at right time according to 19-day ephemeris. The problem is with superoutburst no. XXIII, where instead of supermaximum we noted two ordinary outbursts. Our light curve, however, does not exclude possibility that supermaximum occurred a few days earlier according to the ephemeris.

Mass transfer from the secondary to the disk, building the eccentricity, ignition of the outbursts and superoutbursts due to the thermal and tidal instabilities are stochastic processes, which are far for regularity. The question is why RZ LMi is so regular? Even if we observe some shifts in time of the start of particular supermaximum, the clock returns to stability without shift of the phase of whole pattern. This is hard to explain from the point of view of standard thermal-tidal instability model and might need some help from, for example, external force. The present number of known SU UMa systems reached the level for which the statistics tells us that some of these close binaries might be orbited by a third body. Is this in case of RZ LMi? We do not know. But the hypothesis that 19-day period is the orbital period of the third body (or some kind resonant value) and cause of both the stability of supercycle and high activity of the star, which without this body would be quiet WZ Sge object, is tempting.

7.3 Permanent superhumper?

The standard thermal-tidal instability model is unable to produce supercycles shorter that 40 days. Activity of the ordinary SU UMa variable can be increased by increasing a mass transfer rate. But when it reaches $\dot{M} \approx 3 \cdot 10^{16}$ g/s the supercycle starts to lengthen again due to the fact that superoutburst lasts longer. Further increasing of mass transfer causes transition of the star to the group of permanent superhumpers which are in permanent state of supermaximum and show infinite value of supercycle.

Osaki (1995) tried to explain properties of RZ LMi by artificial ending the superoutburst at the moment, when the disk had shrunk from $0.46a$ to only $0.42a$, whereas a typical value used for ordinary SU UMa stars is $0.35a$. 

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Hellier (2001) suggested that the source of the premature end of superoutburst might be a cooling wave propagating from the region outside $0.46a$ causing transition of the disk to the cold state when still eccentric. This decoupling of tidal and thermal stability brings the star to the minimum light with still precessing and elliptical disk. This hypothesis is confirmed by observations of ordinary superhumps both in quiescence and normal outbursts of V1159 Ori and ER UMa (Patterson et al. 1995, Gao et al. 1999, Zhao et al. 2006).

Our observations shows that RZ LMi also shows superhumps in minimum light. Additionally, for the first time, we demonstrated that in interval covering at least 60 days (including superoutbursts numbers I, II and III) the star was showing superhumps with constant period which can be described by common ephemeris and phased without any phase shift. It indicates that decoupling could have place in this case and the disk of RZ LMi was eccentric and precessing in the entire 60-day period.

8 Summary

We have presented the results of two seasons observational campaign devoted to RZ LMi. In total we detected 12 superoutbursts and 7 normal outbursts. Our main findings may be summarized as follows:

- The $V$ brightness of the star varies in range from 16.5 to 13.9 mag. The superoutbursts occur every 19.07(4) days and last slightly over 10 days. The interval between two successive normal outbursts is 4.027(3) days.

- The mean period of superhumps observed during all superoutbursts is $P_{\text{sh}} = 0.059396(4)$ days (85.530 ± 0.006 min).

- During three consecutive superoutbursts of 2004 the superhump period was constant and the star "remembered" the phase of the superhumps from one superoutburst to another. It supports the hypothesis that ER UMa stars have accretion disks which are tidally unstable over long periods of time.

- The period of superhumps detected in superoutburst no. V was increasing with the rate of $\dot{P}/P_{\text{sh}} = 7.6(1.9) \cdot 10^{-5}$

- On one occasion we observed the ordinary superhumps in quiescence which seems to be common property of ER UMa stars.

- No periodic light variations which can be connected with orbital period of the binary were seen.

- Striking stability of 19-day supercycle of RZ LMi and high activity of the star may be caused by the presence of third body in the system.

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