Kilo-Second Quasi-Periodic Oscillations in the Cataclysmic Variable DW Cancri

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Abstract

Our photometric monitoring revealed that DW Cnc, which was originally classified as a dwarf nova ($V = 15–17.5$), remained at a bright state of $R_c = 14.68 \pm 0.07$ for 61 days. In conjunction with optical spectra lacking a strong He II emission line, we propose that the object is not a dwarf nova, but a non-magnetic nova-like variable. Throughout our monitoring, the object showed strong quasi-periodic oscillations (QPOs) with amplitudes reaching about 0.3 mag. Our period analysis yielded a power spectrum with two peaks of QPOs, whose center periods are $37.5 \pm 0.1$ and $73.4 \pm 0.4$ min and, furthermore, with a significant power in frequencies lower than the QPOs. DW Cnc is a unique cataclysmic variable in which kilo-second QPOs were continuously detected for 61 days. We propose two possible interpretations of DW Cnc: (i) A permanent superhumer below the period minimum of hydrogen-rich cataclysmic variables. (ii) A nova-like variable having an orbital period over 3 hours. In this case, the QPOs may be caused by trapped disk oscillations.

1 Introduction

Cataclysmic variables (CVs) are semi-detached binaries which contain a white dwarf and a late-type secondary star (Warner (1995)). The overflowing gas from the Roche lobe-filling secondary star forms an accretion disk, which plays a key role in various activities of CVs. From the photometric and spectroscopic characteristics, the systems are classified with some sub-groups, for example, classical novae, dwarf novae (DNe), nova-like variables (NLs), and magnetic CVs of polars and intermediate polars (IPs).

Quasi-periodic oscillations (QPOs) have been detected in CVs on a variety of time scales. Rapid QPOs with a period of a few seconds have been observed in some magnetic CVs. They are considered to originate from the shock region between a white dwarf and accretion streams (Langer et al. 1981, 1982). During DN outbursts, we know three types of temporary short-term modulations, that is, dwarf nova oscillations (DNOs), QPOs, and super-QPOs. DNOs are highly coherent modulations with typical periods of a few tens of seconds. The period of QPOs during DN outbursts is generally longer than that of DNOs ($P_{QPO} = 30–1000$ s). DNOs and QPOs have been reported also in some NLs and classical novae (Patterson (1981)). The origin of DNOs has been proposed to be a white dwarf (Warner, Robinson (1972); Papaloizou, Pringle (1978)), an inner edge of the disk (Bath (1973)) or a boundary layer (Okuda et al. (1992); Collins et al. (2000)); however, it is still an issue. On the other hand, the oscillation of a disk or a boundary layer has been suggested for QPOs (Okuda et al. (1992); Collins et al. (2000)). While the amplitudes are quite small ($\sim 0.05$ mag) in DNOs and QPOs, super-QPOs have higher amplitudes, reaching $\sim 0.2$ mag. This modulation, whose period is typically a few minutes, has been detected only in the early and late phase of superoutbursts in some SU UMa-type DNe (Kato et al. (1992); Nogami et al. (1998); Kato (2002)).

Stepanian (1982) discovered new variable stars in the course of their search for galaxies with a low-dispersion objective prism survey. According to Stepanian (1982), the “No. 2” object showed brightness variations of $V = 15–17.5$. In conjunction with strong Balmer emission lines and a weak He II 4686 Å emission line, Stepanian (1982) suggested that it is a DN. This object was called FBS 0756+164 by Kopylov et al. (1988) and given a general GCVS name of DW Cnc (Khlopopov et al. (1981)). Kopylov et al. (1988) supported this classification based on a new spectrum whose characteristics are analogous to that reported by Stepanian (1982).

Here, we report on our time-series photometric monitoring of DW Cnc, in which we discovered unprecedentedly large-amplitude and long-period QPOs. In the next section, we describe our observation method. Our observation results are presented in section 3; we then propose possible interpretations of them in section 4. We summarize our findings in the final section.

