PASJ: Publ. Astron. Soc. Japan **56**, S141–S146, 2004 March 25

A Deeply Eclipsing SU UMa-Type Dwarf Nova with the Shortest Orbital Period, XZ Eridani

Makoto UEMURA, Taichi KATO, and Ryoko ISHIOKA
Department of Astronomy, Faculty of Science, Kyoto University, Sakyo-ku, Kyoto 606-8502
uemura@kusastro.kyoto-u.ac.jp
Greg BOLT
295 Camberwarra Drive, Craigie, Western Australia 6025, Australia
Lewis M. COOK
1730 Helix Court, Concord, CA 94518, USA
Berto MONARD
Bronberg Observatory, PO Box 11426, Tiegerpoort 0056, South Africa
Rod STUBBINGS
19 Greenland Drive, Drouin 3818, Victoria, Australia
Ken'ichi TORII
Cosmic Radiation Laboratory, RIKEN (Institute of Physical and Chemical Research), 2-1, Hirosawa, Wako, Saitama 351-0198
Seiichiro KIYOTA
Variable Star Observers League in Japan (VSOLJ), Center for Balcony Astrophysics, 1-401-810 Azuma, Tsukuba, Ibaraki 305-0031
Daisaku NOGAMI
Hida Observatory, Kyoto University, Kamitakara, Gifu 506-1314
Kenji TANABE
Department of Biosphere-Geosphere Systems, Faculty of Informatics, Okayama University of Science,
1-1 Ridai-cho, Okayama, Okayama 700-0005
Donn R. STARKEY
AAVSO, 2507 County Road 60, Auburn, Auburn, Indiana 46706, USA
and
Atsushi MIYASHITA
Seikei High School, 3-10-13 Kita-machi, Kichijouji, Musashino, Tokyo 180-8633

(Received 2003 June 30; accepted 2003 November 14)

Abstract

We discovered superhumps in an eclipsing dwarf nova, XZ Eridani, during an outburst in 2003 January–February. We determined the orbital and average superhump periods to be $0.061159602 \pm 0.000000044$ d and 0.062808 ± 0.000017 d, respectively. Our observations thus established that XZ Eri belongs to a rare class of deeply eclipsing SU UMa-type dwarf novae. The object has the shortest orbital period among seven known objects in this class. The superhump period decreased with time during a mid-plateau phase of the superoutburst, as observed in a number of ordinary, long-period SU UMa stars. During an early phase of the superoutburst, however, the superhump period increased, as observed in several short-period systems. XZ Eri is a unique object with which we can study the evolution of accretion-disk structures through eclipses during the phase of the superhump period increase.

Key words: accretion, accretion disks — stars: binaries: close — stars: individual (XZ Eri)

1. Introduction

SU UMa stars form a sub-class of dwarf novae characterized by orbital periods shorter than ~ 0.1 d and two types of outbursts: some are relatively short and faint, so-called normal outbursts; the others are long and bright, so-called superoutbursts. A unique feature of superoutbursts is the appearance of short-term periodic variations, called superhumps, whose period is a few percent longer than the orbital period (for a review, see e.g., Warner 1995). It is now widely believed that the superhump phenomenon is caused by the precession of a tidally-distorted accretion disk (Whitehurst 1988). According to the disk instability model, an outburst evolves to a superoutburst when an accretion disk expands over a critical radius, where a circular disk becomes tidally unstable, and then evolves to an eccentric disk (Osaki 1989).

Short-period SU UMa-type dwarf novae ($P_{\rm orb} \lesssim 0.06$ d), including WZ Sge stars, tend to experience unique phenomena during their superoutbursts, for example, a period increase of superhumps and post-outburst rebrightenings (e.g., Patterson et al. 1981; Lemm et al. 1993; Baba et al. 2000). The period increase of superhumps in short-period systems, in particular, receives much attention because long-period systems show a period decrease, an important hint of the development of the tidal instability and the evolution of the accretion disk structure (Kato et al. 2001b). The analysis of eclipses yields vital information about the evolution of the disk structure during outbursts (e.g., Horne 1985; Wood et al. 1992; Rutten et al.

