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A newly discovered SU UMa-type dwarf nova, HS 1449+6415

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Abstract. We report time-resolved photometric observations of the Hamburg Quasar Survey-selected dwarf nova HS 1449+6415 (= RX J1450.5+6403) during the interval from JD 2451672 to 2451724. During a long outburst with a duration of ∼12 days, we detected superhumps with a period of $0^{\rm d}.0601(5)$, revealing that this star is an SU UMa star. A short outburst which lasted 3 days was found about 40 days after the onset of the superoutburst. From quiescence observations, we determine an orbital period of $0^{\rm d}.05898(2)$. The small outburst amplitude of ∼3.5 mag, the short orbital period, and the normal outburst cycle length suggest that HS 1449+6415 is an intermediate object between ER UMa stars with high mass-transfer rates and WZ Sge stars with very low mass-transfer rates.

Key words: accretion, accretion disks – surveys – stars: novae, cataclysmic variables – stars: oscillations – stars: individual: HS 1449+6415

1. Introduction

Dwarf novae are a sub-class of the cataclysmic variable stars (CVs), which show quasi-periodic outbursts (for a review, see Warner 1995). SU UMa-type dwarf novae show two types of outbursts, namely normal outbursts, and so-called superoutbursts. Normal outbursts (typically 2–4 mag) last 3–5 days, and superoutbursts (0.5–1.0 mag brighter than normal outbursts) last about 3–4 times longer than normal outbursts. Between two successive superoutbursts, 3–10 normal outbursts occur. This behavior is now well explained in the thermal-tidal disk instability model (e.g. Osaki 1996): a normal outburst is caused by a thermal limit-cycle based on the strong dependence of the hydrogen opacity on the ionization state. in the accretion disk. When the disk has enough mass to extend itself radially to the critical tidal radius at the maximum of a normal outburst, efficient removal of angular momentum due to tidal stress induced by the secondary maintains the disk longer in the hot state (superoutburst). The tidal effects force the accretion disk into a slowly precessing eccentric form. The beat phenomenon of this disk precession and the orbital motion yields photometric variations with a period slightly longer than the orbital period $P_{\rm orb}$ (e.g. Whitehurst 1988, 1994). Such oscillations called superhumps are observed only during superoutbursts.

Some SU UMa-type systems with short orbital periods (∼ 80–90 min) show various patterns of the outburst and the superhump evolution which are not easily explained in the current disk instability scheme, such as stars of the WZ Sge-subclass (see e.g. Nogami 1998) and the ER UMa-subclass (see e.g. Kato et al. 1998). Although several models have been proposed to explain their outburst behaviors, especially that of WZ Sge stars, a common understanding has not yet been reached. This is partly because there are few observations of dwarf novae just before a superoutburst, owing to the difficulty of predicting a superoutburst.

In this Paper, we report photometric observations of HS 1449+6415 (= RX J1450.5+6403), which has been identified as a CV candidate by Bade et al. (1998) based on its emission-line spectrum in the Hamburg Quasar Survey (HQS, Hagen et al. 1995) and on the X-ray emission in the ROSAT All Sky Survey. The CV nature of HS 1449+6415 has been onfirmed by spectroscopic observations (Jiang et al. 2000). The HQS has lead to discoveries of some interesting dwarf novae, for instance, the eclipsing stars EX Dra (= HS 1804+6753, Fiedler et al. 1997, and references therein) and HS 0907+1902 (Gänsicke et al. 2000). HS 1449+6415 is also identified with USNO–A2.0 1500–05846206: r_mag = 16.3, b_mag = 15.8; $\alpha = 14^{\rm h}\ 50^{\rm m}\ 38^{\rm s}.3$, $\delta = +64^\circ\ 03'\ 29''$ (J2000.0). Skiff (2000) pointed out another identification as FBS 1449+642, a blue stellar object found in the First Byurakan Spectral Sky Survey (Abrahamian & Mickaelian 1994).

