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Dwarf novae in the shortest orbital period regime

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Abstract. Dwarf novae (DNe) having very short orbital periods ($P_{\rm orb}$) are interesting objects in terms of two points of view: the binary evolution and the physics of accretion disks. They are considered as one of the final evolutionary stages of low-mass binaries. It is well known that the observed $P_{\rm orb}$ distribution of cataclysmic variables is inconsistent with that expected from population synthesis studies. We evaluate the intrinsic population of low activity DNe in the shortest $P_{\rm orb}$ regime, which could reconcile the discrepancy between the observation and theory. In the view point of the physics of accretion disks, short $P_{\rm orb}$ DNe, in particular, WZ Sge stars, have received attention because they exhibit unique variations, like early superhumps. We have recently developed a method to reconstruct the structure of disks using multi-band light curves of early superhumps. Here, we introduce the results of this method using the data of the dwarf nova, V455 And.

Key words. Stars: evolution – Stars: novae, cataclysmic variables

1. Introduction

Dwarf novae (DNe) having very short orbital periods ($P_{\rm orb}$) have received attention because of their unique nature in terms of both the binary evolution and the physics of accretion disks. It is widely accepted that they are one of the final evolutionary stages of low-mass binaries. WZ Sge stars form a sub-group of DNe in the shortest $P_{\rm orb}$ regime. They were originally defined by a long recurrence time of superoutbursts ($\gtrsim$ 10 yr) and large outburst amplitudes. Later observations have revealed several unique features, such as early superhumps and rebrightenings (e.g. Howell et al. 1995; Kato et al. 2001).

It is well known that the observed $P_{\rm orb}$ distribution of cataclysmic variables (CVs) is inconsistent with that expected from population synthesis studies (e.g. Howell et al. 1997; Kolb 1993). The theoretical studies predict that most CVs would evolve and accumulated to the minimum $P_{\rm orb}$ ($P_{\rm min}$), which is estimated to be $\sim$ 70 min. However, the observed $P_{\rm orb}$ distribution of CVs shows no such an accumulation of objects near $P_{\rm min}$, and the observed $P_{\rm min}$ is

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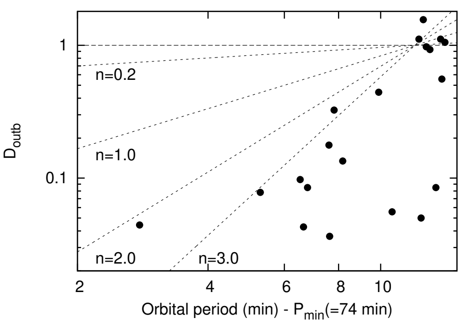

Fig. 1. Outburst detection probability, $D_{\rm outb}$ as a function of $P_{\rm orb} - P_{\rm min}$. The filled circles indicate SU UMa stars whose T_s is known (Uemura 2008). The dotted lines indicate the models (for details, see Uemura et al. 2010).

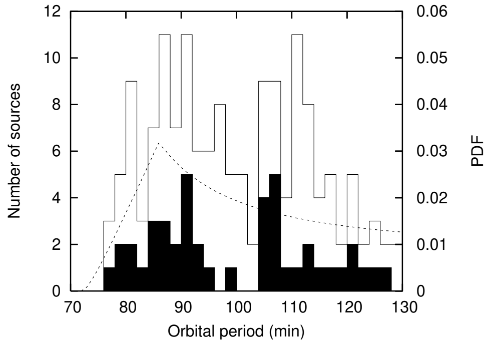

Fig. 2. The distribution of $P_{\rm orb}$ of our DNe sample. The filled and open histograms indicate the ASAS and VSNET samples, respectively. The dashed line indicates the best model derived from our analysis.

$\sim$ 80 min. In § 2, we evaluate the intrinsic population of low activity DNe in the shortest $P_{\rm orb}$ regime, like WZ Sge stars, which could reconcile the discrepancy between the observation and theory.