2 Observation

We performed CCD photometric observations at Kyoto, Ouda Observatory, Nicholas Copernicus Observatory and Planetarium, and Erftstadt. Our equipment and observation log are listed in tables 1 and 2, respectively. After dark subtraction and flat fielding on our
Table 1: Equipment of our observations.

| Site                            | Telescope                  | Camera               | Filter     |
|---------------------------------|----------------------------|----------------------|------------|
| Kyoto                           | 25-cm Schmidt–Cassegrain   | ST-7                 | unfiltered |
| Ouda                            | 60-cm Ritchey–Chretien     | PixelVision (STe SI004AB chip) | Rc         |
| Nicholas Copernicus Observatory | 40-cm Newton               | ST-7                 | I          |
| Masaryk University              | 60-cm Newton               | ST-8                 | I          |
| Erftstadt                       | 20-cm Schmidt–Cassegrain   | ST-6B                | unfiltered |

obtained images, the differential magnitudes of the object were calculated with point spread function (PSF) photometry for images taken at Kyoto. Aperture photometry was performed for images taken at the other sites. The magnitude scales of each observatory were adjusted to that of the Kyoto system, in which we used a comparison star, GSC 1363.2124. The constancy of the comparison brightness was checked by GSC 1363.2014. We could obtain magnitudes almost equal to the Rc system with an unfiltered ST-7 camera, since its sensitivity peak is almost equal to that of the Rc system and the object has B − V ∼ 0. Heliocentric corrections to the observed times were applied before a following analysis.

3 Result

3.1 Long-Term Light Curve and Re-Classification of DW Cnc

Figure 1 shows long-term light curves of DW Cnc. The crosses with error bars represent the average magnitudes with standard errors each night. The light curve in the upper panel includes all visual observations reported to Variable Star Network (VSNET\(^1\)), which are depicted with the open circles and the triangles (upper-limits). The lower panel is a light curve focused on our CCD observations. As can be seen in the upper panel, the object varied between 14–15 mag most of the time. During our observations, shown in the lower panel, the object showed no significant fading or brightening trend. We calculated the average magnitude to be Rc = 14.68.

Stepanian (1982) proposed that DW Cnc is a DN with the variation range of V = 15–17.5. The characteristic which we observed, as shown in figure 1, is, however, inconsistent with that of the DN light curves. Z Cam stars, which form a sub-group of DNes, are known to experience a phase called “standstill”, which is a phase with constant brightness interrupting ordinary outburst cycles (Warner (1995)). It is, however, less likely that the period of constant brightness of DW Cnc is a standstill, because the long monitoring of visual observations shows no ordinary outburst phase over six years. It may be possible that the long bright state is indeed a quiescent state of a dwarf nova having a long recurrence time, such as WZ Sge stars. This scenario, however, apparently contradicts the presence of the faint phase, which is indicated by a few observations fainter than 15 mag in figure 1 and the originally proposed amplitude of V = 15–17.5 (Stepanian (1982)).

The long-term variations of DW Cnc are analogous to NLs or magnetic CVs, rather than DNes. Figure 1 indicates that the duration of the possible faint state is probably shorter than that of the high state. Although we could obtain no estimation of the magnitude at the time when the spectroscopy was performed by Stepanian (1982) and Kopylov et al. (1988), it is less likely that both of the spectra were taken during the temporal short-duration faint states. The case of a magnetic CV is thus apparently inconsistent with the lack of a strong He II emission line (Stepanian (1982); Kopylov et al. (1988)). We hence suggest that DW Cnc is neither a DN nor a magnetic system, but a NL.

We cannot conclude whether DW Cnc has changed its nature as a DN or it was just a mis-classification, since no light curve is available in Stepanian (1982). On the other hand, the hints of possible faint states are reminiscent of the long-term variations of VY Scl-type stars, a sub-group of NLs showing temporary low states (Leach et al. (1999)). The variations between 14–15 mag seen in the visual observations can be explained by short-term variations with relatively large amplitudes, which we describe in the following section.