2. Observations and results

In order to measure the orbital period, we carried out time-resolved photometry of HS 1449+6415 using a standard John-

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Table 1. Observation log.

Coverage HJD−2450000	Int. time (s)	Number of observations	Filter	Average, RMS mag	State	Observatory[1]
1672.394–1672.437	60	46	V	17.3($\pm$ 0.2)	quiescence	CA
1675.437–1675.668	60	145	V	17.5($\pm$ 0.2)	quiescence	CA
1676.604–1676.661	60	19	V	17.6($\pm$ 0.3)	quiescence	CA
1680.344–1680.603	50	407	$R_{\rm c}$	14.2($\pm$ 0.1)	superoutburst	NC
1687.320–1687.466	120	87	$R_{\rm c}$	15.1($\pm$ 0.1)	superoutburst	CR
1691.351–1691.460	250	33	$R_{\rm c}$	16.6($\pm$ 0.1)	decline	CR
1716.366–1716.429	180	26	$R_{\rm c}$	17.3($\pm$ 0.2)	quiescence	CR
1719.364–1719.467	180	45	no filter	17.4[2]($\pm$ 0.2)	quiescence	CR
1720.308–1720.453	180	58	no filter	17.5[2]($\pm$ 0.2)	quiescence	CR
1721.295–1721.457	90	112	$R_{\rm c}$	15.2($\pm$ 0.1)	normal outburst	CR
1722.299–1722.433	120	31	$R_{\rm c}$	15.7($\pm$ 0.1)	normal outburst	CR
1724.298–1724.355	120	28	$R_{\rm c}$	16.8($\pm$ 0.2)	normal outburst	CR

[1]CA = Calar Alto 1.23m, NC = Nicholas Copernicus Observatory 40cm, CR = Crimean Astrophysical Observatory 38cm
[2]These magnitudes are deduced using the $R_{\rm c}$ magnitude of the comparison star.

son V filter and a TEK CCD attached at the Cassegrain focus of the 1.23-m telescope at the Calar Alto Observatory (CA) on 2000 May 7, 10, and 11, when the star was in quiescence. The exposure time was 60 sec, and the dead time between exposures was 12 sec, adopting the fast read-out mode and limiting the read-out region on the CCD. The journal of our observations is shown in Table 1.

The first outburst of this star was reported to the VSNET by Vanmunster (2000a), three days after our CA observations. We immediately started a photometric run at the Nicholas Copernicus Observatory (NC) on 2000 May 15. The NC data were obtained through a Kron-Cousins $R_{\rm c}$-band filter with an SBIG ST-7 camera and a 40cm Newtonian telescope. The exposure time and the dead time were 50 s and typically 5 sec, respectively.

At the Crimean Astrophysical Observatory (CR), we then monitored the behavior of HS 1449+6415 during the late stages of the long outburst. The CR observations were carried out using a 38-cm Cassegrain telescope with an SBIG ST-7 camera and with a Kron-Cousins $R_{\rm c}$ or no filter, depending on the atmospheric condition and the brightness of the target. The exposure time was also varied between 90 s and 250 s. This outburst proved to be in the final decline during the second run at CR, implying that the outburst lasted ∼12 days.

After the standard reduction of the frames, we measured the magnitudes of the variable using either an aperture photometry routine in MIDAS (CA data), the CCD photometry package Munidos (http://ian.cz/munipack), which is based on DAOPHOT (Stetson 1987) (NC data), or an aperture photometry package developed by V. P. Goransky (CR data).

To calibrate the magnitudes, we used the local comparison star ‘C’ (= USNO–A2.0 1500–05845729; Fig. 1), whose photometric properties were given by Henden (2000)[1] as V = 13.151(17), $B-V$ = 0.701(5), and $V-R_{\rm c}$ = 0.384(9). Constancy of the comparison star within 0.02 mag during our run was checked using stars ‘C1’ and ‘C2’.

