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Gravitational radiation of the eclipsing cataclysmic variable WZ Sge near the period minimum

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ABSTRACT

We present the photometric result of the eclipsing cataclysmic variable (CV) WZ Sge near the period minimum (P_{min}). Seven new mid-eclipse times were determined and the orbital ephemeris was updated. Our result shows that the orbital period of WZ Sge is decreasing at a rate of $\dot{P} = -2.72 \times 10^{-13}\, ss^{-1}$. Secular decrease, coupled with previous detection for its donor, suggest that WZ Sge is a pre-bounce system. Further analysis indicates that the observed period decrease rate is about 1.53 times higher than pure gravitational radiation (GR) driving. Moreover, we constructed the evolutionary track of WZ Sge, which predicts that P_{min} of WZ Sge is $\sim 77.98(\pm 0.90)$ min. If the orbital period decreases at the current rate, WZ Sge will evolve past its P_{min} after ~ 25.3 Myr. Based on the period evolution equation we find $\dot{M}_2 \simeq 4.04 \times 10^{-11} M_{\odot} yr^{-1}$, which is compatible with the current concept of CV evolution at the ultrashort orbital period.

Key words: binaries : eclipsing –binaries : evolution –stars : cataclysmic variables –stars : period bouncer–stars: individual (WZ Sge).

1 INTRODUCTION

The evolutionary theory of cataclysmic variables (CVs) predicts that there is an orbital period minimum (P_{min}) present and should be an accumulation of systems (i.e. period spike) at P_{min} (Paczyński & Sienkiewicz 1981; Kolb & Baraffe 1999). The relatively stable mass transfer in CVs is driven by angular momentum losses (AMLs). As a CV evolves, the system requires to shrink its orbit in order to keep the Roche lobe in touch with the donor, resulting in the orbital period decrease. When the system's period reduces to P_{min}, the secondary star is driven out of thermal equilibrium. At this point, the donor becomes a substellar object. The transition from a low-mass star to substellar object leads to its radius to increase in response to mass loss. As a result, the binary separation must expand in order to adapt the internal structure change of the donor. After that, the systems pass through P_{min} and evolve into so-called period bouncers. These predictions have been confirmed by Gänsicke (2009) using the Sloan Digital Sky Survey CVs, who located the position of "period spike" at 82.4(±0.7) min.

In the standard model, the most of CV systems ($\sim 70\%$) were thought to be period bouncers (Kolb 1993). However, only a few period bouncer candidates were reported until now by detecting the brown dwarf secondaries (e.g., Littlefair et al. 2006, 2008; Zharikov et al. 2008; Savoury et al. 2011; McAllister et al. 2015). As one of period bouncer candidates, WZ Sge has a short orbital period of 81.6 min (Patterson et al. 1998) with a low-mass secondary star ($M_2 < 0.11 M_{\odot}$) (Steeghs et al. 2001), which is close to the hydrogen-burning limit. More recently, its donor was estimated to be a L-dwarf by Harrison (2016), suggesting that WZ Sge may not be a period bouncer. To identify period bouncer, the sub-stellar donor is just one of necessary conditions. Therefore, more evidence for identifying period bouncers was required. Fortunately, WZ Sge is an eclipsing CV with a high inclination of $\sim 77°$ (Steeghs et al. 2007). The eclipsing nature provides a rare opportunity to ascertain its evolutionary state. In eclipsing CVs, the most common method for studying the orbital period changes is the timing method by analyzing their $O-C$ diagrams. Recent years

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this method has been used to test the evolutionary state of several short-period eclipsing CVs such as Z Cha (Dai et al. 2009), OY Car (Han et al. 2015), V2051 Oph (Qian et al. 2015). Previous studies revealed that no long-term change in $O-C$ curve of WZ Sge was found (Robinson et al. 1978; Skidmore et al. 1997; Patterson et al. 1998). In present paper, we present new CCD photometric observations of WZ Sge and detect a secular decrease in $O-C$ diagram. Then its evolutionary state was discussed and some parameters were constrained by comparing with theoretical models.

2 OBSERVATIONS

New CCD photometric observations of WZ Sge were obtained by using the 85-cm reflecting telescope mounted an Anor DW436 1K CCD camera at the XingLong station of the National Astronomical Observatory and 2.4-m telescope at the Lijiang observational station of Yunnan Observatories from 2008 to 2016. During the observations, no filters were used in order to improve the time resolution. All observed CCD images were carried out by applying the aperture photometry package of IRAF. Differential photometry was performed, with a nearby non-variable comparison star. Two eclipse light curves of WZ Sge are displayed in Fig. 1. As shown in Fig. 1, both of the eclipse and the out-of-eclipse shapes are variable with time. In addition to the profile changes, the light curves also show the rapid oscillations in brightness, which may be associated with accretion events. The mid-eclipse times are determined by using the same method from Robinson et al. (1978). In this method, mid-eclipse times are the mean of one-half flux times during eclipse ingress and egress. The errors are the standard errors in measuring mid-eclipse times, and they depend on the time resolution and signal-to-noise ratio during observations. All mid-eclipse times and their errors were listed in Table 1. Moreover, the eclipse width was calculated as 184 ± 6 s, which is close to 164 ± 9 s estimated by Robinson et al. (1978) and 210 ± 20 s in Patterson et al. (1998).