1992). To date, we know of six SU UMa stars with deep eclipses; however, no eclipsing system showing the period increase of superhumps has been discovered.

XZ Eri had been a poorly studied object, which was proposed to be a probable dwarf nova (Shapley, Hughes 1935; Howell et al. 1991; Szkody, Howell 1992). Woudt and Warner (2001) revealed that XZ Eri is an eclipsing dwarf nova with an orbital period of 0.0612 d. This short period indicates that XZ Eri is a candidate for an SU UMa-type dwarf nova. A new outburst of XZ Eri was reported to the Variable Star Network (VSNET[1]) on January 27.476, 2003 (JD 2452666.976). We then started an observational campaign, which revealed that XZ Eri is a new member of a rare class of deeply eclipsing SU UMa-type dwarf novae showing a period increase of superhumps.

2. Observation

We performed time-series photometric observations of XZ Eri at 10 observatories with 30-cm class telescopes and unfiltered CCD cameras. The journal of our observations is presented in table 1. A dark-current image was subtracted from the raw CCD images, and then flat fielding was performed. For the images taken in Kyoto, the magnitude of XZ Eri was calculated with a neighbouring comparison star, GSC 5883.347, whose constancy was checked by a nearby star, GSC 5883.961. An unfiltered CCD observation for outbursting dwarf novae yielded a magnitude system close to the R_c-system, since the sensitivity peak of the camera is near to the peak of the R_c-system and the object has $B - V \sim 0$. The unfiltered-CCD magnitude scales of each observatory were adjusted to the Kyoto system, neglecting any possible small differences of the variations between the unfiltered CCD systems of each observatory.

3. Result

Figure 1 shows the whole light curve of the outburst. The abscissa and the ordinate denote the time in Heliocentric Julian Date (HJD) and the differential magnitude of XZ Eri, respectively. After detection of the outburst, the object remained in a phase characterized by a gradual fading for 10 days. The average fading rate was 0.13 mag d^{-1}, a typical value for those in the plateau phase of superoutbursts. The fading was, however, not monotonic: the object remained at almost constant brightness during JD 2452667–2452669 and experienced a rebrightening during JD 2452672–2452674. Assuming these are quasi-periodic deviations from the average fading trend, a sin-curve fitting to the residual data from the average decline yielded a period of 4.7 d and an amplitude of 0.09 mag. The object rapidly faded on JD 2452677 (figure 1) until it reached a magnitude of $\sim$ 1.5 mag brighter than the quiescent magnitude ($V \sim 19$; Woudt, Warner 2001). As observed in other short-period SU UMa stars (e.g., Kato et al. 2001b; Patterson et al. 1998), XZ Eri experienced a gradual fading phase after a superoutburst plateau lasting for at least 8 d, after which it returned to a near-quiescent level on JD 2452700.

[1] ⟨http://vsnet.kusastro.kyoto-u.ac.jp/vsnet/⟩

Table 1. Journal of observations.