3.2 Discovery of Kilo-Second Quasi-Periodic Oscillations

During our CCD monitoring, we detected oscillations whose typical light curves are shown in figure 2. As shown in this figure, they appear to have no constant period, but variable profiles and a quasi-periodic nature. They have a coherence time of at least a few cycles, as can be seen in figure 2. We cannot find any firm evidence of a long-term coherence of these varia-

\(^1\)(http://www.kusastro.kyoto-u.ac.jp/vsnet/)
Table 2: Journal of observations.

| Date (HJD)   | Duration (hr) | $T_{\text{exp}}$ (s) | $N$ | Site  |
|--------------|---------------|-----------------------|-----|-------|
| 2451986.9965| 2.17          | 60                    | 118 | O     |
| 2451987.9076| 5.15          | 30                    | 286 | O     |
| 2451988.2804| 5.42          | 50                    | 345 | N     |
| 2451988.4684| 1.91          | 90                    | 71  | E     |
| 2451988.9076| 5.53          | 30                    | 274 | O     |
| 2451988.9596| 4.68          | 30                    | 161 | K     |
| 2451990.0891| 2.43          | 30                    | 235 | K     |
| 2451991.9635| 5.52          | 30                    | 327 | K     |
| 2451995.0318| 1.77          | 30                    | 85  | K     |
| 2451996.3280| 2.36          | 90                    | 48  | E     |
| 2451999.3545| 3.45          | 90                    | 92  | E     |
| 2451999.9361| 1.89          | 30                    | 184 | K     |
| 2452000.9436| 1.97          | 30                    | 189 | K     |
| 2452001.9265| 2.82          | 30                    | 279 | K     |
| 2452003.2971| 3.46          | 50                    | 134 | M     |
| 2452004.0013| 0.84          | 30                    | 83  | K     |
| 2452004.2945| 3.21          | 50                    | 172 | N     |
| 2452005.0134| 0.19          | 30                    | 19  | K     |
| 2452006.0340| 0.88          | 30                    | 80  | K     |
| 2452009.9474| 1.52          | 30                    | 149 | K     |
| 2452011.9400| 2.11          | 30                    | 146 | K     |
| 2452012.3150| 1.22          | 50                    | 66  | N     |
| 2452014.9504| 0.08          | 30                    | 9   | K     |
| 2452015.9234| 1.12          | 30                    | 107 | K     |
| 2452016.9480| 1.88          | 30                    | 165 | K     |
| 2452018.9189| 1.38          | 30                    | 136 | K     |
| 2452019.9214| 1.89          | 30                    | 186 | K     |
| 2452021.9212| 1.46          | 30                    | 144 | K     |
| 2452022.9230| 1.59          | 30                    | 160 | K     |
| 2452029.9318| 0.19          | 30                    | 21  | K     |
| 2452032.9592| 0.08          | 30                    | 10  | K     |
| 2452033.9419| 0.23          | 30                    | 21  | K     |
| 2452039.0084| 0.15          | 30                    | 16  | K     |
| 2452039.9603| 0.09          | 30                    | 10  | O     |
| 2452040.9686| 0.47          | 30                    | 44  | K     |
| 2452041.9350| 0.91          | 30                    | 93  | O     |
| 2452041.9407| 1.71          | 30                    | 172 | K     |
| 2452045.9426| 0.08          | 30                    | 10  | K     |
| 2452046.9454| 0.09          | 30                    | 10  | K     |
| 2452047.9466| 0.11          | 30                    | 12  | K     |

Site: K = Kyoto, O = Ouda, N = Nicholas Copernicus Observatory, M=Masaryk University Telescope, E = Erftstadt

Figure 1: Long-term light curve of DW Cnc. The abscissa and the ordinate denote HJD (also calendar date) and the $R_c$-magnitude, respectively. The open circles and the crosses are observations reported to Variable Star Network (VSNET), and our CCD observations, respectively. The open triangles show upper-limits of visual observations. Upper panel: Light curve including all visual observations from 1995 to 2001. Lower panel: Light curve focused on our CCD observations.
Figure 3: Average light curve of modulations. The abscissa and the ordinate denote the phase and the differential magnitude, respectively. The phase was calculated with the 73.4-min period and an arbitrary epoch.

Figure 4: Power spectrum of the light curve of DW Cnc. The abscissa and the ordinate denote the frequency in cycles per day and the power in arbitrary units, respectively.

