Discovery of Negative Superhumps during a Superoutburst of January 2011 in ER Ursae Majoris

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Abstract

We report on a discovery of "negative" superhumps during the 2011 January superoutburst of ER UMa. During the superoutburst which started on 2011 January 16, we detected negative superhumps having a period of 0.062242(9) d, shorter than the orbital period by 2.2%. No evidence of positive superhumps was detected during this observation. This finding indicates that the disk exhibited retrograde precession during this superoutburst, contrary to all other known cases of superoutbursts. The duration of this superoutburst was shorter than those of ordinary superoutbursts and the intervals of normal outbursts were longer than ordinary ones. We suggest a possibility that such unusual outburst properties are likely a result of the disk tilt, which is supposed to be a cause of negative superhumps: the tilted disk could prevent the disk from being filled with materials in the outmost region which is supposed to be responsible for long-duration superoutbursts in ER UMa-type dwarf novae. The discovery signifies the importance of the classical prograde precession in sustaining long-duration superoutbursts. Furthermore, the presence of pronounced negative superhumps in this system with a high mass-transfer rate favors the hypothesis that hydrodynamical lift is the cause of the disk tilt.

Key words: accretion disks — stars: dwarf novae — stars: individual (ER UMa) — stars: cataclysmic variables

1. Introduction

SU UMa-type dwarf nova is a subgroup of dwarf novae (For reviews, Warner 1995) and characterized by the presence of long-lasting, bright outbursts called superoutbursts, in addition to ordinary dwarf-nova outbursts. During these superoutbursts, variations with periods a few percents longer than the orbital period, called positive (ordinary) superhumps, are ubiquitously observed, and are considered as the defining characteristics of SU UMa-type dwarf novae (Vogt 1980).

The cause of this phenomenon is widely believed to be a dynamical prograde precession of the elongated disk, which is believed to be formed by a the tidally driven eccentric instability of the disk excited by the 3:1 resonance to the orbital motion of the secondary (Whitehurst 1988). This tidal instability at the radius of the 3:1 resonance is generally considered to enable the disk to expand than in ordinary outbursts to produce long, bright superoutbursts (Osaki 1989).

This picture naturally explains the phenomenon that positive superhumps with period longer than the orbital period are always observed during superoutbursts, and the presence of positive superhumps is a logical consequence of this picture. Indeed, not a single definite exception against the ubiquitous presence of positive superhumps
during superoutbursts has been reported in the nearly 40 yrs history since the discovery of positive superhumps. On the other hand, superhumps shorter than the orbital periods (negative superhumps) are also reported (Udalski 1988; Harvey et al. 1995; Ringwald et al. 2012).

Unlike positive superhumps, negative superhumps are exclusively detected in the hot, thermally stable disk in novalike CVs, and during quiescence and some normal outbursts in a small number of dwarf novae including SU-UMa type dwarf novae (Patterson et al. 1995; Gao et al. 1999; Pavlenko et al. 2010). Negative superhumps are detected in V344 Lyr except during the superoutburst (Still et al. 2010, Wood et al. 2011. As to negative superhumps in superoutburst stage, a few cases have been reported (Patterson et al. 1995, Cannizzo et al. 2012, ) but otherwise yet not recorded during superoutbursts.

The origin of negative superhumps has not been well-understood. They are usually considered as a result of some kind of retrograde precession in the accretion disk. There are several suggestions that the torque by the secondary on the tilted or warped disk produces a retrograde precession. Especially Montgomery (2009) suggested that this retrograde precession in the disk is due to the same tidal force as the Moon on the retrogradely processing Earth. However, the mechanisms for producing a tilt or a warp are still controversial (Wood et al. 2000; Murray et al. 2002).

ER UMa is a member of SU UMa-type dwarf novae, whose intervals of superoutburst (supercycle) are very short (Kato, Kunjaya 1995). This object is known as the prototype of a subgroup, “ER UMa type” among SU-UMa type stars (e.g. Robertson et al. 1995; for a review see Kato et al. 1999). In terms of the presence of positive superhumps during superoutbursts, ER UMa shares common properties with other SU UMa-type dwarf novae (Kato et al. 2003), although peculiar aspects of its behavior have been reported (Kato et al. 1996; Kato et al. 2003). Although Gao et al. (1999) and Kjurkchlieva, Marchev (2010) suggested on the presence of negative superhumps during quiescence and a normal outburst, only positive superhumps were observed during the following superoutburst.

In this Letter, we report on the discovery of “negative” superhumps during the 2011 January superoutburst of ER UMa.