T_{start} (HJD)	ΔT (hr)	T_{exp}	N	Site
2452667.9736	3.72	30	310	Kyoto
2452668.0051	2.18	60	57	Wako
2452668.0119	3.23	90	117	Craigie
2452668.8838	5.06	60	274	Wako
2452668.8940	1.03	30	92	Wako
2452668.8972	4.25	30	374	Tsukuba
2452668.8985	2.77	30	283	Okayama
2452669.0071	2.56	15	410	Okayama
2452669.0085	4.05	90	148	Craigie
2452669.2721	3.85	45	207	Bronberg
2452669.4962	5.08	60	220	Indiana
2452669.9147	4.43	60	243	Wako
2452669.9801	3.38	30	328	Kyoto
2452669.9886	2.38	30	206	Tsukuba
2452670.0098	4.04	90	149	Craigie
2452670.0712	1.53	60	60	Seikei
2452670.8965	4.90	60	199	Wako
2452670.9360	2.30	30	184	Tsukuba
2452670.9592	3.50	30	198	Kyoto
2452671.0279	3.61	90	133	Craigie
2452671.2514	4.33	45	209	Bronberg
2452671.8185	2.11	30	134	Pahala
2452671.8864	5.26	60	275	Wako
2452671.9100	0.86	30	78	Tsukuba
2452672.3208	2.09	45	101	Bronberg
2452672.7235	3.50	30	277	Pahala
2452673.2432	3.57	45	173	Bronberg
2452673.7357	2.22	30	179	Pahala
2452673.8739	4.97	60	257	Wako
2452673.9712	2.53	30	94	Kyoto
2452674.0071	3.81	90	112	Craigie
2452674.2508	3.72	45	180	Bronberg
2452674.7641	2.43	30	190	Pahala
2452674.9159	3.01	30	53	Kyoto
2452675.0084	3.63	60	191	Craigie
2452675.8258	2.00	30	169	Pahala
2452676.0050	2.98	90	107	Craigie
2452676.8817	5.02	60	273	Wako
2452676.9176	4.47	30	354	Kyoto
2452677.0164	1.64	90	61	Craigie
2452677.2343	4.29	45	259	Bronberg
2452677.7367	1.52	120	25	Pahala
2452677.9195	4.25	30	221	Kyoto
2452677.9930	2.02	30	110	Okayama
2452679.9525	2.07	60	115	Wako
2452679.9603	2.85	30	283	Okayama
2452679.9711	2.99	30	280	Kyoto
2452680.9397	3.02	30	194	Kyoto
2452683.9196	0.42	30	43	Kyoto
2452687.8921	1.30	30	126	Kyoto
2452700.9234	2.36	60	123	Hida

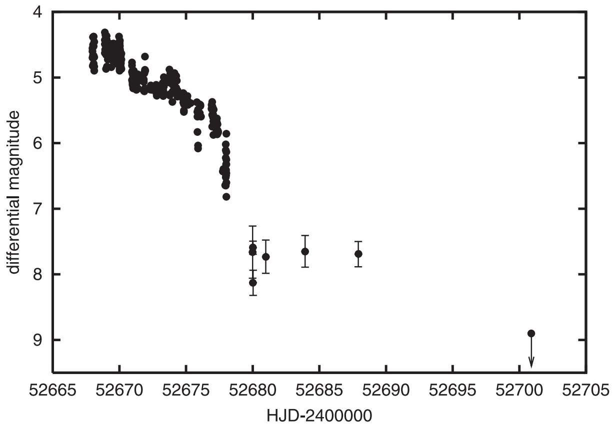

Fig. 1. Light curve of the superoutburst of XZ Eri in 2003 January–February. The abscissa and the ordinate denote the time in HJD and the magnitude, respectively. The magnitude system is a differential one relative to the comparison star, GSC 5883.347 (V = 10.61, $B-V$ = 0.95). The arrow on JD 2452700 denotes an upper limit of the magnitude.

No post-outburst rebrightening was recorded.

We detected short-term periodic variations as well as eclipses during the outburst, examples of which are shown in figure 2. Using 25 eclipses observed during the superoutburst and the mid-eclipse time reported in Woudt and Warner (2001) (HJD 2451905.4419), we derived an eclipse ephemeris for XZ Eri as follows:

$$\mathrm{HJD_{min}} = \mathrm{HJD}\ 2452668.04099(\pm 0.00011) + 0.061159602(\pm 0.000000044) \times E. \quad (1)$$

The orbital period is in agreement with that reported in Woudt and Warner (2001). The times and $O-C$s of the 25 mid-eclipses are listed in table 2. No periodic variations were detected in these $O-C$s.

After removing eclipses from the light curves, we performed a period analysis for the residual periodic variations using the light curve during JD 2452668–2452677, from which the linear fading trend and the 4.7-d modulations had been subtracted. A phase dispersion minimization analysis (PDM: Stellingwerf 1978) yielded a best period of 0.062808$\pm$0.000017 d (figure 3). The period of the variations is 2.7% longer than the orbital period. We hence conclude that they are superhumps, which