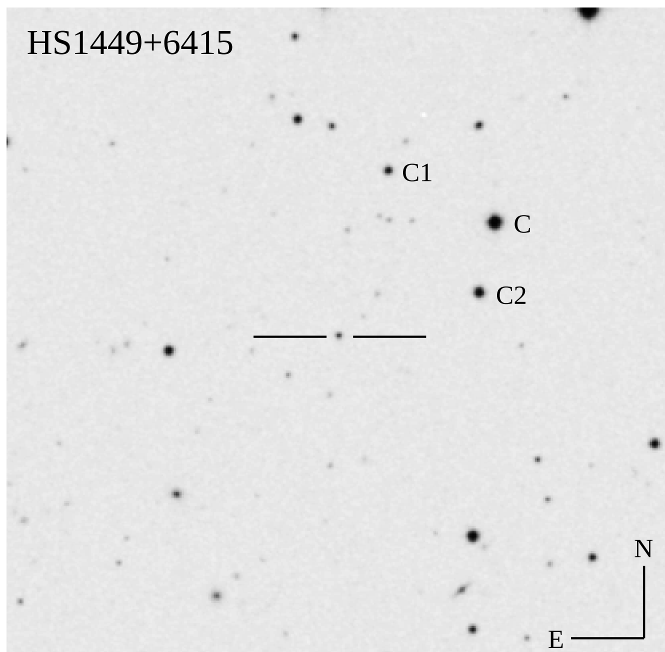

Fig. 1. Finding chart of HS 1449+6415 obtained from the Digitized Sky Survey. The field of view is $7' \times 7'$. The star ‘C’ is the comparison star, and the stars ‘C1’ and ‘C2’ are the check stars.

HS 1449+6415 was in quiescence during the CA observations (Table 1). The light curves in quiescence are shown in Fig. 2; large amplitude flickering seen each night with no hint of an eclipse. After subtraction of nightly averages from the quiescent CA data, a period analysis using the Phase Dispersion Minimization (PDM) method (Stellingwerf 1978) yields two candidate periods, $0\overset{\rm d}{.}0558(2)$ (= 17.9 d^{-1}, 80.4 min) and $0\overset{\rm d}{.}0590(2)$ (= 17.0 d^{-1}, 85.0 min) as shown in Fig. 3, which are one-day aliases of each other. We can not distinguish between

[1] His original BVRI photometry file for this star is available at ftp://ftp.nofs.navy.mil/pub/outgoing/aah/sequence/j1450.dat.

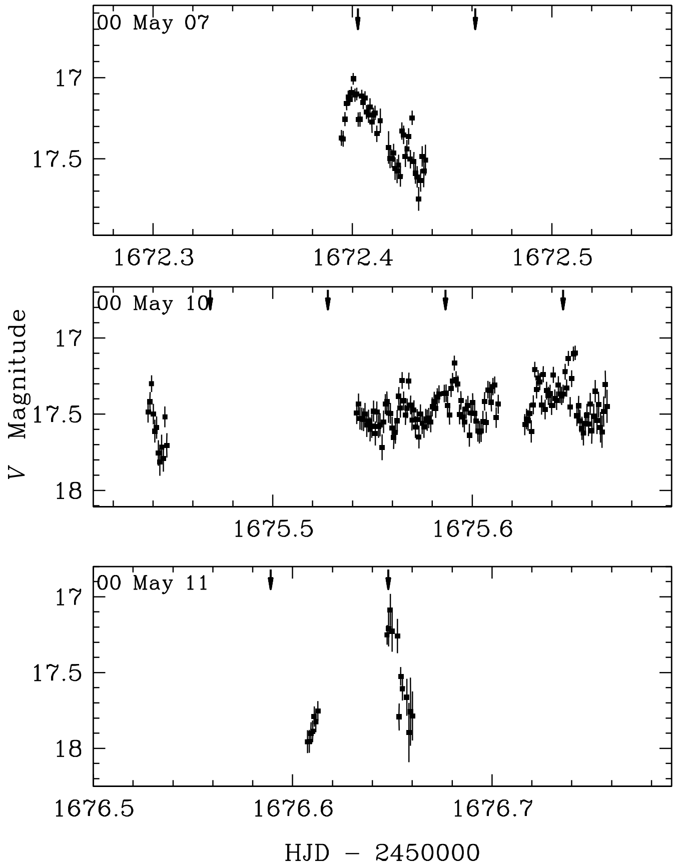

Fig. 2. CA Light curves of HS 1449+6415 in quiescence. The arrows indicate times at $\phi_{\rm phot}$ = 0.0, which corresponds to the phase in Fig. 3.