2. Observations and Result

ER UMa underwent an outburst on 2011 January 16, and this outburst lasted for 12 days (fig 1). Since this duration is far longer than those (2-3 days) of ordinary (normal) outbursts of the same object, and we identified this outburst as a superoutburst and conducted a world-wide wide-band photometric campaign with CCD cameras equipped on 23.5 – 40cm telescopes distributed on the globe. The log of observations and instruments will be listed in forthcoming paper. We performed dark subtractions and flat-fielding and measured the differential magnitude against other stars using standard aperture photometry.

The overall light curve of the superoutburst is shown in upper panel of fig 2. Throughout these observations, large-amplitude variations up to 0.6 mag were recorded (fig 2).

We performed a period analysis with the Phase Dispersion Minimization (PDM) method after zero-point adjustments between different observers and the conversion to Barycentric Julian Date (BJD) and subtraction of the global trends of the outburst (interval BJD 2455581 - 89.5). This analysis yielded a unique period of 0.06226 d, safely excluding any possibilities of either the orbital period (0.06366 d, Thorstensen et al. 1997) or positive superhumps (0.06549 – 0.06573 d, Kato, Kunjaya 1995). The 99% confidence limit of this period was determined (0.0622804 $^{+0.00006} _{-0.00005}$ d) by modeling the data using the Markov-Chain Monte Carlo (MCMC) method and the averaged profile of variations (Kato et al. 2010). These analysis clearly demonstrates the presence of a periodicity shorter than the orbital period by 2.2%. There was no clear indication of positive superhumps evolving during this superoutburst, contrary to all existing observations of superoutbursts. The possibility that positive superhumps remained so weakly as not to appear in these period analysis.

The times of maxima of negative superhumps were determined by numerically fitting the light curve with the template mean superhump profile for ER UMa obtained during this observation (Kato et al. 2009). A linear regression to these times yielded the following equation as the ephemeris of the superhump maxima:

\[ BJD(\text{max}) = 2455581.4540(11) + 0.062242(9) \times E \]  

where E is the number of periodic cycles.

The $O-C$ diagram using this equation is shown in fig 2.

Negative superhumps did not disappear even after the termination of the superoutburst, in contrast to usual decay of positive superhumps. The $O-C$ diagram indicates that the signals up to the next superoutburst were essentially negative superhumps, with small systematic drifts in the period (fig 2). Negative superhumps were also seen during four successive normal outbursts and quiescence between normal outbursts. Negative superhumps finally disappeared when the next superoutburst started on 2011 March 3 and showed a smooth transition to ordinary superhumps without a phase shift, when the amplitude of negative superhumps got very small temporally (fig 3).

Negative superhumps had been detected almost constantly although negative superhumps were not observed clearly in the early phase of superoutburst. The behavior in longer-time scale will be described in the future paper.

3. Discussion

The origin of negative superhumps has not been well-understood. There is one attempt to explain the light modulations, observed as negative superhumps, by considering the periodic variations of luminosity of the stream
impact point (hot spot) on a tilted disk (Wood, Burke 2007). If the disk is tilted, the stream can hit the outer edge of the accretion disk only twice in per orbit, and the stream can impact the inner portion of the disk at other times, and the cyclically variable gravitational energy release produces negative superhumps. This picture has an advantage in explaining that negative superhumps are observed with high amplitudes in quiescence of dwarf novae, when the luminosity of the hot spot dominates. (Wood et al. 2009) implied that negative superhumps were detected even in the case that mass transfer shut off. However, in this paper, this phenomenon occurs when the mass ratio is rather large \((q \geq 0.30)\) and the mass ratio of ER UMa system is not so large. Thus this effect will not be discussed in this paper. While the amplitudes of negative superhumps during the present outburst reached 0.1–0.2 mag even in full outburst, a previous marginal detection of negative superhumps during the rising stage of the same object reported only 0.07 mag (Gao et al. 1999). The amplitude of negative superhumps in the present superoutburst is thus far larger, and this amplitude is also far larger than the amplitude of negative superhumps reproduced by the numerical simulation (Montgomery 2012). This suggests that the present negative superhumps were more excited than that in Gao et al. (1999). As suggested in Montgomery 2009, this may be the change of the angle of tilt.

The fact that negative superhumps were detected in the superoutburst stage implies that another view. There is an argument that the slow growth rate of the dynamical tilt instability requires sufficient time to grow, enabling them only observable in long-lasting stable states as in novalike CVs (Osaki 1995a). The present phenomenon would alternately implies that negative superhumps can grow in much shorter time-scales under rapidly variable conditions. There may be a mechanism in exciting negative superhumps other than a dynamical tilt instability, and the mechanism may be related to the one exciting positive superhumps. This view is also supported by the case of V1504 Cyg, where negative superhumps were excited in failed superoutburst (Kato et al. 2012).

