The SU UMa Nature of the Dwarf Nova, DM Lyrae

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Abstract

We carried out time-resolved V-band photometry of DM Lyr during long outbursts in 1996 July and in 1996 February-March at Ouda Station, Kyoto University and at Osaka Kyoiku University. Since superhumps were clearly detected in the light curves, DM Lyr was first identified with an SU UMa-type dwarf nova. The superhump period is 0.0673(2) d, and the superhump excess is 2.8(3) %. The duration of the superoutburst, the outburst amplitude, the decline rate in the plateau phase, and the superhump excess were typical values for a usual SU UMa star. According to visual and CCD observations reported to VSNET, this star has experienced a dramatic change of the outburst pattern from a superoutburst phase to a normal outburst phase. There may exist mechanisms to decrease the number of the normal outburst between two successive superoutbursts and to elongate the recurrence cycle of the superoutburst.

Key words: accretion, accretion disks — stars: novae, cataclysmic variables — stars: dwarf novae — stars: individual (DM Lyr)

1. Introduction

Cataclysmic variable stars (CVs) are close binary systems of a white dwarf (primary star) and a late-type main-sequence star (secondary star) filling its Roche-lobe (for a review, e.g. Warner 1995a). The surface gas of the secondary is transfered for the primary star, and an accretion disk is formed around the primary star. Some CVs quasi-periodically show sudden brightenings, namely, outbursts. This behavior is generally explained by the thermally unstable accretion disk in the disk instability model (for a review, Osaki 1996). Such CVs are called dwarf novae.

Dwarf novae are classified into three basic subclasses, which are SS Cyg stars showing (normal) outbursts, Z Cam stars showing normal outbursts and standstills, and SU UMa stars showing normal outbursts and superoutbursts (see Ch. 3 in Warner 1995a). The basic physics differentiating these three subclasses is currently understood in the scheme of the thermal-tidal disk-instability theory mentioned above. Thorough exploration to explain a variety of behavior of CVs, however, is being continued.

DM Lyr is a poorly studied dwarf nova. This star was discovered as a nova or a U Gem-type variable star by Hoffmeister (1929), who originally designated it as 250.1929. He also reported a long outburst which lasted at least 12 days. Hoffmeister (1930) gave a find-ing chart. Based on records of 6 dwarf nova-type outbursts, Petit (1960) estimated the outburst properties of DM Lyr, which were the recurrence cycle of outburst of over 100 d, and the magnitude range of 13.7–17.5:. Bruch et al. (1987), nevertheless, listed DM Lyr as an unidentified dwarf novae. Downes, Shara (1993) then correctly re-identified DM Lyr. Very recently, Thorstensen, Fenton (2003) obtained spectra having singly-peaked emission lines indicative of a low inclination, and measured the orbital period ($P_{\rm orb}$) to be 0.06546(6) d.

This object is identified with 1RXS J185845.1+301548 (Voges et al. 1999), while no counterpart is found in the 2 micron All Sky Survey (Hoard et al. 2002). The X-ray hardness ratios of the object are compatible with those of dwarf novae.

Based on the long outburst reported by Hoffmeister (1929), we had kept DM Lyr in mind as a good candidate of an SU UMa-type dwarf nova, and had watched our chance to reveal its nature. Under this situation, we started time-resolved photometry, following the VSNET[1] report of an outburst caught at 1996 July 7.040 (UT) by G. Poyner (vsnet-obs 3060) and subsequent confirmations. After this outburst, we again carried out photometric observations of DM Lyr during

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[1]   see htpp://vsnet.kusastro.kyoto-u.ac.jp/vsnet/

Table 1. Log of the observations.