Figure 4: Power spectrum of the light curve of DW Cnc. The abscissa and the ordinate denote the frequency in cycles per day and the power in arbitrary units, respectively. We show a wide-range power spectrum in figure 4. In this figure, the abscissa and the ordinate denote the frequency in cycle day$^{-1}$ and the power in arbitrary units, respectively. We can find two prominent peaks with wide widths, which demonstrate the QPO nature of the oscillations. We determined their center periods to be 37.5 ± 0.1 and 73.4 ± 0.4 min by fitting Gaussian functions. The shorter QPO period is probably the first harmonic of the longer one; however, due to the small difference between them, we cannot completely exclude the possibility that they are periodicity independent. We show the average light curve of modulations folded with the 73.4-min period in figure 3. We can see the main peak around the phase $\sim 0.8$ and the sub peak around the phase $\sim 0.4$.

The QPO in DW Cnc is unique regarding its long lifetime, large amplitude and long period of kilo-second. QPOs in CVs generally have periods of over one order of magnitude shorter than that in DW Cnc (Patterson (1981)). Although kilo-second QPOs have been reported in some CVs (e.g. Udalski (1988); Kralcheva et al. (1999)), their amplitudes are quite small ($\sim$ a few percent) compared with those in DW Cnc. The amplitude of QPOs in DW Cnc is typically about 0.3 mag and, furthermore, we detected a large flare-like peak whose amplitude reached to 0.6 mag, as can be seen in the upper-right panel of figure 2. We clearly detected the oscillation, or a part of it, in our all observations with a long time-coverage, as shown in figure 2. Although the light curves in the lower-middle and right panel in figure 2 are more noisy due to the bad seasonal condition, they show a clear presence of oscillations with amplitudes and period similar to those in the upper panels. It is thus probable that the QPO has appeared throughout our observations for 61 days.

Except for the two QPOs, the power spectrum shows other noteworthy characteristics. It indicates the presence of a significant power for frequencies lower than 10 cycle d$^{-1}$. The power suddenly weakens at frequencies higher than the 37.5-min QPO. These features of the power spectrum are qualitatively analogous to that in black hole binaries (Rutledge et al. (1999)). The poisson noise dominates for frequencies higher than 100 cycle d$^{-1}$, where the spectrum becomes flat.

4 Discussion

In this section, we compare DW Cnc with the other CVs which also show similar oscillations to evaluate whether their proposed models can be applied to the QPO in DW Cnc.
Figure 2: Quasi-periodic variations of DW Cnc. The abscissa and the ordinate denote HJD and the differential magnitude, respectively. We show typical errors in each panel.
4.1 Spin of White Dwarf

Some IPs show periodic variations on the order of kilosecond (e.g. Schrijver et al. (1985); Patterson, Price (1981)), which are interpreted as being the rotational period of a white dwarf. In the case of GK Per, the long-period QPO (∼5000 s) reported in Watson et al. (1985) is proposed to be a beat phenomenon between the spin of a white dwarf and blobs orbiting at a disk-overflow impact site (Hellier, Livio (1994)) or between the accreting curtain and ordinary DN QPOs (Morales-Rueda et al. (1999)). The long period seen in DW Cnc may prefer a beat scenario rather than a direct spin variation. The most essential objection against this model is that DW Cnc shows no direct evidence for an IP. The two spectra obtained by Stepanian (1982) and Kopylov et al. (1988) show no strong He II emission and, moreover, we detected no firm evidence of a short periodicity originating from the white-dwarf spin. It may be possible that the shorter periodicity of 37.5-min is not the first harmonic of the longer periodicity, but is associated with the spin period. In this case, the kilosecond QPO can be interpreted with the beat between the white-dwarf spin and ∼25-min QPO. Within our available data, the broad profile of the 37.5-min peak in the power spectrum, however, supports that this also has the QPO nature, and probably corresponds to the first harmonic of the 73.4-min QPO.

4.2 Disk Oscillation

Thin-disk oscillations have been proposed to explain the characteristics of QPOs both in DNe and X-ray binaries (Kato (2001)). In a standard disk during DN outbursts, the oscillation wave propagating inward is reflected at the radius where the wave frequency is equal to the epicyclic frequency. Since the wave cannot propagate in an outer cool disk, the wave is trapped in a narrow region. The wave is thus excited enough to be detected as QPOs in DNe (Yamasaki et al. (1995); Yamasaki, Kato (1996)). Although DW Cnc is definitely not a DN, we can expect the condition of an accretion disk analogous to that during DN outbursts, since the object is most likely to be a NL, which is generally believed to have a sufficiently high mass-accretion rate to form a fully-ionized disk (Osaki (1996)). The Balmer emission lines, furthermore, indicate the presence of an optically thin plasma around the disk. In the case of DN outbursts, the QPO frequency is theoretically expected to become higher with time due to an inward propagation of the transition layer (Yamasaki et al. (1995)). On the other hand, the model can explain the long lifetime of the QPO in DW Cnc with no apparent period shortening, since we can expect a quasi-steady disk system in the case of NLs. Kraicheva et al. (1999) reported 50-min QPOs in a NL, MV Lyr and also suggest applying of the trapped disk oscillation model.

