Unusual Phase Reversal of Superhumps in ER Ursae Majoris

Taichi Kato
Department of Astronomy, Kyoto University, Sakyo-ku, Kyoto 606-8502
tkato@kusastro.kyoto-u.ac.jp

Daisaku Nogami
Hida Observatory, Kyoto University, Kamitakara, Gifu 506-1314
nogami@kwasan.kyoto-u.ac.jp

and

Seiji Masuda
Okayama Astrophysical Observatory, National Astronomical Observatory, Okayama 719-0232

Abstract

We studied the evolution of superhumps in the peculiar SU UMa-type dwarf nova, ER UMa. Contrary to the canonical picture of the SU UMa-type superhump phenomena, the superhumps of ER UMa show an unexpected phase reversal during the very early stage (∼5 d after the superoutburst maximum). We interpret that a sudden switch to so-called late superhumps occurs during the very early stage of a superoutburst. What had been believed to be (ordinary) superhumps during the superoutburst plateau of ER UMa were actually late superhumps. The implication of this discovery is briefly discussed.

Key words: accretion, accretion disks — stars: dwarf novae — stars: individual (ER Ursae Majoris) — stars: novae, cataclysmic variables — stars: oscillations

1. Introduction

ER UMa stars (Kato, Kunjaya 1995; Robertson et al. 1995; Misselt, Shafter 1995; Nogami et al. 1995) are a small, but a very unusual, subclass of SU UMa-type dwarf novae (cf. Osaki 1996; Warner 1995). What most distinguishes ER UMa stars from other SU UMa-type dwarf novae (hereafter we call them ordinary SU UMa stars) is the shortness (19–50 d) of their supercycles (the interval between successive superoutbursts). This gap between ER UMa stars and ordinary SU UMa stars has not been yet filled even by recent observations. From the theoretical standpoint, the outburst properties of ER UMa stars require unusually high mass-transfer rates within the framework of the disk-instability theory (Osaki 1995a; Osaki 1995b), which is hard to achieve within the standard framework of the evolution of compact binaries (e.g. Rappaport et al. 1982).

Patterson et al. (1995) was one of the first authors who questioned the distinction between ER UMa stars and ordinary SU UMa stars. Patterson et al. (1995) described that the evolution of superhumps in V1159 Ori, one of the ER UMa stars, has the same properties as in ordinary SU UMa stars. Here we present previously unnoticed, totally unexpected, time-evolution of the superhumps in ER UMa. Similar time-evolution of the superhumps has not been recorded in any ordinary SU UMa stars.

2. Observation and Analysis

The observations were performed between 1995 January 26 (the next night of the superoutburst maximum) and

Table 1. Times of superhump maxima.

| $E^*$ | BJD−2400000 | $O - C_1$ | $O - C_2$† |
|-------|-------------|-----------|-----------|
| 0     | 49744.2525  | -0.0019   | -0.0003   |
| 1     | 49744.3172  | -0.0030   | -0.0011   |
| 14    | 49745.1696  | -0.0054   | -0.0012   |
| 15    | 49745.2329  | -0.0079   | -0.0035   |
| 16    | 49745.3010  | -0.0055   | -0.0010   |
| 17    | 49745.3655  | -0.0068   | -0.0020   |
| 28    | 49746.0869  | -0.0087   | -0.0020   |
| 29    | 49746.1548  | -0.0065   | 0.0004    |
| 31    | 49746.2842  | -0.0086   | -0.0014   |
| 32    | 49746.3486  | -0.0100   | -0.0026   |
| 43    | 49747.0702  | -0.0117   | -0.0023   |
| 58    | 49748.0943  | 0.0261    | 0.0054    |
| 61    | 49748.2878  | 0.0223    | 0.0022    |
| 62    | 49748.3533  | 0.0221    | 0.0021    |
| 120   | 49752.1618  | 0.0168    | 0.0072    |
| 121   | 49752.2277  | 0.0169    | 0.0076    |
| 167   | 49755.2412  | 0.0057    | 0.0046    |
| 168   | 49755.3067  | 0.0054    | 0.0045    |
| 183   | 49756.2826  | -0.0050   | -0.0032   |
| 184   | 49756.3501  | -0.0033   | -0.0013   |
| 197   | 49757.2051  | -0.0031   | 0.0012    |
| 198   | 49757.2647  | -0.0092   | -0.0047   |
| 229   | 49759.2936  | -0.0187   | -0.0087   |

*Cycle count since BJD 49744.2525.
†$O - C$ calculated against equation 1.
‡$O - C$ calculated against equation 2.
February 10, using a CCD camera (Thomson TH 7882, 576 × 384 pixels, on-chip 2 × 2 binning adopted) attached to the Cassegrain focus of the 60 cm reflector (focal length = 4.8 m) at Ouda Station, Kyoto University (Ohtani et al. 1992). An interference filter was used which had been designed to reproduce the Johnson V band. The frames were analyzed as in the same manner described in Kato, Kunjaya (1995) and Kato et al. (1996). The differential magnitudes were measured against GSC 3439.1211, which was commonly used in Kato, Kunjaya (1995) and Kato et al. (1996).

We first removed the linear decline trend (superoutburst plateau) from the observed magnitudes, and removed small nightly deviations from the linear decline by subtracting constants from nightly observations. Barycentric corrections to the observed times were applied before the following analysis.