	Date (UT)		N	Exposure time (s)	Mean V Mag.	Site*
1996	July	15.525 − 15.752	225	60	14.49	OS
		16.536 − 16.752	253	60	14.66	OS
		17.574 − 17.703	153	60	14.79	OS
		17.606 − 17.769	50	120	14.78	OKU
		18.584 − 18.749	46	150	14.97	OKU
		21.558 − 21.566	6	120	17.25	OS
		24.540 − 24.543	4	90	17.52	OS
		29.636 − 29.641	5	90	18.42	OS
1997	March	1.754 − 1.852	112	60	14.28	OS
		4.790 − 4.863	86	60	14.55	OS
		5.856 − 5.857	3	60	14.81	OS
		7.847 − 7.861	15	60	15.21	OS
		8.848 − 8.852	5	60	16.46	OS

* OS represents Ouda Station, and OKU represents Osaka Kyoiku University.

the outburst in 1997 February-March. Tentative results were listed in table 1 in Nogami et al. (1997). We here report the details of the observations, and discuss the nature of DM Lyr.

2. Observation

We performed the observations at the Ouda Station (OS), Kyoto University, and at Osaka Kyoiku University (OKU). At OS, a 60-cm reflector (focal length=4.8 m) and a CCD camera (Thomson TH 7882, 576 × 384 pixels) attached to the Cassegrain focus were used (for more information of the instruments, see Ohtani et al. 1992). At OKU, we used a 51-cm reflector (focal length=6.0 m) and a CCD camera (Astromed EEV 88200, 1152 × 790 pixels). The on-chip 2 × 2 binning mode was selected to reduce the read-out and saving dead time. Johnson V-band interference filters were adopted. Table 1 gives the journal of the observation.

After standard de-biasing and flat fielding, the frames obtained at OS on 1996 July 15, 16, and 17, and on 1997 March 1, 4, 5, 7, and 8 were processed by a microcomputer-based aperture photometry package, and those obtained on 1996 July 21, 24, 29 were reduced by a PSF photometry package. Both packages were developed by one of the authors (TK). There is no systematic difference larger than 0.03 mag between results by aperture photometry and those by PSF photometry. In the similar way, the OKU frames were reduced by the aperture photometry, using the IRAF package[2].

The magnitude of DM Lyr was measured, relative to the local standard star GSC 2639.2575 ($V = 12.47$ in the VSNET chart[3]) at OS and GSC 2639.2348 ($V = 12.77$ in the VSNET chart) at OKU. Then, we subtracted 0.12 mag from the OKU data to smoothly connect the OKU data
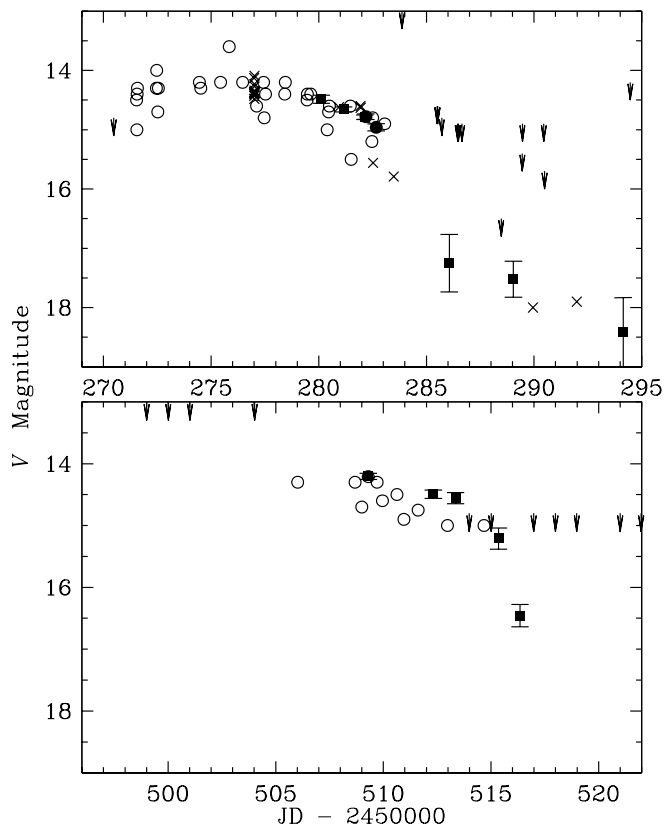