According to Yamasaki et al. (1995), the trapped oscillation model provides the expected QPO period, which is the inverse of the Keplerian frequency at the transition layer, that is, $P_{\text{QPO}} \sim 600 \text{ s} \times (r_{\text{front}}/10^{10} \text{ cm})^{3/2}(M/M_{\odot})^{-1/2}$. With the ∼73 min QPO, we estimate $r_{\text{front}} = 3.8 \times 10^{10} \text{ cm}$, assuming a white-dwarf mass of $1M_{\odot}$. This $r_{\text{front}}$ is reasonable in CVs with an orbital period longer than about three hours. The disk-oscillation scenario can thus be an acceptable model for the QPO in DW Cnc if its orbital period is above the period gap. This scenario, however, was originally proposed to explain the ordinary DN QPO, which has amplitudes typically smaller than 0.1 mag (e.g. Yamasaki et al. (1995)). While Kraicheva et al. (1999) proposed this model for ∼0.2 mag QPOs observed in MV Lyr, the amplitude reaching ∼0.3 mag in DW Cnc may be too large for this model to reproduce.

4.3 Superhump

The large amplitude and the relatively long period are rather analogous to superhumps which are observed during superoutbursts in SU UMa-type DNe (Warner (1985)). Superhumps are modulations which generally have a period a few percent longer than an orbital period. According to the tidal instability model, this phenomenon is caused by the gradual precession of an eccentric disk which is developed by an enhanced tidal effect at the 3:1 resonance (Osaki (1989)). As expected from this model, superhumps have been reported not only in SU UMa-type DNe, but also in NLs and AM CVn stars (Patterson et al. (1997); Taylor et al. (1998)). If QPOs in DW Cnc are superhumps, its period is probably the longer one, i.e., 73.4 min. This is because the 37.5-min period indicates that the system is an AM CVn object; however, it contradicts the Balmer emissions observed in the optical spectra. According to Patterson (2001), a system with a shorter orbital period generally has a smaller superhump excess, $\varepsilon = |P_{\text{superhump}} - P_{\text{orb}}|/P_{\text{orb}}$. Assuming $0.02 < \varepsilon < 0.03$ (Patterson (2001)), we can roughly estimate the orbital period of DW Cnc to be 71.3–72.0 min. This is the shortest orbital period in hydrogen-rich CVs, except for the SU UMa-type DNe, V485 Cen ($P \sim 59$ min; Augusteijn et al. (1996)) and 1RXS J232953.9+062814 ($P \sim 64$ min; Uemura et al. (2001)). DW Cnc may thus be a permanent superhumper below the period minimum if its orbital period is 70–80 min.

5 Summary

Our photometric monitoring of the cataclysmic variable DW Cnc revealed that the object remained at
$R_c = 14.68$ mag for 61 days. This characteristic of the long term light curve indicates that it is not a dwarf nova, which was originally proposed in Stepanian (1982), but a nova-like object. It is less likely that the object includes a white dwarf with a strong magnetic field, since both optical spectra obtained by Stepanian (1982) and Kopylov et al. (1988) show only weak He II emission. The possible presence of faint states implies the VY Scl-type nature of DW Cnc. We discovered kilosecond quasi-periodic oscillations (QPOs) in DW Cnc, whose center periods were calculated to be $37.5 \pm 0.1$ and $73.4 \pm 0.4$ min. Compared with typical dwarf-nova QPOs, the oscillation of DW Cnc is unique regarding the large amplitude, long period, and long lifetime. We propose possible interpretations for DW Cnc QPOs: (i) The trapped disk oscillation scenario, which can be acceptable if the orbital period is above the period gap. (ii) The superhump scenario, which can be acceptable if it is below the period minimum.

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