The nature of V359 Centauri revealed: New long-period SU UMa-type dwarf nova

T. Kato1, R. Stubbings2, P. Nelson3, R. Santallo4, R. Ishioka1, M. Uemura1, T. Sumi5,6, Y. Muraki5, P. Kilmartin7, I. Bond8, S. Noda5,9, P. Yock10, J. B. Hearnshaw7, B. Monard11, and H. Yamaoka12

1 Department of Astronomy, Kyoto University, Kyoto 606-8502, Japan
2 19 Greenland Drive, Drouin 3818, Victoria, Australia
3 RMB 2493, Ellinbank 3820, Australia
4 Southern Stars Observatory, PO Box 60972, 98702 FAAA TAHI'TI, French Polynesia
5 Solar-Terrestrial Environment Laboratory, Nagoya University, Nagoya 464-8601, Japan
6 Department of Astrophysical Sciences, Princeton University, Peyton Hall, Princeton, NJ 08544, USA
7 Department of Physics and Astronomy, University of Canterbury, Christchurch, New Zealand
8 Inst. of Astronomy, University of Edinburgh, Royal Observatory, Edinburgh, UK
9 Astronomical Data Analysis Center, National Astronomical Observatory of Japan, Mitaka, Tokyo 181-8588, Japan
10 Department of Physics, University of Auckland, Auckland, New Zealand
11 Bronberg Observatory, PO Box 11426, Tiegerpoort 0056, South Africa
12 Faculty of Science, Kyushu University, Fukuoka 810-8560, Japan

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Abstract. We detected four outbursts of V359 Cen (possible nova discovered in 1939) between 1999 and 2002. Time-resolved CCD photometry during two outbursts (1999 and 2002) revealed that V359 Cen is actually a long-period SU UMa-type dwarf nova with a mean superhump period of 0.08092(1) d. We identified its supercycle length as 307–397 d. This secure identification of the superhump period precludes the previously supposed possibility that V359 Cen could be related to a WZ Sge-type system with a long persistence of late superhumps. The outburst characteristics of V359 Cen are, however, rather unusual in its low occurrence of normal outbursts.

Key words. accretion, accretion disks – novae, cataclysmic variables – stars: dwarf novae – stars: individual: V359 Cen

1. Introduction

Cataclysmic variables (CVs) are close binary systems consisting of a white dwarf and a red dwarf secondary transferring matter via the Roche lobe overflow (for a review of CVs, see Warner 1995a). CVs are subdivided into several categories, including dwarf novae (DNe) and novae. Both DNe and novae are characterized by the presence of a sudden increase of brightness (outburst). Although the mechanisms of DN-type outbursts (cf. Osaki 1996) and nova outbursts (cf. Starrfield & Sparks 1987; Starrfield 1999; Starrfield et al. 2000) are different, observational discrimination between rarely outbursting DNe and novae can be sometimes difficult (see Downes & Margon 1981 and Kato et al. 2001b for classical and recent examples, respectively). Since rarely outbursting DNe can be easily confused with very fast novae, these confusions may have skewed our statistical view of classical novae (Downes 1986; Liller & Mayer 1987; Shafter 1997).

A large fraction of such confusions turned out to be SU UMa-type dwarf novae or WZ Sge-type dwarf novae (Kato et al. 2001b). SU UMa-type dwarf novae are a subclass of DNe. WZ Sge-type dwarf novae are still enigmatic, both in theory and to observations, SU UMa-type dwarf novae, which are rarely outbursting (once in ~10 yr) show large-amplitude (~8 mag) outbursts (Bailey 1979; Downes & Margon 1981; Patterson et al. 1981; O’Donoghue et al. 1991). All SU UMa-type dwarf novae, including WZ Sge-type dwarf novae, show superhumps during their long, bright outbursts (superoutbursts). (For a recent review of dwarf novae and SU UMa-type dwarf novae, see Osaki 1996 and Warner 1995b, respectively.) Superhumps have periods (superhump period: \( P_{\text{SH}} \)) a few percent longer than the orbital periods (\( P_{\text{orb}} \)) (Vogt 1980; Warner 1985), which is believed to be a consequence of the apsidal motion (Osaki 1985; Molnar & Kobulnicky 1992) of a tidally induced eccentric accretion disk (Whitehurst 1988; Hirose & Osaki 1990; Lubow 1991). WZ Sge-type dwarf novae are known to show a different kind of (super) humps during the earliest stage of superoutbursts (Kato et al. 1996; Matsumoto et al. 1998;
remained rather uncertain. The periodicity of 0.0779 d (112 min), but interpretation of this period shows that the object was near the detection limit (presumably a result of a large air-mass). This impression may have a cause of its faintness (V fainter than 20.5). Gill & O’Brien (1998) obtained a deep image around V359 Cen, and showed that the profile is indistinguishable from that of a normal star; there was no evidence of a nova shell.