Fig. 1. Outbursts in 1996 July and 1997 February-March. The open circles and crosses are visual observations reported to VSNET and our unfiltered CCD observations (25cm Schmidt-Cassegrain telescope + ST-7), respectively. The filled squares represent our observations. The lower arrows indicate the upper limits.
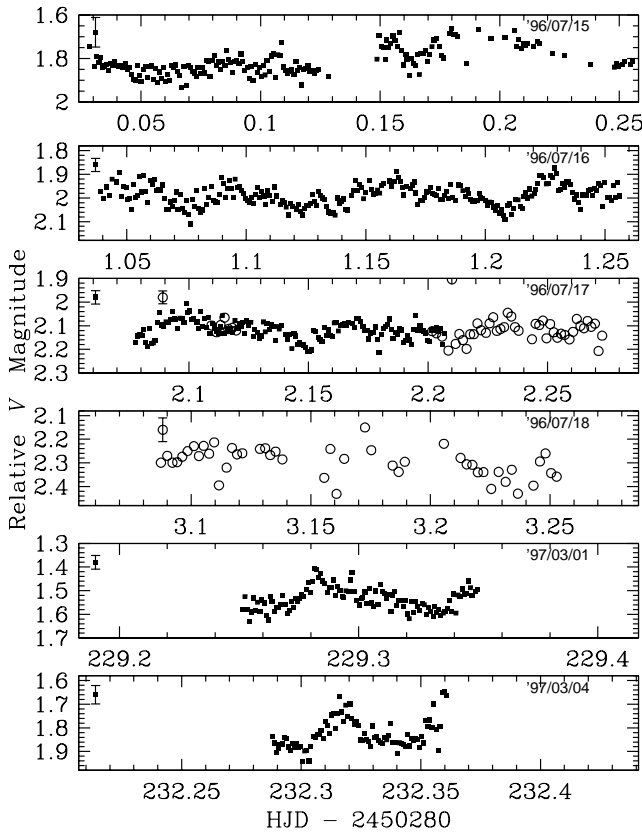
Fig. 2. Short-term light curves with long coverages. The filled squares represent the OS data, and the OKU data are denoted by the open circles. The typical 1-sigma error of each point is indicated at the upper-left corner of each panel. The magnitudes are given relative to GSC 2639.2575. Prominent superhumps are seen, indicative of the SU UMa nature of DM Lyr.

Fig. 3. (upper panel) Theta diagram of the PDM period analysis on the data during the 1996 superoutburst. The superhump period is 0.0673(2) d (= 14.85 d^{-1}). (lower panel) The average light curve of the superhumps obtained by folding the data by the period of 0.0673 d.

with the OS data. Using local comparison stars, constancy of the standard star during our runs was confirmed within 0.06 mag, and the nominal 1-σ error for each point was estimated. Heliocentric corrections to observation times were applied before the following analysis.