3 RESULTS

Mid-eclipse times of WZ Sge have been published in the literatures and the orbital period analysis have been presented by several authors. Robinson et al. (1978) showed that no sign of any orbital period change. Later, Skidmore et al. (1997) updated the orbital ephemeris and suggested that the long-term evolution in the orbital period cannot be detected. After just one year, Patterson et al. (1998) revised the ephemeris again and indicated that the best description for $O-C$ is still a linear ephemeris.

Using our new data (see Table 1) together with all of timings in the literatures, the latest version of $O-C$ diagram was displayed in Fig. 2 (or Fig. 3). The $O-C$ values of all observed timings were computed with the linear ephemeris given by Patterson et al. (1998):

$$Min.I = HJD\,2437547.7284 + 0.056687846 \times E, \qquad (1)$$

where HJD 2437547.7284 is the initial epoch and 0.056687846 d is orbital period. The updated $O-C$ diagram has more coverage with a timescale of ~ 55 yrs.

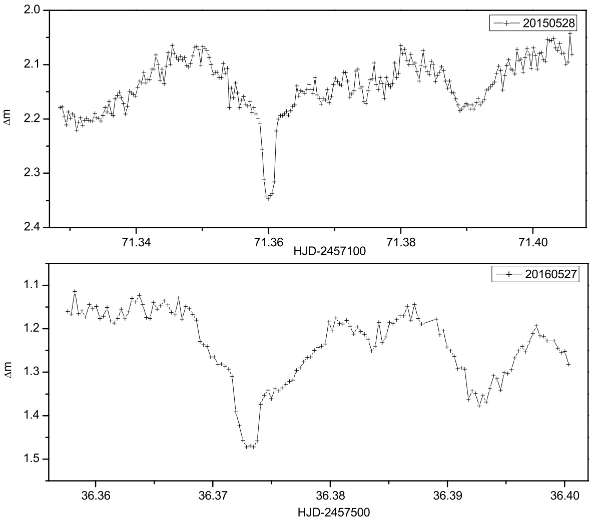

Figure 1. Two eclipsing light curves of WZ Sge obtained with 2.4-m telescope in China.

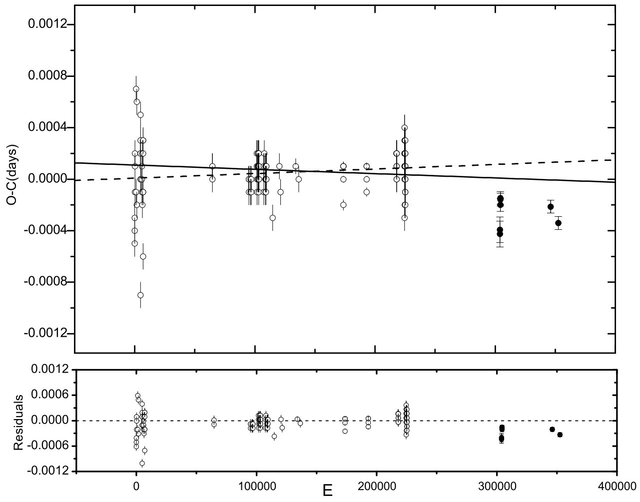

Figure 2. $O-C$ diagram of WZ Sge constructed with a linear ephemeris. The open circles and solid circles refers to the data in literature and our observations, respectively. The dashed line in the upper panel is the linear fit derived by Patterson et al. (1998). The solid line represents the linear ephemeris from our best fitting. The lower panel displays the fitting residuals from the complete linear ephemeris.

Besides, we removed some mid-eclipse times with quoted errors larger than 0.001 days in our analysis. As shown in the top panel of Fig. 2, new data (solid circles) don't follow the previous predicted by a constant-period ephemeris (dash line), implying that a simple linear ephemeris may not be a good description. Nevertheless, it cannot be apriori excluded. Thus a linear least-squares fit was first used to represent the $O-C$ curve. The solid line in the upper panel

Table 1. New CCD mid-eclipse times of WZ Sge.