3. Timing Analysis of Superhumps

We determined the maximum times of the prominent maxima from a light curve by eye. The averaged times of a few points close to the maximum were used as representatives of the maximum times. The errors of the maximum times were usually less than ∼ 0.003 d. We did not use a cross-correlation method to obtain individual maxima because of the variable superhump profiles. The resultant superhump maxima are given in table 1. The values are given to 0.0001 d in order to avoid any loss of significant digits in a later analysis. The cycle count (E) was first determined using the previously adopted superhump period (P_{SH} = 0.06566 d). The O − C’s (O − C_1 in table 1) were determined against the following linear fit to all the maxima. Figure 1 clearly shows that there is a striking O − C (corresponding to ∼ 0.5 phase) jump between E = 43 and E = 58. This complete phase reversal clearly indicates that the humps before E = 43 and those after E = 58 are essentially different in nature.

BJD(max) = 2449744.2525 + 0.065755E. \hspace{1cm} (1)

As is well known, there is a superhump-type phenomenon showing a ∼ 0.5 phase jump during the very late stage of, or shortly after a superoutburst. This phenomenon is called late superhumps (Haefner et al. 1979; Vogt 1983; van der Woerd et al. 1988; Hessman et al. 1992). By allowing a 0.5 phase jump (or phase reversal) between E = 43 and E = 58, the O − C variation (O − C_2 in table 1) becomes continuous (figure 2). The linear fit is represented by the following formula.

BJD(max) = 2449744.2528 + 0.065575E_1. \hspace{1cm} (2)

where E_1 = E for E ≤ 43 and E_1 = E + 0.5 for E ≥ 58.

These results indicate that the humps with E ≥ 58 can be best interpreted as late superhumps (we phenomenologically use this terminology purely based on the phase jump). In contrast to the usual evolution of superhumps in SU UMa-type dwarf novae (Vogt 1980; Warner 1985), ordinary superhumps in ER UMa last only for a short time just following the superoutburst maximum and late superhumps predominate during the most period of the superoutburst plateau.

In order to show this transition more clearly, we first determined the true superhump period using the maximum times with E ≤ 43. The observed maximum times can be well expressed by a linear ephemeris (equation 3). A parabolic fit only yielded a negligible quadratic term of 1.4 ± 0.4 × 10^{-6} d cycle^{-1} (for a comparison, a fit to E ≥ 58 yields −2.3 ± 0.5 × 10^{-6} d cycle^{-1}). A PDM analysis (Stellingwerf 1978) of the corresponding light curve yielded a period of 0.065582(56) d (figure 3). We thus adopted P_{SH} = 0.06556(2) d. Figure 4 shows nightly averaged hump profiles folded by this P_{SH}. Ordinary superhumps (around phase ∼ 0) prominently appeared only on the first four nights (until Δt = 5 d since the start of the superoutburst). After then, late superhumps (phase around ∼ 0.5) appeared, and the late superhumps were the predominant signal during the most part of the superout-
burst plateau.

\[ \text{BJD}(\text{max}) = 2449744.2517(3) + 0.065552(25)E. \quad (3) \]

4. Discussion

Since such an early interchange between ordinary superhumps and late superhumps is quite unexpected in any known SU UMa-type dwarf novae, we first inspected the time-evolution of the superhumps during other superoutbursts of ER UMa. Figure 5 shows the time evolution of the humps during the 1994 December superoutburst (the data are from Kato et al. 1996). The time-evolution of the hump profiles followed the same course as in the 1995 January–February superoutburst. Although the earliest stage of the superoutburst was not observed, the 1994 January superoutburst (Kato, Kunjaya 1995) followed the same course after \( \Delta t = 7 \) d. Thus, what had been believed to be (ordinary) superhumps during the superoutburst plateau of ER UMa were actually late superhumps. What were observed as a rapidly decaying giant superhumps at the very early stage of a superoutburst (Kato et al. 1996) were ordinary superhumps. These independent observations confirmed that the evolution of the superhumps seen during the 1995 January–February superoutburst is a feature common to different superoutbursts.

Late superhumps in ordinary SU UMa stars usually appear late in their superoutbursts. This is consistent with the widely believed interpretation that late superhumps originate from a region close to the stream-impact point (hot spot), whose luminosity periodically varies due to a varying release of the potential energy on an eccentric disk (Vogt 1983). A significant contribution to the light variation from the hot spot requires a condition that the luminosity of the accretion disk is comparable to that of the hot spot. Generally observed “late” appearance of late superhumps in ordinary SU UMa stars is consistent with this picture in that the late superhumps become predominant only when the luminosity of the accretion disk drastically decays during the late stage of a superoutburst.

However, such a condition is difficult to meet during the fully outbursting state, in which the release of the potential energy in the disk is \( 10^{\sim} \) times larger than at the hot spot (see e.g. Osaki 1974). The (phenomenological) late superhumps in ER UMa should therefore have a different physical origin than in ordinary SU UMa stars, unless the energy release at the hot spot is dramatically enhanced. From a viewpoint of the disk-instability model (Osaki 1989), a long duration of a superoutburst is maintained by a snow-plowing effect caused by the tidal instability. Since it is widely believed that the ordinary superhumps are the manifestation of the increased tidal dissipation, a co-existence of a long-lasting plateau phase and an early decay of the ordinary superhumps looks like a contradiction. We consider that the increased tidal dissipation continues even after the initial \( \Delta t \leq 5 \) d phase, and the location of the strongest tidal dissipation moves...
Fig. 5. Nightly averaged hump profiles during the 1994 December superoutburst. BJD 2449696 corresponds to the maximum ($\Delta t = 0$ d) of the superoutburst. After $\Delta t = 5$ d, the ordinary superhumps disappeared and late superhumps appeared. The time-evolution of the hump profiles followed the same course as in the 1995 January–February superoutburst.

We conclude that the superhump evolution in ER UMa is by no means typical for an SU UMa-type dwarf nova, in contrast to the previous supposition.

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