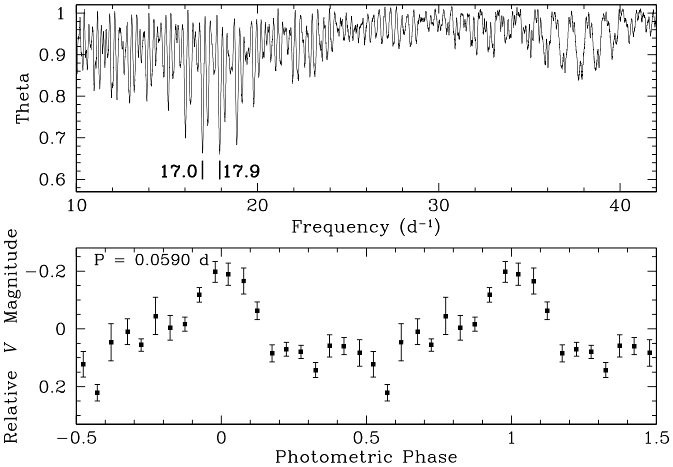

Fig. 3. Upper panel: Theta diagram of the period analysis for the CR data in Fig. 2 using the PDM method. There are two candidates for the orbital period: $0.^{\rm d}0558(2)$ (17.9 $\rm d^{-1}$) and $0.^{\rm d}0590(2)$ (17.0 $\rm d^{-1}$). Lower panel: Light curve folded by the period of $0.^{\rm d}0590$.

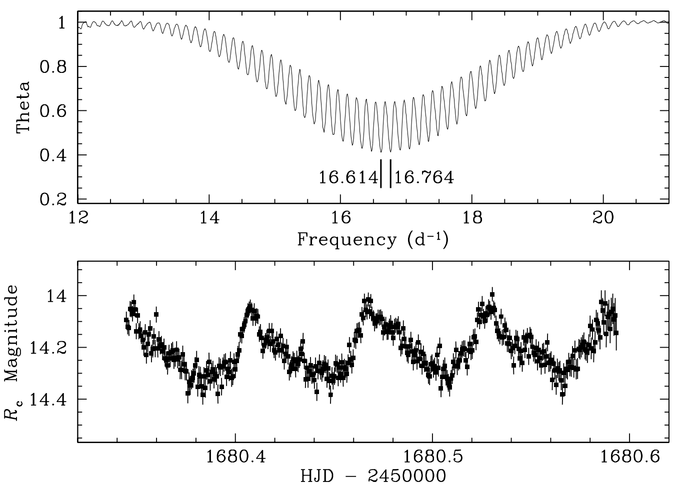

Fig. 4. Fully grown superhump seen on 2000 May 15 (NC data, upper panel). A PDM period analysis yields two candidates of the superhump period of $0.^{\rm d}06019(2)$ and $0.^{\rm d}05965(2)$ (lower panel), but the latter is rejected from Vanmunster et al. (2000).

these candidates from our CA data alone because of the short coverage.