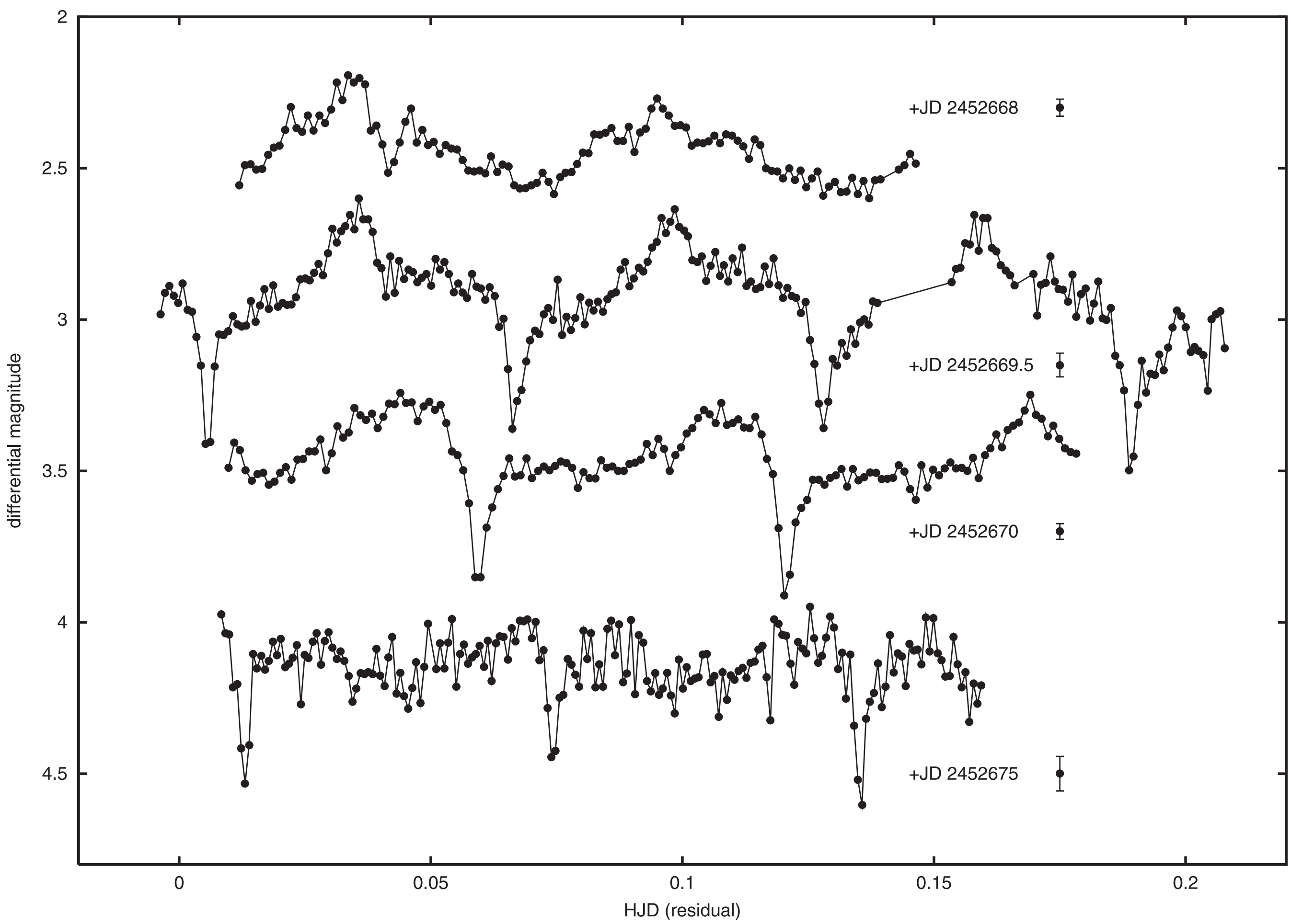

Fig. 2. Examples of time-series light curves during the superoutburst. The abscissa and the ordinate denote the time in HJD and the differential magnitude, respectively. From top to bottom, they are light curves in JD 2452668, 2452669.5, 2452670, and 2452675. The magnitude scale in JD 2452669.5 is shifted to -1.7 mag, and those in JD 2452670 and 2452675 are shifted to $+0.8$ mag. Typical errors of each point are shown at the right side of the dates.