3. Result

The over-all light curves of the outbursts in 1996 July and 1997 February–March are shown in figure 1. The 1996 outburst was caught on July 7.040 (UT, JD 2450271.540), and lasted at least until July 19 (JD 2450283), means that the duration was 12 days or some more, followed by a gradual decline for several days after the rapid decline from the outburst. Our observations were performed in the late phase of this long outburst. The enlarged light curves of our data are depicted in figure 2. In these light curves, we succeeded in detecting the clear superhumps with an amplitude of ∼0.12 mag on 1996 July 16 and 17, although these oscillations were smeared by the relatively
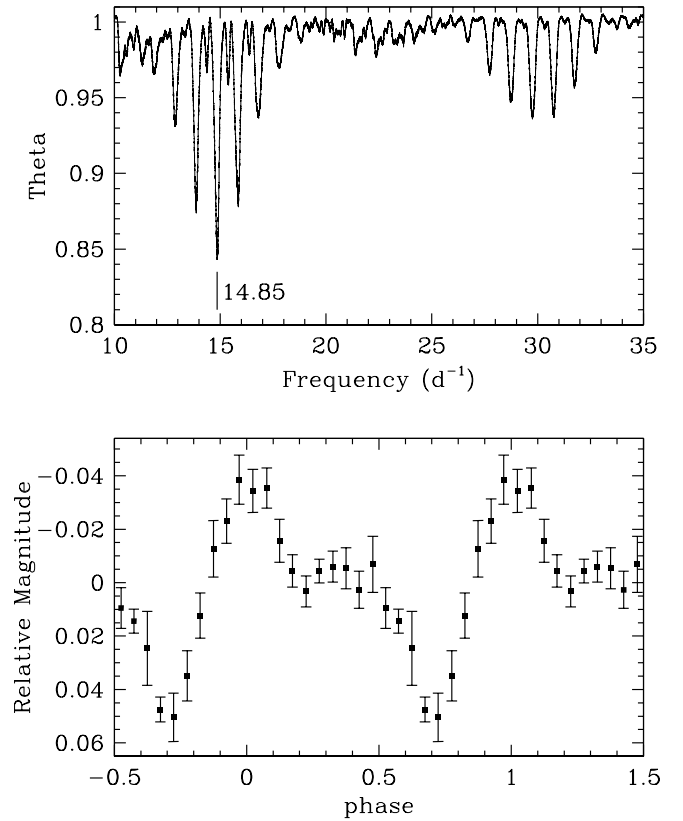
large errors on July 15 and 18. This observation revealed that DM Lyr is really an SU UMa-type dwarf nova and the current outburst is a superoutburst.

The linear decline trend between July 15 and 18 was 0.15 mag d^{-1}, which is a typical, or a little bit large value during the plateau phase in SU UMa stars. We performed a period analysis of the phase dispersion minimization (PDM) method (Stellingwerf 1978) on the data after subtraction of the decline trend. The resultant theta diagram is shown in the upper panel of figure 3. The superhump period ($P_{\rm SH}$) is securely determined to be 0.0673(2) d, and the lower panel of figure 3 exhibits the light curve folded by this period. The superhumps did not have the textbook shape of a rapid rise and a slow decline, but had a secondary maximum around the phase of 0.4. This secondary maximum may be a hint of late superhumps which grows in the very late phase of the superoutburst (Hessman et al. 1992, and references therein).

We measured the maximum timings of these superhumps by eye to check variation of the superhump period. Table 2 summarizes the results. The typical error of the timings is 0.002 d. The cycle count E is adopted to set

Table 2. The superhump-maximum timings during the 1996 superoutburst.

E	HJD*	E	HJD*
1	0.088	18	1.229
2	0.156	31	2.099
16	1.095	32	2.171
17	1.160	33	2.234

* HJD - 2450280.

$E = 1$ at the first maximum timing. The linear regression gives an equation (figure 4):

$$HJD = 2450280.0212(11) + 0.06709(5)E. \qquad (1)$$

The superhump period deduced here is in accordance with the one obtained by the PDM period analysis within the error. By fitting the deviations of the observed timings from the calculation, we obtain a quadratic polynomial:

$$O-C = 0.0003(15) - 0.7(2.0) \times 10^{-4}E + 1.9(5.8) \times 10^{-6}E^2. (2)$$

The change rate derived from the quadratic term is $\dot{P}_{\rm sh}/P_{\rm sh} = 5.7(17.2) \times 10^{-5}$, which covers the almost whole range of distribution of the $P_{\rm SH}$ change rate of SU UMa stars (see Kato et al. 2001). Consequently, the present data were not sufficient to accurately derive the change rate, and even to judge the sign of the rate.

During the 1997 outburst, we again made time resolved photometry in the late phase (figure 1). Superhumps were observed also in this outburst (figure 2), which indicates that this is the second superoutburst observed in DM Lyr, apart from the first superoutburst by $\sim$230 d. After subtracting the linear decline trend of 0.10 mag d^{-1} from the data obtained on 1997 March 1 and 4, we made a PDM period analysis. Apparent evidence of periodicity, however, was not found because of the insufficient coverages, although figure 5 shows peaks with very small significance around the superhump frequency.