In the view point of the physics of accretion disks, WZ Sge stars are noteworthy objects because they exhibit unique variations, like early superhumps. Recent observations have suggested that early superhumps are caused by the rotation effect of asymmetrically expanded disks (Kato 2002; Maehara et al. 2007; Matsui et al. 2009). It indicates that the light curves of early superhumps have information of the spatial structure of accretion disks. We have recently developed a method to reconstruct the disk structure using multi-band light curves of early superhumps. In § 3, we introduce the results of this method using the data of the dwarf nova, V455 And.

2. WZ Sge stars as the missing population near $P_{\rm min}$

We can consider that the detectability of superoutbursts, $D_{\rm outb}$ is inversely proportional to the supercycle, T_s. The $D_{\rm outb}$ which are calculated from the observed T_s are shown in figure 1, in which they are normalized by an average T_s of 470 d in $P_{\rm orb} > 85$ min. As can be seen in the figure, $D_{\rm outb}$ decreases toward $P_{\rm min}$, in other words, superoutbursts are less frequent in shorter $P_{\rm orb}$ systems. Therefore, a number of undiscovered WZ Sge stars could be present in the shortest $P_{\rm orb}$ regime.

In Uemura et al. (2010), we estimate the intrinsic $P_{\rm orb}$ distribution of DNe. We assume that the observed distribution, $Q(P_{\rm orb})$ can be expressed with the detectability of superoutbursts, $D(P_{\rm orb})$, and the intrinsic distribution, $I(P_{\rm orb})$, as $Q \propto DI$. D is constructed by $D_{\rm outb}$ and the dependency of the absolute magnitude at the supermaximum on $P_{\rm orb}$. The sample, Q is taken as DNe whose superoutbursts are detected with VSNET or ASAS database between 2003 January and 2007 December (Kato et al. 2004; Pojmanski 2002). Figure 2 shows the $P_{\rm orb}$ distributions of the two sets of samples. The intrinsic distribution, I, is expressed with two parameters, α and $P_{\rm min}$ as follows:

$$I(p) = \begin{cases} p^{-\alpha} e^{-\alpha/p}/A_I & (p \geq 1) \\ 0 & (p < 1) \end{cases} \quad (1)$$

$$p = P_{\rm orb} - P_{\rm min} + 1 \ ({\rm min}). \quad (2)$$

Here, α is a parameter for the degree of the concentration. A larger α yields a distribution with a stronger spike near $P_{\rm min}$. The distribution becomes flat in the case of $\alpha = 0$. A_I is a normalization factor of I. While this formula itself has no physical meaning, it can reproduce the profile of the CV distribution below the period gap predicted by population synthesis studies, with high α.

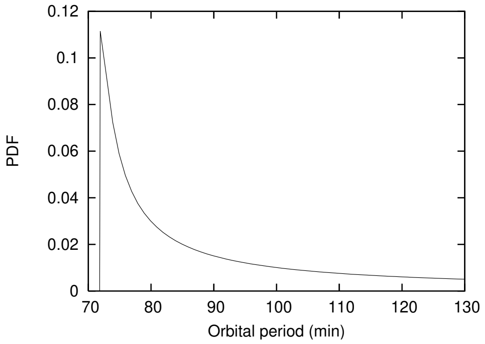

Fig. 3. Intrinsic P_{orb} distribution of DNe estimated from the observed sample of DNe.

We can regard the P_{orb} distributions of our samples as a probability density distributions. Then, we can estimate I in the framework of the Bayesian statistics. We calculated posterior probability distributions of α and P_{min} using the Markov Chain Monte Carlo method (MCMC). Figure 3 shows the intrinsic P_{orb} distribution of DNe with the best parameters of $\alpha = 0.88 \pm 0.30$ and $P_{\mathrm{min}} = 70.5^{+2.6}_{-4.6}$ min for the ASAS sample. The prominent "period spike" feature can be seen. The estimated P_{min} is significantly shorter than the observed one. These features are in agreement with those obtained from the VSNET sample.