Time resolved photometry obtained at NC on May 15 (Fig. 4) and 22 during the long outburst clearly revealed the existence of superhumps, proving the SU UMa nature of HS 1449+6415. These superhump data help to determine the true orbital period. After subtraction of nightly averages from the data, we performed a PDM period analysis. The two best candidates for the superhump period $P_{\rm sh}$ are $0.^{\rm d}06019(2)$ (= 16.614(5) $\rm d^{-1}$, 86.67 min) and its 7-day alias, $0.^{\rm d}05965(2)$ (= 16.764(5) $\rm d^{-1}$, 85.90 min). Nevertheless, the latter possibility can be rejected from Vanmunster et al. (2000), who have much denser coverage of this superoutburst than we have. The superhump period is, therefore, determined to be $0.^{\rm d}06019(2)$, which exactly accords with the value in Vanmunster et al. (2000). The superhump excess ϵ (= $(P_{\rm sh} - P_{\rm orb})/P_{\rm orb}$) is 7.9 % and 2.0 % for the two $P_{\rm orb}$ candidates of $0.^{\rm d}0558$ and $0.^{\rm d}0590$, respectively. Since SU UMa stars with short orbital periods have $\epsilon \simeq$ 1–3 % (see e.g. Nogami et al. 1997), this well-determined superhump period strongly supports the latter $P_{\rm orb}$ candidate. Moreover, Thorstensen (2000) reported two orbital period candidates of $0.^{\rm d}0588$ and $0.^{\rm d}0599$ deduced from radial velocity measurements. The former is in good agreement with our candidate period of $0.^{\rm d}0590(2)$. Hence, we can safely regard this period as the orbital period of HS 1449+6415. The lower panel of Fig. 3 shows the light curve obtained by folding all the CA data with the orbital period. The phase was determined to place the large peak at ϕ = 0.0.

To check whether our periodogram may be biased by night-to-night variability, we made another period analysis using only the longest continuous observing sequence obtained on May 10. The resultant theta diagram yields two broad peaks around frequencies of ∼18.0 $\rm d^{-1}$ and ∼38 $\rm d^{-1}$ with almost the same significance. This may indicate the underlying double-peaked form of the orbital light curve found by Kato et al. (2000) in observations obtained during quiescence on 2000 February 24 at the Nyrola Observatory. Their period analysis has yielded two strong peaks at $0.^{\rm d}0289$ and its double. Double-peaked orbital modulations in quiescence are found in WZ Sge (e.g. Warner & Nather 1972) and AL Com (see e.g. Szkody et al. 1989).

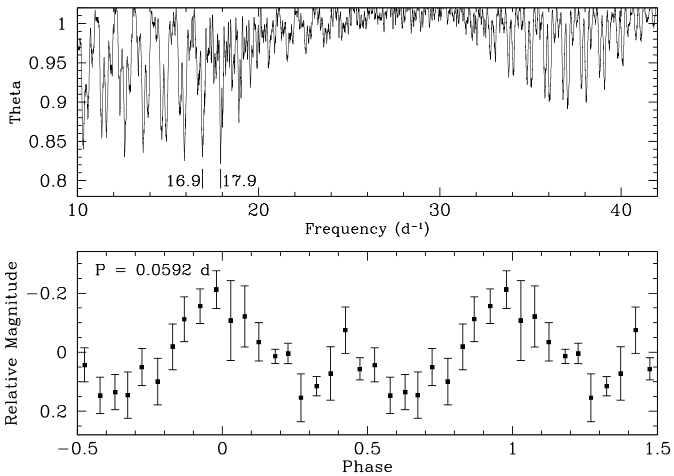

Fig. 5. Upper panel: Theta diagram for the CR data obtained between JD 2451716 and JD 245120 in quiescence. There are also peaks at $0\overset{\mathrm{d}}{.}0559(4)$ (17.9 d^{-1}) and $0\overset{\mathrm{d}}{.}0592(4)$ (16.9 d^{-1}), in good agreement with the result of Fig. 3. Lower panel: Light curve folded by the period of $0\overset{\mathrm{d}}{.}0592$ and howing a double-peaked shape.

Quiescent data was also obtained at CR around JD 2451716. Fig. 5 exhibits the result of a PDM period analysis after subtraction of nightly averages and the folded light curve of the data from JD 2451716 to 2451720. The shape of the orbital modulation is almost the same as in Fig. 3 (for instance, the full amplitude of ∼0.4 mag) but the secondary peak around ϕ = 0.4 is stronger.