We took power spectra of each-night data to search for quasi-periodic oscillations (QPOs), but no signal was detected.

4. Discussion

As noted in section 1, Thorstensen, Fenton (2003) measured the orbital period of 0.06546(6) d. The fractional superhump excess ($\epsilon = (P_{\rm SH} - P_{\rm orb})/P_{\rm orb}$) in DM Lyr is then 2.8(3) %. Generally, the superhump period decreases with the superoutburst evolving in SU UMa stars with a similar orbital period (see Kato et al. 2001), although the present data were not sufficient to derive a change of $P_{\rm SH}$. If the superhumps were observed from the earlier phase in the 1996 superoutburst, the superhump excess was expected to be a little larger. The superhump excess of 2.8 % or a little larger is, however, just on the known $P_{\rm orb}$-ϵ correlation (e.g. Patterson 1998). In this meaning, DM Lyr is a normal SU UMa-type dwarf nova.

The duration of the 1996 superoutburst was 13($\pm$1) d, while that of the 1997 superoutburst was constrained only
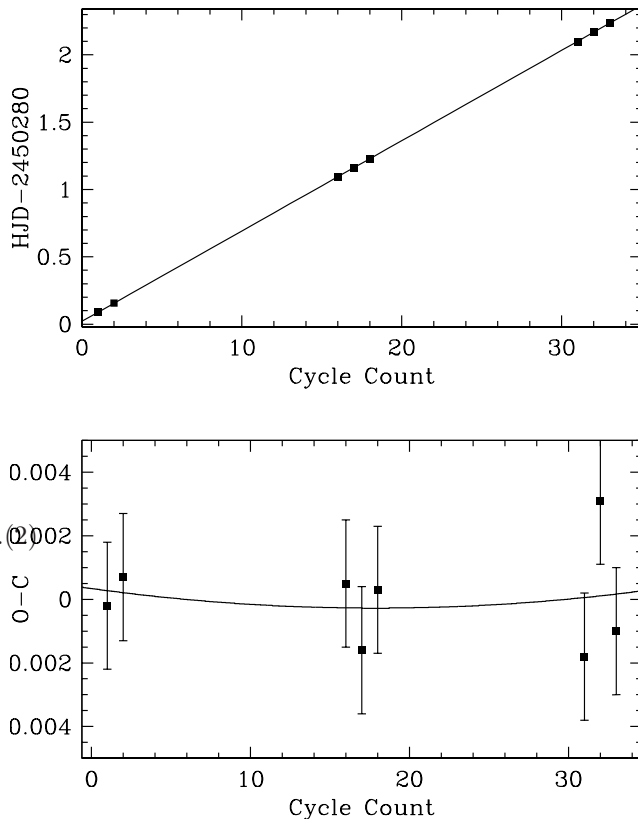

Fig. 4. (upper panel) Superhump maximum timings during the 1996 superoutburst and its linear regression (equation (1)). The error bar is hidden by the filled marks. (lower panel) $O-C$ diagram of the superhump maximum timings. The curve represents the quadratic polynomial (equation (2)) obtained by fitting the $O-C$.

as being longer than 9 days. This duration is a typical value for an SU UMa star.

The visual magnitudes reported to VSNET seems to include a rather large error (see figure 1), probably because of lack of a reliable sequence of comparison stars' magnitudes and the effect of the close companion star. The outburst amplitude is, however, estimated to be 4.3($\pm$0.5) mag in figure 1, which is supported by the fact that the General Catalog of Variable Stars (Kholopov et al. 1985) lists 13.6-18.0p as the maximum and minimum photographic magnitudes. This outburst amplitude is also a typical value for an SU UMa star.