This experimental approach indicates that long T_s DNe, like WZ Sge stars, could be responsible for the missing population near P_{min}. Another formulation of I and samples should be tested in this model to validate the present conclusion. Details of the model and calculation can be found in Uemura et al. (2010).

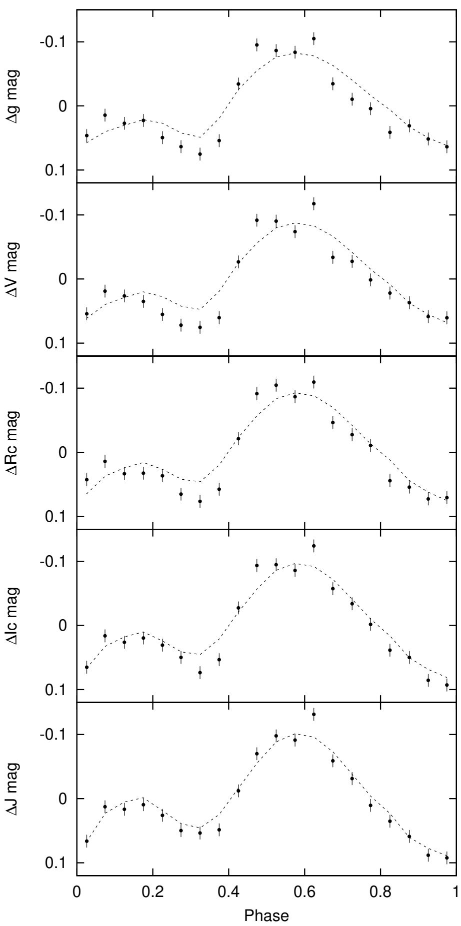

Fig. 4. Light curves of early superhumps of V455 And. From top to bottom, the panels show g, V, R_c, I_c, and J-band light curves. The magnitudes are differential ones from the average magnitudes for each band.

3. Early superhump mapping using multi-band light curves

Figure 4 shows the multi-band light curves of early superhumps observed in V455 And. Based on these data, Matsui et al. (2009) report that the object was bluest at the hump minimum, and the color of the hump component was totally red. It supports the scenario that early superhumps are caused by the geometrical effect of accretion disks which are vertically deformed non-axisymmetrically. Several models have been proposed for the mechanism of such a deformation of disks, for example, a tidal deformation scenario (Kato 2002) and the 2:1 resonance scenario (Osaki, Meyer 2002).

The geometrical structure of disks can be reconstructed from multi-band light curves of early superhumps because its information of the azimuthal direction can be obtained from the time-series data, and that of the radial one from color variations. We have developed a model to reconstruct a height map of disks with the following key assumptions: 1) the observed flux is all from the disk surface, which emits multi-temperature blackbody radiation. 2) The temperature is given as $T = T_{\rm in}(r/r_{\rm in})^{-3/4}$, where $T_{\rm in}$ and $r_{\rm in}$ denote the innermost temperature and radius. 3) The outermost radius of the disk is set to be $r = 0.6a$, where a is a binary separation, corresponding to the 2:1 resonance radius. In addition, the eclipse by the secondary star and self-occultation effect in the disk are considered. Giving $T_{\rm in}$, a, mass-ratio, and inclination angle, we can calculate the multi-band light curves by rotating the disk having a height map, $h(r, \theta)$. Our model is a Bayesian model, which estimates $h(r, \theta)$ from observed light curves. Details of the model and calculation will be published in our forthcoming paper (Uemura, et al. 2011, in prep.).

Figure 5 shows the reconstructed height map of the disk of V455 And, which was calculated from the light curves in figure 4. The model light curves are indicated by the dotted lines in figure 4. We can confirm that the observed light-curves are well reproduced by the model. In the height map, we can see two outermost flaring parts, which are responsible for the primary and secondary maxima of the light curves. In addition to those two major parts, we can see arm-like patterns elongated to relatively inner parts of the disk. They are emphasized in the lower panel of figure 5.