It is noteworthy that the duration of the present superoutburst is significantly shorter (≈12 days) than those (≈20 days) in usual superoutbursts of the same object. It is less likely this difference was caused by a dramatic change in the global mass-transfer rate since the interval (44 days) between the successive three superoutbursts, which occurred on 2010 December 3, 2011 January 26, March 3, exactly matches the general supercycle, where the supercycle is generally considered as a good measure of the global mass-transfer rate (Osaki 1989).

It has been suggested that particularly long-lasting superoutbursts in ER UMa and related systems are a result of an exceptionally large mass-transfer rate from the secondary to the outer edge of the accretion disk (Osaki 1995a). Assuming a tilted disk, the mass supply is prone to the inner portion of the accretion disk, and the supply to the outer edge is expected to be insufficient to achieve this condition. The insufficient mass supply to the outer edge could naturally leads to an early quenching of the superoutburst, or prevents the excitation of the ordinary 3:1 tidal resonance as observed in the present outburst. Although there have been arguments whether long-lasting superoutbursts are sustained by the 3:1 tidal resonance or by the irradiation-induced enhanced mass-transfer, our present observations suggest that the presence of the 3:1 tidal resonance producing positive superhumps is more essential to maintaining long-duration superoutbursts.

Although the mechanisms to cause tilt are still unclear, Montgomery, Martin (2010) recently proposed that hydrodynamic lift as the common source of disk tilts, and indicated that there is a minimum mass-transfer rate to generate tilts. The exceptionally high mass-transfer rates in ER UMa and related systems (Osaki 1996) may provide a favorable condition in continuously exciting tilts even in various states, and this very condition might explain unusual properties recorded in these objects (Kato et al. 2003; Osaki 1995b). The same high-mass-transfer rate and potentially resultant triggered tilts also universally explain occasional low frequencies of normal outbursts, reported in dwarf novae exhibiting negative superhumps(Kato et al. 2002a; Kato et al. 2002b) and may be related to suggested early quenching of superoutbursts in some extreme dwarf novae(Osaki 1995b; Hellier 2001). The present discovery appears to be consistent with the prediction by Montgomery (2010) who suggested that negative superhumps might appear in some high-dotM dwarf novae in outburst, including SU UMa stars and ER UMa.

The interval of outbursts between the two superoutbursts is ≈7 d, which is longer than one reported in Robertson et al. (1995) (4 d). This reduced number of outbursts also supports the interpretation suppressing of normal outbursts.

The present discovery of negative superhumps in an unprecedented condition implies that the tilted or warped disk can be easily excited in more universal conditions. Tilted disks and precessing jets are universally, and in various scales, seen or proposed in a variety of astrophysical objects and jet systems, such as SS 433, X-ray binaries (ex: Pringle 1996; Montgomery, Martin 2010). Some of mechanisms suggested in these objects require the strong radiation field or the magnetism of the central object, which does not apply to the present non-magnetic dwarf nova. This unexpected discovery is expected to contribute to generally understanding the physics of various fields of accretion disks.