Table 2. Times and $O - C$s of mid-eclipses.

E	$T_{\rm ecl}$	$O - C$
0	2452668.04066	−3.3
16	2452669.01932	−2.4
17	2452669.08118	4.8
18	2452669.14305	11.9
22	2452669.38708	5.8
33	2452670.05983	5.7
34	2452670.12020	−2.2
48	2452670.97707	4.1
50	2452671.09838	−5.9
51	2452671.15980	−3.3
54	2452671.34345	−1.6
62	2452671.83278	−1.1
63	2452671.89430	2.6
86	2452673.29982	−8.9
87	2452673.36251	6.3
94	2452673.79030	3.1
98	2452674.03502	3.9
102	2452674.27940	1.3
103	2452674.34023	−2.0
111	2452674.82863	−10.8
115	2452675.07393	−4.2
116	2452675.13557	0.7
128	2452675.86938	−0.4
131	2452676.05211	−7.9
132	2452676.11445	3.9

E = cycle, $T_{\rm ecl}$ = times of mid-eclipses in HJD, $O - C = O - C$ in $\times 10^{-4}$ d.

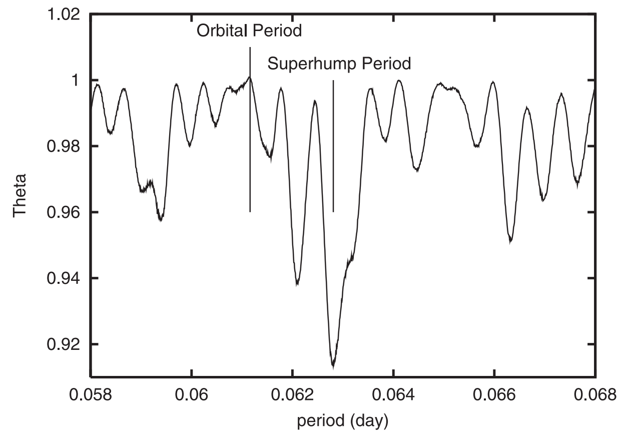

Fig. 3. Period–*Theta* diagram calculated from the data during JD 2452668–2452677. The abscissa and the ordinate denote the period in days and *Theta*, calculated the phase dispersion minimization method (Stellingwerf 1978).

established XZ Eri as being the seventh member of the deeply eclipsing SU UMa-type dwarf novae, and the one with the shortest orbital period. The physical parameters of these objects are summarized in table 3.

The superhump period excess, ε, generally provides an estimation of the mass ratio, q, of the system (Osaki 1985). Using the empirical relation ε–q in Patterson (2001), we estimate $q = 0.12 \pm 0.01$ for XZ Eri. This is a typical value for objects having similar orbital periods and an unevolved secondary star. The supercycle of XZ Eri is still uncertain. Its known outbursts in 1995 March ($V \sim 14.1$), 1998 January ($V \sim 14.6$), and 1999 February ($V \sim 14.6$) were recorded at magnitudes similar to the supermaximum in 2003 January–February, and thus may be superoutbursts. If all of these outbursts were superoutbursts, the supercycle of XZ Eri is ~ 400 d.

The top light curve in figure 2 was obtained on JD 2452668, one day after outburst detection, during which the eclipses were broad and shallow. The profile of eclipses became deeper and asymmetric on JD 2452669. The orbital phase of the superhump maxima is 0.50 on JD 2452669. The broad egress profile at the phase 0.5 has also been observed in other eclipsing system, Z Cha (Warner, O'Donoghue 1988). As shown in the lower two light curves, the eclipses then became narrow around the end of the plateau phase. A detailed analysis of the eclipse profiles is beyond the scope of this paper, and will be presented elsewhere.

Figure 4 shows the time evolution of the average superhump profiles. One day after outburst detection, the superhumps were already fully grown with broad hump-profiles and large amplitudes of 0.3 mag. During relatively rapid fading

Table 3. Physical parameters of the known eclipsing SU UMa stars.