A PDM period analysis using all our quiescence data obtained at CA and CR yields the refined photometric ephemeris:

$$HJD_{\max} = 2451672.047(2) + 0.05898(2) \times E\,. \qquad (1)$$

The superhump maxima in Fig. 4 are around ϕ = 0.77 in this ephemeris.

A short outburst lasting only 3 days were caught on JD 2451721 in the course of our monitoring of this star at CR (Fig. 6). This duration is typical for a normal outburst of SU UMa stars. There are no periodic variations but weak flickering in the first and the second night of this outburst. Large flickering of $\sim$ 0.5 mag can be seen on HJD 2451724, when this variable star was still about 0.5 mag brighter than its quiescence level.

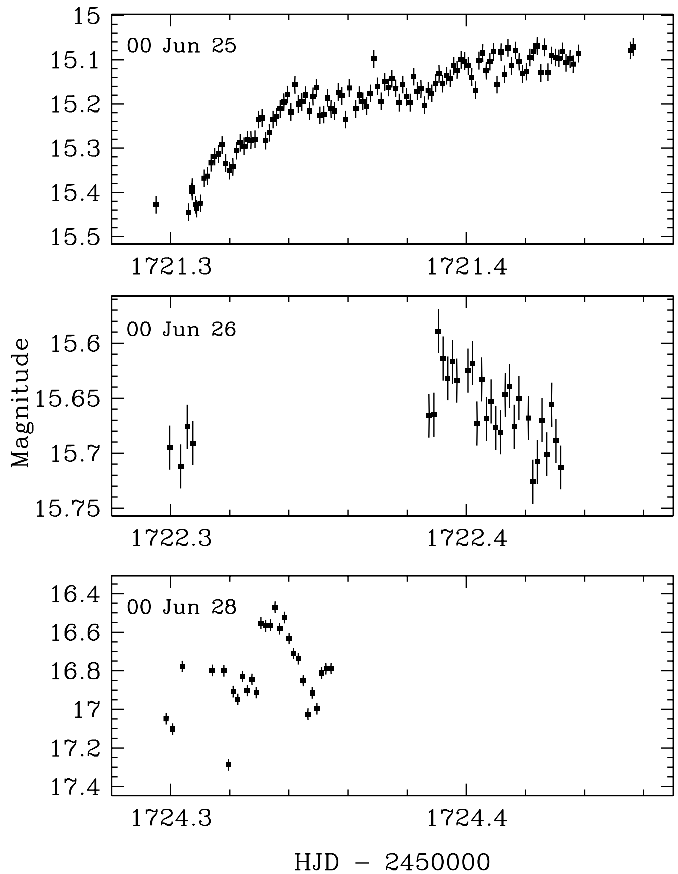

Fig. 6. Light curves during a normal outburst lasting only 3 days. While no periodic variations and only weak flickering are seen on June 25 and 26, flickering of $\sim$ 0.5 mag on June 28 when HS 1449+6415 is about 0.6 mag brighter than in quiescence.

3. Discussion

The superhump period we derived is $0\overset{\mathrm{d}}{.}0601(6)$, 1.9 % longer than $P_{\rm orb}$ of $0\overset{\mathrm{d}}{.}05898(2)$. This orbital period is close to the minimum of the period distribution of SU UMa-type dwarf novae (see e.g. Nogami et al. 1997). In general, observations have shown that the amount of time after the maximum of a superoutburst needed for SU UMa stars to evolve superhumps increases towards shorter orbital periods (see e.g. Table 1 in Osaki 1996). This correlation is also expected on the theoretical grounds: Lubow (1991) showed that the growth rate of the eccentricity is proportional to q^2, where q is the mass ratio of the secondary mass to the primary mass (= M_2/M_1). Thus, if a normal SU UMa star, superhumps in HS 1449+6415 are expected to appear at least 4 days after the supermaximum. In contrast, fully grown superhumps with an amplitude of 0.32 mag were detected less than 2 days after the maximum of the superoutburst detected on 2000 May 14.864 (UT), only 2.7 day after the end of our CA observations (Vanmunster 2000b; Vanmunster et al. 2000), taking into account the rise time to the supermaximum. A determination of the binary parameters of HS 1449+6415 by spectroscopy may thus be able to test the tidal instability theory.