The situation dramatically changed when one of the authors (Rod Stubbings) detected the second historical outburst on 1999 July 13 (vsnet-alert 3216). The object further underwent outbursts in 2000 May, 2001 April and 2002 June. We photometrically observed two outbursts (1999 July and 2002 June) and revealed that V359 Cen is an SU UMa-type dwarf nova. A finding chart of the proposed quiescent counterpart was presented in Duerbeck (1987).

Munari & Zwitter (1998) tried to study the proposed quiescent counterpart spectroscopically, but the attempt failed because of its faintness (V fainter than 20.5). Gill & O’Brien (1998) obtained a deep image around V359 Cen, and showed that the profile is indistinguishable from that of a normal star; there was no evidence of a nova shell.

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2. Observations
The 1999 observation by the MOA team was performed using a 61 cm Ritchey-Chrétien Cassegrain telescope (f/6.25) with the MOA-cam2 (Yanagisawa et al. 2000), constructed with three Site back-illuminated CCDs (2047×4095 pixels). The MOA blue filter (MOA B) covers 395–620 nm and MOA red filter covers 620–1050 nm. The exposure times were 300 and 180 s for the 1999 July 14 and 15 data, respectively. The magnitudes of the object were measured with Dophot package. The absolute calibration of the magnitudes was done using an ensemble of ~40 neighboring stars, whose zero-point was determined using about 100 LMC standard stars measured with the Hubble Space Telescope. The MOA magnitudes can be linked to the standard V and $R_c$ systems using Eq. (1), where red and blue denote MOA red and MOA blue magnitudes (Noda et al. 2002). Since the blue and red observations were not completely simultaneous, we list the magnitudes on the MOA photometric system in Table 1.

$$V = \text{blue} - 0.16(\text{blue} - \text{red}) + \text{const}_1$$

$$R_c = \text{red} + 0.29(\text{blue} - \text{red}) + \text{const}_2.$$ (1)

The 2002 observations were undertaken by the VSNET Collaboration2. The equipment and reduction software are summarized in Table 2. The Kyoto observations were analyzed using the Java™-based PSF photometry package developed by one of the authors (TK). The other observers performed aperture photometry. The magnitudes were given relative to GSC 7750.220, whose constancy during the observation was confirmed by a comparison with USNO-A1.0 0450.13739601. All systems are close to $R_c$. The journal of the 2002 observations are summarized in Table 3.

Barycentric corrections to the observed times were applied before the following analysis.

3. Astrometry and quiescent counterpart
Astrometry of the outbursting V359 Cen was performed on CCD images taken by R. Santallo (2002 June 1). An average of measurements of five images (GSC—2.2 system, about 20 reference stars; internal dispersion of the measurements was ~0.05) has yielded a position of $11^h58^m 15^s330, -41^\circ 46'08''44$ (J2000.0). The position agrees with the GSC—2.2 star at $11^h58^m 15^s322, -41^\circ 46'08''35$ (epoch 1995.392 and magnitudes $r = 18.46, b = 19.15$) and the USNO—A2.0 star at $11^h58^m 15^s330, -41^\circ 46'09''16$ (epoch 1982.262 and magnitudes $r = 17.7, b = 18.7$).

This identification confirms the quiescent magnitude ($V = 18.7$) reported by Woudt & Warner (2001). The quiescent magnitudes (21 or V fainter than 20.5) reported by Duerbeck (1987) and Munari & Zwitter (1998) seem to be underestimated. An examination of POSS I red plate (limiting magnitude $R ~ 18.5$) shows that the object was near the detection limit (presumably a result of a large air mass). This impression may have affected the estimate by Duerbeck (1987).

The failure by Munari & Zwitter (1998) in obtaining a quiescent spectrum is, however, difficult to reconcile with the value of $V = 18.7$. Since a few dwarf novae categorized to established or suspected SU UMa-type dwarf novae are known to show high and low states in quiescence (HT Cas: Zhang et al. 1986; Wood et al. 1995; Robertson & Honeycutt 1996; IR Com: Richter & Greiner 1995; Kato et al. 2002a and less established BZ UMa: Kaluzny 1986). Although it is still premature to draw a firm conclusion, V359 Cen may belong to a small class of SU UMa-type dwarf novae with high/low transitions in quiescence.