Table 3 lists all outbursts reported to VSNET so far[4]. We can see that the first four superoutbursts almost regularly occurred with a recurrence times of 229 d, 235 d, and 275 d. These recurrence intervals are normal, or a little small values for an SU UMa star with the orbital period of $\sim$0.067 d (see Nogami et al. 1997). However, it should be pointed out that only one normal outburst was

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[4]   freely   available   via   the   VSNET   data   browser,
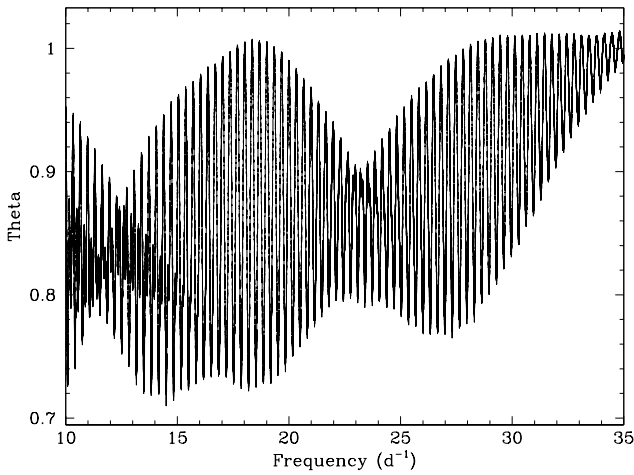   http://vsnet.kusastro.kyoto-u.ac.jp/vsnet/etc/searchobs.html

Fig. 5. Theta diagram of the PDM period analysis on the data during the 1997 superoutburst. Due to the short coverages in conjunction with the relatively large errors, clear periodicity could not be detected.

Table 3. Previous outbursts.

	Date*		V_{max}	D†	Type‡	Comment
1995	Nov.	20	13.9	>8	S	
1996	Jul.	07	13.6	>12	S	
1996	Oct.	15	15.2:	1?	N?	Single Obs.
1997	Feb.	26	14.2	>10	S	
1997	May	25	14.9	1?	N	
1997	Nov.	29	14.1	>7	S	
1998	Mar.	10	14.8	<3	N	
1998	Jul.	13	14.5	3	N	
1998	Aug.	26	15.8	1?	N	
1998	Nov.	09	15.2:	1?	N?	Single Obs.
1998	Dec.	08	15.0	2?	N	
1999	Aug.	20	15.5	<2	N	Single Obs.
1999	Sep.	28	14.5	2	N	
2000	May	24	15.7	1?	N?	Single Obs.
2000	Jun.	27	15.5:	1?	N?	
2000	Jul.	11	14.1	>8	S	
2000	Aug.	25	15.5	1?	N	
2001	Jul.	4	15.1:	1?	N?	Single Obs.
2001	Aug.	1	15.7:	1?	N?	Single Obs.
2001	Aug.	15	16.0:	1?	N?	Single Obs.
2001	Sep.	4	14.5	2?	N	
2002	Feb.	16	16.0:	1?	N?	Single obs.
2002	May	11	15.1	3?	N	
2002	Jun.	3	15.7:	1?	N?	Single obs.
2002	Jul.	14	15.5	2	N	
2002	Aug.	15	14.8	3?	N	
2002	Sep.	8	15.5	1?	N	Single obs.

* The discovery date.
$\dagger$ Duration of the outburst in a unit of day.
$\ddagger$ N: normal outburst, S: superoutburst

caught during this period. Warner (1995b) derived a correlation between the mean recurrence cycles for normal outbursts (T_n) and for superoutbursts (supercycle, T_s). This correlation expects $T_n \sim 46$ d for $T_s = 250$ d.

In contrast, since 1997 November, only one superoutburst in 2000 August was caught for about 5 years. Instead, many normal outbursts were repeatedly found with intervals of 14-238 days. DM Lyr has been rather closely monitored these years, except in winter when DM Lyr is not observable. Therefore, it is unlikely that many superoutbursts have been missed. If we assume T_s to be ~950 d, which is the period between the 1997 November superoutburst and the 2000 July superoutburst, no normal outburst is expected according to the T_n-T_s relation mentioned above, like WZ Sge-type stars or related objects (see Kato et al. 2001). Although normal outbursts may have more easily escaped from the eye because of the faintness and the short duration (table 3), the frequency of the normal outburst clearly changed between until 1997 and since 1998. This change was coincident with the transition between the *high/low states* regarding superoutburst. In other words, DM Lyr has two states: 1) the superoutburst phase when the superoutburst happens with a supercycle of ~250 d, but DM Lyr experience few normal outbursts, and 2) the normal-outburst phase when the normal outbursts occurs with a recurrence cycle of a few tens-a few hundreds of days, but the supercycle is ~1000 d. DM Lyr sharply showed the transition between these two states.