Kato et al. (1998) pointed out that all ER UMa stars, i.e., the most active SU UMa-type dwarf novae, exhibit a peculiar phenomenon: the amplitude of the superhump is largest around the superoutburst maximum and decreases as the time proceeds even though the superhump period remains almost constant (see also Kato et al. 1996). ER UMa stars also have very short $P_{\rm orb}$ close to that of HS 1449+6415. The early development of the superhump in the present system may be related to the superhump evolution in ER UMa stars which is still theoretically unexplained. To trace the variation of the superhump in HS 1449+6415 throughout a superoutburst is another future work which should be performed.

WZ Sge stars, another extreme subset of SU UMa-type dwarf novae (O'Donoghue et al. 1991, and references therein) also have very short orbital periods, similar to that of HS 1449+6415. However, WZ Sge stars shows only superoutbursts with a very long recurrence time ($\geq$ 10 yr) and with a very large amplitude ($\Delta V \geq 7$), but no normal outbursts. For this behavior, Meyer-Hofmeister et al. (1998) proposed a model in which the accretion disk steadily grows during quiescence, and the tidal instability starts before the superoutburst onset. If this model were applicable to HS 1449+6415, we could observe superhumps also before the onset of a superoutburst. However, only modulations with the orbital period were detected in our data. The amplitude variation in our data before the superoutburst may indicate a beat phenomenon of the orbital hump and the superhump, but a much longer photometric pre-outburst observation would be needed to confirm this hypothesis.

Note that the average profile of the orbital modulation is almost the same between just before the superoutburst and before the normal outburst. This implies that the physical status of the accretion disk and the hot spot, which are thought to emit most of the optical light in quiescence, is quite similar in both these periods. Nothing special seemed to occur before the superoutburst, compared to the situation before the normal outburst, although more observations of the orbital modulation with much smaller errors are needed to strictly probe differencies of the accretion disk in different phases.

The brightest magnitude of HS 1449+6415 reported to VSNET is $m_{\rm vis}$ = 14.1 (Kinnunen 2000), after calibration using the magnitude of the comparison star (Kinnunen, private communication) given by Henden (2000). The amplitude of the superoutburst, thus, is $\sim$3.5 mag, which is the smallest among SU UMa stars with orbital periods shorter than 90 min, other than ER UMa stars (see e.g. Table 1 in Nogami et al. 1997). As mentioned above, the normal outburst was caught about 40 days after the onset of the superoutburst. If this value is considered as the recurrence cycle of the outbursts, this is typical for an SU UMa star (see e.g. Table 1 in Nogami et al. 1997). The VSNET data[2] can exclude the possibility of an outburst-recurrence cycle shorter than 14 days. The combination of the outburst amplitude of 3.5 mag and the recurrence cycle of 40 days is almost the same as that in SX LMi, which is regarded as the dwarf nova bridging the gap between ER UMa stars and SU UMa stars (Nogami et al. 1997). The orbital period of $0\overset{\rm d}{.}06717(11)$ (= 97 min) of SX LMi (Wagner et al. 1998) is, however, a little out of range of the orbital period distribution of ER UMa stars and WZ Sge stars. Thus, HS 1449+6415 is an intermediate object between ER UMa stars and WZ Sge stars, and might be in the evolutionary transition state between ER UMa and WZ Sge phases. HS 1449+6415 deserves to be monitored over long timescales to measure the accurate recurrence cycles of the normal outburst and the superoutburst and to reveal variations of these cycles and the outburst amplitude.

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