4. Long-term light curve
Figure 1 shows the long-term visual light curve of V359 Cen constructed from the observations reported to the VSNET Collaboration. Large and small dots represent positive and negative (upper limit) observations, respectively. Four outbursts (1999 July, starting on JD 2451373; 2000 May, on JD 2451680; 2002 June 1).

1. http://www.kusastro.kyoto-u.ac.jp/vsnet/Mail/alert3000/msg00216.html
2. http://www.kusastro.kyoto-u.ac.jp/vsnet/
2001 April, on JD 2452025 and 2002 June, on JD 2452422) are clearly seen. The intervals between the detected outbursts are in the range of 307–397 d. Although there were unavoidable seasonal gaps in observations, these values seem to be a representative outburst cycle length. The observed maximum magnitudes of the outbursts were $\sim$13.8. This constancy of the maximum magnitudes likely precludes the previously supposed possibility that the maximum of the 1939 outburst was missed (Duerbeck 1987).

### 5. The 1999 outburst

Figure 2 shows the enlarged light curve of V359 Cen during the 1999 outburst. The data are from the MOA observations. Although complete phase coverage was impossible because of the short available runs, the object clearly exhibited variations with amplitudes of $\sim$0.15 mag, which can be attributed to superhumps.

A period analysis of the MOA blue data using Phase Dispersion Minimization (PDM; Stellingwerf 1978) has yielded the theta diagram presented in Fig. 3. Although a unique alias selection is impossible from these data only, we
can safely choose the correct alias of $P_{\text{SH}} = 0.0824(4)$ d based on the later determination of the superhump period (Sect. 6.2).

6. The 2002 outburst

6.1. Course of the outburst

The 2002 outburst was detected by Rod Stubbings on May 28 at $m_{\text{vis}} = 13.8$ (vsnet-alert 7356). CCD time-resolved photometry started within a day following this detection. Figure 4 shows the overall light curve of the 2002 superoutburst. The magnitudes are relative to GSC 7750.220 and are on a system close to $R_c$. After two days of the outburst, the system started to fade linearly at a rate of 0.16 mag d$^{-1}$. This slowly and linearly fading phase (often referred to as superoutburst plateau) is very characteristic of an SU UMa-type superoutburst (Warner 1980; Warner 1985).

The mean decline rate of 0.16 mag d$^{-1}$ during the plateau phase is larger than those of other SU UMa-type dwarf novae (Table 4) with similar $P_{\text{SH}}$ to that of V359 Cen (cf. Sect. 6.2). Since a higher mass-transfer rate from the secondary star tends to thermally stabilize the accretion disk and reduce the decay rate (e.g. Osaki 1995), a rather exceptionally large decay rate in V359 Cen may be a result of a systematically smaller mass-transfer rate.

6.2. Superhump period and evolution

Figure 5 shows enlarged nightly light curves. Superhumps are clearly visible on all observed nights. Figure 6 shows the result of a PDM period analysis of the 2002 data between May 31 and June 6 (superoutburst plateau). The linear declining trend has been subtracted before the analysis. The resultant best $P_{\text{SH}}$ is 0.08092(1) d. The selection of the correct alias has been confirmed by independent period analyses of individual long continuous runs. This period established that V359 Cen is a long-period SU UMa-type dwarf nova. Figure 7 shows the phase-averaged profile of superhumps. The rapidly rising and slowly fading superhump profile is characteristic to an SU UMa-type dwarf nova (Warner 1980, 1985).

We extracted the maxima times of superhumps from the light curve by eye. The averaged times of a few to several

### Table 4. Mean decline rates of SU UMa-type dwarf novae.

| Object | $P_{\text{SH}}$ (d) | Mean rate$^a$ | Ref. |
|--------|----------------|--------------|-----|
| HV Aur | 0.0855         | 0.035        | 1   |
| TU Crt | 0.0854         | 0.092        | 2   |
| AW Gem | 0.0794         | 0.08         | 3   |
| TT Boo | 0.0781         | 0.11         | 4   |

$^a$ Mean decline rate (mag d$^{-1}$) during the superoutburst plateau.

References: 1: Nogami et al. (1995), 2: Mennickent et al. (1998), 3: Kato (1996), 4: Kato (1995).
points close to the maximum were used as representatives of the maxima times. The errors of the maxima times are usually less than $\sim 0.002$ d. The resultant superhump maxima are given in Table 5. The values are given to 0.0001 d in order to avoid the loss of significant digits in a later analysis. The cycle count ($E$) is defined as the cycle number since BJD 2452423.939.