The disk instability theory predicts that both of T_n and T_s are tightly related to the mass transfer rate from the secondary star ($\dot{M}$). In case of normal SU UMa stars, T_n and T_s is expected to be roughly proportional to $\dot{M}^{-2}$ and $\dot{M}$, respectively (see section 5.4 in Osaki 1996). Decrease of the mass transfer rate is thus predicted to lead to in-

crease of both T_n and T_s and to decrease of the number of the normal outburst during one supercycle. This trend well agrees with the empirical T_n-T_s relation, although other parameters, such as, the orbital period, masses of the components, and so on, are neglected in this qualitative discussion. The phase transition from the superoutburst phase to the normal outburst phase in DM Lyr presented here completely opposes this theoretical and empirical relation in that increase of the supercycle is accompanied with increase of the number of the normal outburst in one T_s.

Changes of the outburst patterns in SU UMa stars have been reported in recent years, e.g. in DI UMa (Fried et al. 1999), SU UMa (Rosenzweig et al. 2000; Kato 2002), V1113 Cyg (Kato 2001), and V503 Cyg (Kato et al. 2002). The behavior of V503 Cyg among these is closest to the present case. Kato et al. (2002) reported the dramatic decrease of the number of the normal outburst in one T_s, and proposed existence of a mechanism to decrease or even quench the normal outburst. The most important difference between the behavior of V503 Cyg and that of DM Lyr is constancy of T_s. T_s in V503 Cyg has been almost

constant, regardless of decrease of the number of the normal outburst between two successive superoutbursts. In DM Lyr, however, T_s became longer at the same time when normal outbursts came to arise with shorter T_n of a few tens-a few hundreds of days.

Since the set of T_s in the superoutburst phase and T_n in the normal outburst phase almost satisfies the empirical T_n-T_s, the mass transfer rate may be constant also in DM Lyr, and a mechanism to decrease the number of the normal outburst had worked during the superoutburst phase. Then, a mechanism to elongate T_s might start working in the normal outburst phase. To check the stability of the mass transfer rate, it is important to measure the quiescence magnitude and the amplitude of the orbital hump during the current normal outburst phase. In addition, closer monitoring is needed to confirm the existence of the future superoutburst phase and to avoid to miss normal outbursts then. In SU UMa, Kato (2002) reported their superhump detection during a faint outburst (or a minor brightening) which arose in an anomalously outbursting state, and proposed that an long-lasting, tidally unstable state following the preceding superoutburst may suppress normal outbursts. We should try to make the monitoring going as deep as possible and to start photometric observations soon on finding a brightening. DM Lyr may be a key object to lead to find a new mechanism to control the state of the accretion disk.

DM Lyr in the superoutburst phase seems a perfect twin of another peculiar SU UMa-type dwarf nova, V844 Her. This object show superoutbursts with T_s of 220-290 d, but no normal outburst has been caught (see Kato, Uemura 2000, and visual observations available via the VSNET data browser)[5]. The differences between DM Lyr and V844 Her are that the outburst amplitude of V844 Her ($\sim$5.7 mag) is larger than that of DM Lyr, and that the orbital period of V844 Her is near the period minimum ($P_{\rm orb}$= 0.054643(7) d, Thorstensen et al. 2002). V844 Her will possibly change the outburst pattern in future like DM Lyr, and deserves intensive watch.

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[5] Very recently, the first-ever normal outburst was caught in 2002 October 23-25 (see vsnet-campaign-dn 2933)