Object name	$V_{\rm quies}$	$V_{\rm super}$	$T_{\rm super}$	$P_{\rm orb}$	$P_{\rm SH}$
Z Cha	15.3	11.9	229	0.074499	0.07740
OY Car	15.3	11.4	318	0.063121	0.064544
V2051 Oph	15.0	11.7*	227♯	0.062428	0.06423†
HT Cas	16.4	11.9‡		0.073647	0.076077
DV UMa	18.6	14.0*	970*	0.08587§	0.08867§
IY UMa	18.4*	13.0	285.5♯	0.073913	0.07588
XZ Eri	19♭	14.6	~ 400	0.061160	0.062808

$V_{\rm quies}$: magnitude at quiescence, $V_{\rm super}$: maximum magnitude during superoutburst, $T_{\rm super}$: supercycle, $P_{\rm orb}$: orbital period, and $P_{\rm SH}$: superhump period.
Data without symbols from Ritter and Kolb (2003).
* From VSNET data, † Kiyota and Kato (1998), ‡ Mattei, Kinnunen, and Hurst (1985), § Uemura et al. in preparation, ♯ Kato et al. (2001c), ♭ Woudt and Warner (2001).

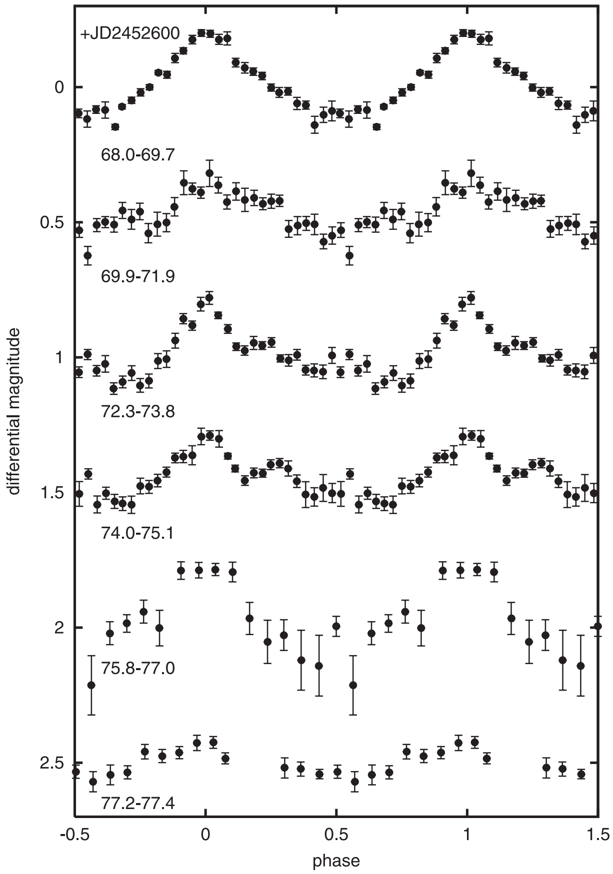

Fig. 4. Averaged profiles of superhumps. The abscissa and the ordinate denote the phase and the differential magnitude, respectively. The phase was calculated with the average superhump period of 0.062808 d. The light curves were normalized with each average magnitude, and plotted with 0.5-mag step. From top to bottom, they are averaged light curves in JD 2452668.0–2452669.7, JD 2452669.9–2452671.9, JD 2452672.3–2452673.8, JD 2452674.0–2452675.1, JD 2452675.8–2452677.0, and JD 2452677.2–2452677.4.

(JD 2452670–2452672), the superhump amplitudes decreased to 0.15 mag. After the fading trend had stopped, the superhumps grew again, with a narrower profile of the main hump. We can also see the appearance of a secondary hump after the main hump, which then developed additional substructures. Even around the end of the plateau phase, the object still exhibited 0.3-mag humps. These humps significantly decreased in amplitude at the onset of the rapid fading phase.

We calculated the $O-C$s of the superhump peaks with the average superhump period. The result is shown in figure 5. The cycle in the figure is defined with the averaged superhump period of 0.062808 d and the first cycle at HJD 2452668.9179. As can be seen from the $O-C$ diagram, the superhump period first increased, and then decreased with time, relative to the average superhump period.