A linear regression to the observed superhump times gives the following ephemeris:

$$\text{BJD(maximum)} = 2452423.9503 + 0.08108E.$$ (2)

Figure 6 shows the (O–C)'s against the mean superhump period ($0.08108$ d) from Eq. (2). Although the general trend can be expressed by a negative quadratic term of $\dot{P} = -10.8(1.5) \times 10^{-6}$ d cycle$^{-1}$, or $\dot{P}/P = -13.3(1.9) \times 10^{-5}$, superhump maxima with $E \geq 23$ can be well expressed by a constant period of $P = 0.08094$ d and $|O-C|$'s less than 0.005 d. This finding indicates that the superhump period was virtually constant during the plateau phase (the nominal $P$ during this period is $-5.3(2.8) \times 10^{-6}$ d cycle$^{-1}$). A sudden change between $E = 0$ and $E = 23$ can be interpreted as a result of rapid evolution of superhumps during the earliest stage of the superoutburst. The “textbook” evolutionary time-scales (2–3 d) of superhumps in long-period SU UMa-type dwarf novae (Warner 1985) also support this interpretation. The large period change of $P_{\text{SH}}$ observed during the earliest stage of the 2002 superoutburst may explain the slight discrepancy of the periods between the 1999 and 2002 observations (the 1999 observation corresponds to the earliest stage of a superoutburst). The period determined from $0 \leq E \leq 23$ observations is 0.0817 d, sufficiently longer than the most likely orbital period (Sect. 7.2), precludes the possibility of WZ Sge-type early (super)humps as the origin of these early modulations.

6.3. Super-QPOs

Some SU UMa-type dwarf novae are known to show large-amplitude, highly coherent quasi-periodic oscillations (QPOs) during the evolution stage of superhumps (Kato et al. 1992; Kato 2002b). These QPOs are sometimes referred to as “super-QPOs”. The light curve of V359 Cen on May 29 shows a hint of such QPOs. The lower panel of Fig. 9 shows residuals of the May 29 light curve after subtracting the superhump signal by using a Fourier decomposition of the superhump profile up to the third harmonics, and subtracting a slow linear trend. Small-amplitude modulations with a typical time scale of $\sim 0.02$ d are present. Figure 10 shows a power spectrum of the residual shown in the lower panel of Fig. 9. The strongest power
is present at a frequency of $\sim 49 \text{ d}^{-1}$, which corresponds to a period of $\sim 0.02 \text{ d}$.

Although the QPOs were not as prominent as seen in SW UMa (Kato et al. 1992) or (Kato 2002b), the absence of similar signals on later nights suggest that this variation is a kind of super-QPOs. As shown in Sect. 6.2, the epoch of the detection of QPOs corresponds to the rapidly evolving stage of superhumps. This finding further supports an idea that super-QPOs are associated with the growth of superhumps (Kato et al. 1992; Kato 2002b)

7. V359 Cen as an SU UMa-type dwarf nova

7.1. Outburst characteristics

Table 6 lists the observed parameters of the four recorded outbursts. All the recorded outbursts have durations longer than 4 d, which indicate that all the recorded outbursts were superoutbursts. The intervals between these outbursts (307–397 d) are thus regarded as the supercycle of this SU UMa-type dwarf nova. Since the present duty cycle of observations is about 50%, there remains a small possibility that the true supercycle is the half of this value. Further dense monitoring is strongly encouraged to completely exclude this possibility. It is well established that almost all well-studied SU UMa-type dwarf novae with similar supercycle lengths show a few to $\sim$ten normal outburst within one supercycle (Warner 1995b; Nogami et al. 1997). Since normal outbursts of SU UMa-type dwarf novae are usually only 0.5–1.0 mag fainter than superoutbursts (Warner 1985), some of such normal outbursts should have been detected. The present non-detection of normal outbursts seems to suggest that V359 Cen has fewer normal outbursts than in usual SU UMa-type dwarf novae. Although future deeper monitoring for normal outbursts is absolutely needed, the occurrence of normal outbursts in V359 Cen may be effectively suppressed by an unknown mechanism; similar instances have been reported
in other SU UMa-type dwarf novae (Kato 2001; Kato et al. 2002b). If normal outbursts are entirely missing, V359 Cen would become the first long-period analog of V844 Her which has been known to show only superoutbursts (Kato & Uemura 2000: \( P_{\text{SH}} = 0.05592 \) d, supercycle lengths = 220–290 d). Similar SU UMa-type dwarf novae with predominance of superoutbursts are highly concentrated in the short period region (cf. Kato & Uemura 2000). V359 Cen may be an exceptional object in its combination of outburst characteristics and the superhump (or orbital) period.