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References

Cannizzo, J. K., Smale, A. P., Wood, M. A., Still, M. D., & Howell, S. B. 2012, ApJ, 747, 117
Gao, W., Li, Z., Wu, X., Zhang, Z., & Li, Y. 1999, ApJL, 527, L55
Harvey, D., Skillman, D. R., Patterson, J., & Ringwald, F. A. 1995, PASP, 107, 551
Hellier, C. 2001, PASP, 113, 469
Kato, T., et al. 2009, PASJ, 61, 395
Kato, T., Ishioka, R., & Uemura, M. 2002a, PASJ, 54, 1029
Kato, T., & Kunjaya, C. 1995, PASJ, 47, 163
Kato, T., et al. 2012, PASJ, 64, 21
Kato, T., et al. 2010, PASJ, 62, 1525
Kato, T., Nogami, D., Baba, H., Masuda, S., Matsumoto, K., & Kunjaya, C. 1999, in Disk Instabilities in Close Binary Systems, ed. S. Mineshige, & J. C. Wheeler (Tokyo: Universal Academy Press), 45
Kato, T., Nogami, D., & Masuda, S. 1996, PASJ, 48, L5
Kato, T., Nogami, D., & Masuda, S. 2003, PASJ, 55, L7
Kato, T., Poyner, G., & Kinnunen, T. 2002b, MNRAS, 330, 53
Kjurkchieva, D., & Marchev, D. 2010, Publications de l’Observatoire Astronomique de Beograd, 90, 147
Montgomery, M. M. 2009, ApJ, 705, 603
Montgomery, M. M. 2010, in American Institute of Physics Conference Series, ed. K. Werner & T. Rauch Vol. 1273 of American Institute of Physics Conference Series(. pp 358–361
Montgomery, M. M. 2012, ApJL, 745, L25
Montgomery, M. M., & Martin, E. L. 2010, ApJ, 722, 989
Murray, J. R., Chakrabarty, D., Wynn, G. A., & Kramer, L. 2002, MNRAS, 335, 247
Osaki, Y. 1989, PASJ, 41, 1005
Osaki, Y. 1995a, PASJ, 47, L11
Osaki, Y. 1995b, PASJ, 47, L25
Osaki, Y. 1996, PASP, 108, 39
Patterson, J., Jablonski, F., Koen, C., O’Donoghue, D., & Skillman, D. R. 1995, PASP, 107, 1183
Pavlenko, E., et al. 2010, in American Institute of Physics Conference Series, ed. K. Werner & T. Rauch Vol. 1273 of American Institute of Physics Conference Series(. pp 320–323
Pringle, J. E. 1996, MNRAS, 281, 357
Ringwald, F. A., Velasco, K., Roveto, J. J., & Meyers, M. E. 2012, New Astron., 17, 433
Robertson, J. W., Honeycutt, R. K., & Turner, G. W. 1995, PASP, 107, 443
Still, M., Howell, S. B., Wood, M. A., Cannizzo, J. K., & Smale, A. P. 2010, ApJL, 717, L113
Thorstensen, J. R., Taylor, C. J., Becker, C. M., & Remillard, R. A. 1997, PASP, 109, 477
Udalski, A. 1988, Acta Astron., 38, 315
Vogt, N. 1980, A&A, 88, 66
Warner, B. 1995, Cataclysmic Variable Stars (Cambridge: Cambridge University Press)
Whitehurst, R. 1988, MNRAS, 232, 35
Wood, M. A., & Burke, C. J. 2007, ApJ, 661, 1042
Wood, M. A., Montgomery, M. M., & Simpson, J. C. 2000, ApJL, 535, L39
Wood, M. A., Still, M. D., Howell, S. B., Cannizzo, J. K., & Smale, A. P. 2011, ApJ, 741, 105
Fig. 1. Upper and middle panels represent the overall light curve of ER UMa superoutburst in 2011 January. The individual points represent averaged observations in 0.02-date bins. The superoutburst stage at around 12.8 mag is until BJD 2455591, and continuous about a day is the quiescence (stayed at around 15 mag.). The next normal outburst started BJD 2455591 and reached 13 mag. The inset in the upper panel is a enlarged light curve. The two lines with small ticks above the light curve are plotted at the interval of two kinds of period. The ticks on lower line represent the timings of maxima of negative superhumps, and the ticks on upper line represent expected times assuming the period of orbital humps. The individual points represent averaged observations in 0.0003-date bins. The low panel represents PDM diagram. Theta stands for the ratio of variance. The blue dashed vertical line indicates the orbital period (Thorstensen et al. 1997), and the vertical gray strip indicates the range of the periods of positive superhumps reported in earlier works (Kato, Kunjaya 1995). The left inset in the lower panel represents posterior probability density function with the Markov-Chain Monte Carlo analysis. The right one represents profile of negative superhumps phase-averaged by the period obtained by MCMC, 0.0622804 d for the interval of BJD 2455587.8 – 2455588.4. Each point represents an average of each 0.025-phase bin.

Fig. 2. The upper panel represents the overall light curve from the superoutburst of 2011 January till the next superoutburst of 2011 March. SO represents for a superoutburst and NO represents for a normal outburst. Although not observed by us, the superoutburst of January is reported to have started on BJD 2455578 (January 16). The lower panel is $O-C$ diagram in the same term. The negative superhumps had disappeared when the superoutburst of March started and showed a smooth transition to positive superhumps. As to circles without a error bar, errors are smaller than the circle radius (this applies to fig 3).

Fig. 3. The upper panel is enlarged $O-C$ diagram between BJD 245623.3 – 26.0. This diagram apparently shows that the smooth transition from negative superhumps to positive superhumps without a phase shift. The lower panel is variations of the amplitudes of superhumps. The amplitude got to smaller shortly before this transition occurred. The dotted line represents the $O-C$ variations in the case of variations with the orbital period. This represents the transition from negative superhumps to positive superhumps.