The early phase (JD 2452668.0–2452669.4) is characterized by a superhump period of $P_{\mathrm{SH}} = 0.062603 \pm 0.000065$ days, shorter than the average superhump period. The superhump period must have increased before the subsequent period-decrease phase, while it is unclear whether the period increase occurred continuously during HJD 2452668–2452669

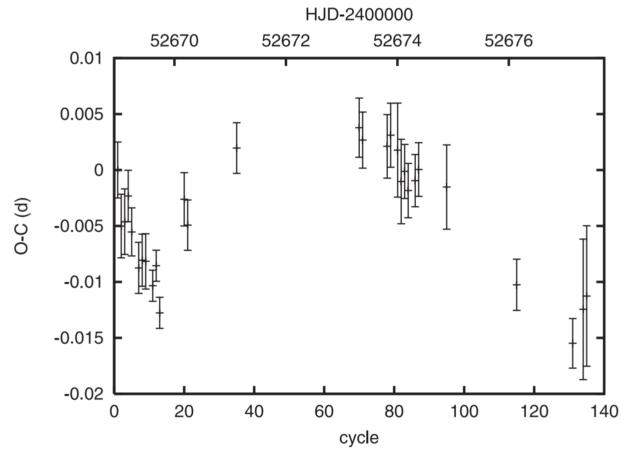

Fig. 5. $O-C$ diagram of superhumps. The abscissa and the ordinate denote the cycle and the $O-C$ in days, respectively. We show the corresponding HJD of the cycle at the upper edge. The $O-C$ values were calculated with the epoch of HJD 2452668.9179 and a period of 0.062808 d.

or rather abruptly at the end of HJD 2452669. Assuming a continuous period increase, we fitted a second-order polynomial curve to the $O-C$s and derived a lower limit of the period derivative of $P_{\mathrm{dot}} \gtrsim 1.63 \pm 0.30 \times 10^{-4}$.

After the initial period increasing phase, the superhump period began decreasing, as mentioned above. Around the transition phase between them, the superhump temporarily weakened, and then showed regrowth, as can be seen in figure 4. Figure 5 indicates that the period decreasing phase may have been terminated by a subsequent constant period phase. Assuming the period decreasing phase continued throughout the superhump plateau phase, we obtained an upper limit of the period derivative to be $P_{\mathrm{dot}} \lesssim -1.41 \pm 0.24 \times 10^{-5}$.

4. Discussion

The period decrease of superhumps is a well-known phenomenon in SU UMa-type dwarf novae, which has been proposed to be a result of decreasing apsidal motion due to a decreasing disk radius (Warner 1985; Patterson et al. 1993). On the other hand, SU UMa stars having orbital periods shorter than ~ 0.06 d tend to show a period increase of superhumps throughout the plateau phase of superoutbursts (Kato et al. 2001b). The nature of this unusual period increase is still poorly understood; on the other hand, observations exhibit that such a phase appears in systems having low mass-transfer rates (Kato et al. 2001b, 2001a).

The superhump evolution of XZ Eri is unique in that the superhump period first increased, and then decreased. Changes of the period derivative in a superoutburst plateau have also been observed in V1028 Cyg and T Leo: V1028 Cyg has a superhump period (0.06154 d) similar to that of XZ Eri (0.062808 d) (Baba et al. 2000). During its superoutburst in 1995, the superhump period first rapidly decreased in a very early phase, then temporarily increased, and finally decreased again. In the case of XZ Eri, the very early phase, corresponding to the rapid period decreasing phase in V1028 Cyg, can be overlooked in our sample. Early phase observations of superoutbursts in the future are important to study the similarity between XZ Eri and V1028 Cyg. On the other hand, the duration of the temporary period increasing phase is longer in V1028 Cyg ($\sim$ 100 cycles) than in XZ Eri ($\sim$ 20 cycles). T Leo, which has an orbital period of 0.05882 d, is another example which experienced a possible period increasing phase during an early phase (Kato 1997). The duration of its period increasing phase, however, is much shorter than that in XZ Eri (Kato 1997). In conjunction with the $P_{\rm SH}$–$P_{\rm dot}$ relationship in Kato et al. (2001b), the systems mentioned above are on the borderline between systems showing only a period increasing or decreasing phase. XZ Eri is an important object to reveal the continuous disk evolution from an increasing phase to a decreasing phase through observations of eclipses. Our analysis of the eclipses of XZ Eri will be reported in another paper.