We also note that the outburst characteristics of V359 Cen also resemble those of long-period SU UMa-type dwarf novae EF Peg (Howell et al. 1993; Kato 2002b) and V725 Aql (Uemura et al. 2001). Both EF Peg and V725 Aql only infrequently show normal outbursts, which is exceptional among long-\( P_{\text{orb}} \) SU UMa-type dwarf novae (cf. Warner 1995b).

While long outburst recurrence times imply that these systems have low mass-transfer rates (Ichikawa & Osaki 1994; Osaki 1996), recent detailed calculations of the evolution of CVs (e.g. Podsiałowski et al. 2001) suggest that mass-transfer rates are higher in long-period systems even if the effect of stellar core evolution is properly taken into account. These systems (EF Peg, V725 Aql and possibly V359 Cen) may be violating the modern evolutionary scenario of CVs. Future determination of the binary parameters and stellar composition analysis of these systems are therefore strongly encouraged.

### 7.2. Superhump excess and late superhumps

Woudt & Warner (2001) tentatively identified their photometric period (112 min) as late superhumps (Haefner et al. 1979; Vogt 1983; van der Woerd et al. 1988; Hessman et al. 1992), which are known to have similar periods with ordinary superhumps (i.e. a few percent longer than \( P_{\text{orb}} \)), but have phases of \( \sim 0.5 \) different from those of ordinary superhumps. Since this signal was observed long after the cessation of the 1999 outburst, Woudt & Warner (2001) suggested that V359 Cen may have shown a long persistence of late superhumps as was observed in a WZ Sge-type dwarf nova in EG Cnc (Kato et al. 1997; Patterson et al. 1998).

The present correct identification of the superhump period, however, indicates that the 112 min periodicity observed by Woudt & Warner (2001) can not be attributed to superhumps, but can be better understood to represent \( P_{\text{orb}} \). This observation, on the contrary to the suggestion by Woudt & Warner (2001), indicates that the superhumps or late superhumps in V359 Cen must have decayed more rapidly, as in other usual SU UMa-type dwarf novae (see Kato et al. 2001a for a recent example of the decay of late superhumps). V359 Cen is thus unlikely related to WZ Sge-type dwarf novae which always show long persistence of late superhumps.

By adopting \( P_{\text{orb}} = 0.0779 \) d, we obtain a fractional superhump excess (\( \epsilon = P_{\text{SH}}/P_{\text{orb}} - 1 \)) of 3.9% for the best \( P_{\text{SH}} \) of 0.08092(1) d (cf. Sect. 6.2). Using the “mean” \( P_{\text{SH}} = 0.08108 \) d from the entire 2002 superoutburst, we obtain \( \epsilon = 4.1 \)%. These fractional superhump excesses are not unusual for an SU UMa-type dwarf nova with this \( P_{\text{orb}} \) (Molnar & Kobulnicky 1992; Patterson 1998), suggesting that V359 Cen should have a normal binary mass ratio \( q = M_2/M_1 \) in spite of its rather unusual outburst characteristics.

### 8. Summary

We detected four outbursts of V359 Cen (possible nova discovered in 1939) between 1999 and 2002. Time-resolved CCD photometry during two outbursts (1999 and 2002) revealed that V359 Cen is actually a long-period SU UMa-type dwarf nova with a mean superhump period of 0.08092(1) d. We identified its supercycle length as 307–397 d. This secure identification of the superhump period precludes the previously supposed possibility that V359 Cen could be related to a WZ Sge-type system with a long persistence of late superhumps. The outburst characteristics of V359 Cen are, however, rather unusual in its low occurrence of normal outbursts. The fractional superhump excess is 3.9–4.1%, which suggests that V359 Cen should have a normal binary mass ratio in spite of its rather unusual outburst characteristics. We also obtained a secure identification of the quiescent counterpart and discussed on the possibility of high/low state changes. The evolution of superhumps and their period change was closely followed. We also detected super-QPO-type variation (period \( \sim -0.02 \) d) during the earliest stage of the 2002 superoutburst.

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### Table 6. List of outbursts.

| JD start \(^{a}\) | JD end \(^{a}\) | Maximum | Duration (d) |
|-----------------|-----------------|---------|-------------|
| 51372.9         | 51377.9         | 13.8    | >5          |
| 51680.0         | 51690.0         | 13.8    | >10         |
| 52025.0         | 52029.0         | 14.0    | >4          |
| 52422.9         | 52433.0         | 13.8    | >10         |

\(^{a}\) JD–2 400 000.