The two outermost flaring parts and the right-lower arm-like feature are apparently similar to the disk structure which is expected from the tidal deformation scenario (Ogilvie 2002; Kato 2002). On the other hand, it is difficult to explain the left-upper arm-like feature, which is responsible for the secondary minimum at phase ~ 0.3 of the light curve.

Thus, our new tomography method will provide a new insight into the physics of accretion disks.

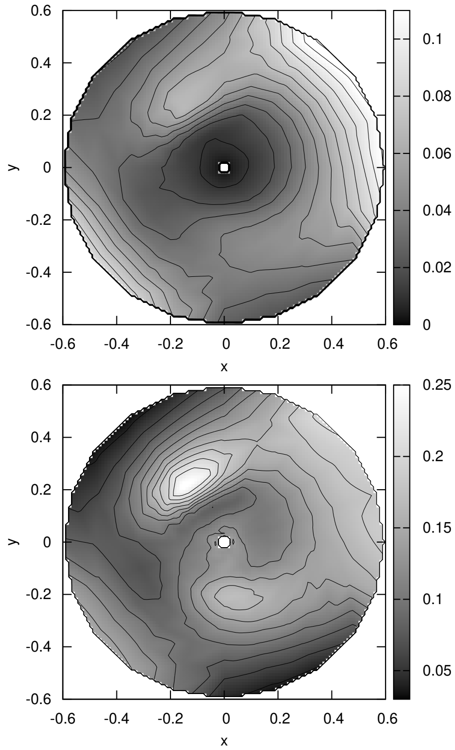

Fig. 5. Height map for the data of V455 And. The upper and lower panels show the maps of h and h/r, respectively. Both the contours and color-maps represent the same h or h/r. The upper panel draws the contours of h = 0.00–0.15 with an interval of 0.01. The lower panel draws the contours of h/r = 0.00–0.24 with an interval of 0.02. The secondary star is located at $(x, y) = (1.0, 0.0)$.

4. Summary

DNe with shorter $P_{\rm orb}$ tend to have longer recurrence time of superoutburst in the shortest period regime of $P_{\rm orb} \lesssim 85$ min. It implies that a number of DNe is left undiscovered near $P_{\rm min}$. Our Bayesian estimation of their intrinsic population reproduces a period spike feature at $P_{\rm min} \sim 70$ min in the $P_{\rm orb}$ distribution, as expected from population synthesis studies. Our new tomography method enables us to reconstruct the structure of accretion disks from multi-band light curves of early superhumps. The reconstructed disk-structure from the data of V455 And is analogous to that expected from tidal deformation, while the arm-like structure at phase ~ 0.3 is an unexpected feature.

5. Discussion

ELENA PAVLENKO: Did you compare colors of early superhumps and ordinary superhumps also?

MAKOTO UEMURA: Yes. The color variations of ordinary superhumps were distinct from those in early superhumps. In particular, a clear bluing trend was associated with the rising phase of ordinary superhumps. I interpret it as a sign of viscous heating. No sign of viscous heating was seen in early superhumps.

VITALY NEUSTROEV: Can the proposed method of multicolour tomography be used not only for superhumps study, but also for other orbital variabilities?

MAKOTO UEMURA: Generally speaking - yes. However, our approach is restricted by blackbody approximation.

CHRISTIAN KNIGGE: How do you reconcile the very short $P_{\rm min}$ you derive with the much longer $P_{\rm min}$ derives by Gänsicke et al. for the SDSS sample?

MAKOTO UEMURA: The short $P_{\rm min}$ is partly due to our model assumption. Since our model assumes that the recurrence time of superoutbursts reaches infinity at a real $P_{\rm min}$, $P_{\rm min}$ is estimated to be shorter than the observed one. The validity of our model assumption should be tested, for example, by a search for superoutbursts of DNe having $P_{\rm orb} \sim 70$ min.

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