In addition to the peculiar superhump evolution, XZ Eri has another noteworthy features, which may be atypical for short-period SU UMa stars. First, the duration of superoutburst was relatively short compared with other systems. Several short-period SU UMa stars experience superoutbursts lasting over two weeks. The duration of the superoutburst of XZ Eri was at least 10 d, and presumably shorter than 14 d, since it was reported to be fainter than 15.0 mag on JD 2452662.967 (January 23.467 UT). Second, no post-outburst activity was detected, although close monitoring was performed after the superoutburst. Finally, the 4.7-d quasi-periodic variation during the superoutburst plateau is too long to be interpreted by the beat phenomenon between the orbital and superhump periods. The 4.7-d variation may, hence, have another mechanism; however, it is interesting to note that the expected beat period is 2.33 d, which is roughly half of the observed period. Since these detailed characteristics, however, depend on distinct superoutbursts, even in the same system, follow-up observations of another superoutbursts are definitely important.

This work is partly supported by Grants-in-Aid from the Ministry of Education, Culture, Sports, Science and Technology (No. 13640239, 15037205). Part of this work is supported by a Research Fellowship of Japan Society for the Promotion of Science for Young Scientists (MU and RI).

References

Baba, H., Kato, T., Nogami, D., Hirata, R., Matsumoto, K., & Sadakane, K. 2000, PASJ, 52, 429
Horne, K. 1985, MNRAS, 213, 129
Howell, S. B., Dobrzycka, D., Szkody, P., & Kreidl, T. J. 1991, PASP, 103, 300
Kato, T. 1997, PASJ, 49, 583
Kato, T., Matsumoto, K., Nogami, D., Morikawa, K., & Kiyota, S. 2001a, PASJ, 53, 893
Kato, T., Sekine, Y., & Hirata, R. 2001b, PASJ, 53, 1191
Kato, T., Stubbings, R., Nelson, P., Pearce, A., Garradd, G., & Kiyota, S. 2001c, Inf. Bull. Variable Stars, 5159
Kiyota, S., & Kato, T. 1998, Inf. Bull. Variable Stars, 4644
Lemm, K., Patterson, J., Thomas, G., & Skillman, D. R. 1993, PASP, 105, 1120
Mattei, J. A., Kinnunen, T., & Hurst, G. 1985, IAU Circ., 4027
Osaki, Y. 1985, A&A, 144, 369
Osaki, Y. 1989, PASJ, 41, 1005
Patterson, J. 2001, PASP, 113, 736
Patterson, J., et al. 1998, PASP, 110, 1290
Patterson, J., Bond, H. E., Grauer, A. D., Shafter, A. W., & Mattei, J. A. 1993, PASP, 105, 69
Patterson, J., McGraw, J. T., Coleman, L., & Africano, J. L. 1981, ApJ, 248, 1067
Ritter, H., & Kolb, U. 2003, A&A, 404, 301
Rutten, R. G. M., Kuulkers, E., Vogt, N., & van Paradijs, J. 1992, A&A, 265, 159
Shapley, H., & Hughes, E. M. 1935, Ann. Harvard Coll. Obs., 90, 163
Stellingwerf, R. F. 1978, ApJ, 224, 953
Szkody, P., & Howell, S. B. 1992, ApJS, 78, 537
Warner, B. 1985, in Interacting Binaries, ed. P. P. Eggleton & J. E. Pringle (Dordrecht: D. Reidel Publishing Company), 367
Warner, B. 1995, Cataclysmic Variable Stars (Cambridge: Cambridge University Press)
Warner, B., & O'Donoghue, D. 1988, MNRAS, 233, 705
Whitehurst, R. 1988, MNRAS, 232, 35
Wood, J. H., Horne, K., & Vennes, S. 1992, ApJ, 385, 294
Woudt, P. A., & Warner, B. 2001, MNRAS, 328, 159