Date	Min.(HJD)	E	O-C	Err	Filters	Telescopes
2008 Nov 07	2454777.99890	303950	-0.00039	0.00010	N	85cm
2008 Nov 10	2454781.00332	304003	-0.00043	0.00010	N	85cm
2008 Nov 26	2454796.98958	304285	-0.00015	0.00005	N	2.4m
2008 Nov 29	2454799.99398	304338	-0.00020	0.00005	N	2.4m
2008 Nov 30	2454801.01440	304356	-0.00016	0.00005	N	2.4m
2015 May 28	2457171.35995	346170	-0.00021	0.00005	N	2.4m
2016 May 27	2457536.37287	352609	-0.00034	0.00005	N	2.4m

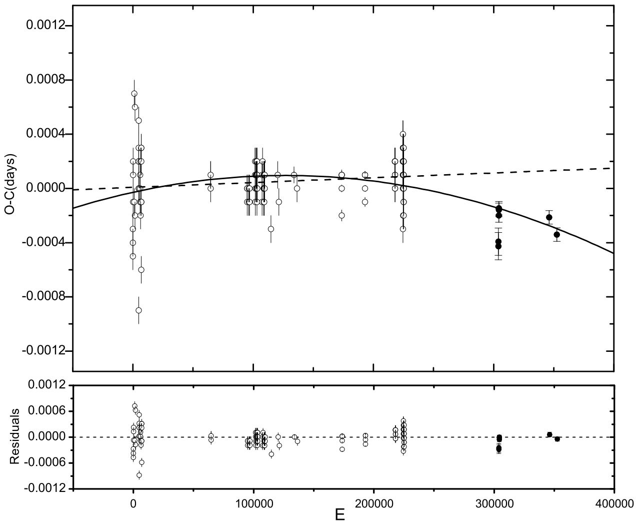

Figure 3. $O-C$ diagram of WZ Sge. The open circles and solid circles denote the data in literature and our observations, respectively. The dashed line in the upper panel represents the linear fit derived by Patterson et al. (1998). The solid line refers to the quadratic ephemeris from our best fitting. After the downward parabolic change was removed, the residuals are plotted in the lower panel.

of Fig. 2 refers to the best-fitting linear ephemeris for the latest $O-C$ diagram. Clearly, the observed data reveal significant deviations from this ephemeris, especially for newly added data, and the residuals show a possible secular decrease (see Fig. 2). It seems that a quadratic ephemeris can describe the general trend of the $O-C$ well. We added a quadratic term to the ephemeris and found that it is a better fit than the linear ephemeris (solid line in Fig. 3). All results of the least-squares fitting are summarized in Table 2. The values of χ^2 also suggest that the quadratic ephemeris fits the data better than the linear ephemeris. In the analysis process above, the $O-C$ values were weighted by the inverse squares of their errors. Fitting residuals are plotted in the lower panel of Fig. 3. A downward parabola in upper panel of Fig. 3 indicates a secular decrease at a rate of $\dot{P} = -1.54 \times 10^{-14}\, days/cycle = -2.72 \times 10^{-13}\, ss^{-1}$.

4 DISCUSSION

When a short-period CV evolved into a period bouncer, its orbital period should increase and the donor becomes a sub-stellar object. With an orbital period near the period minimum and a late-type donor, WZ Sge was classified as a possible period bouncer by Patterson (1998). Meanwhile, Ciardi et al. (1998) claimed that WZ Sge has been passed P_{min} and the donor was a sub-stellar object with a low temperature of $\leq 1700K$. Until recently, a direct detection for the donor of WZ Sge suspected that it may not be a bounce-back system (Harrison 2016). Harrison pointed out that the L2-L5 donor is earlier than the predicted spectral type in period bouncers by Knigge et al. (2011). However, this solution still has some deficiencies. First, the predicted result by Knigge et al. (2011) is based on a semi-empirical donor evolution sequence, and the samples contain the intrinsic dispersions. Second, the L2-L5 donor was detected by using K-band spectra. In effect, J-band is much better than K-band for L-dwarfs identification. Therefore, further evidence should be provided to confirm WZ Sge's classification. As noted above, the orbital period of WZ Sge is decreasing at a rate of $\dot{P} = -2.72 \times 10^{-13}\, ss^{-1}$. If it is a period-bounce system, the period should be increasing rather than decreasing. Combining the decreasing period with a L2-L5 donor presented by Harrison (2016), we believe that WZ Sge is a pre-bounce CV and has not yet evolved past P_{min}.

WZ Sge-type CVs are generally thought to be the dominant objects at P_{min} (Zharikov 2014). As a prototype star of these stars, WZ Sge has a short period of 81.6 min, which is close to the current estimated P_{min} of $\sim 81.8 \pm 0.9$ min by Knigge et al. (2011). Hence, its evolutionary state is crucial for understanding the evolution of CVs and testing theoretical model. In the standard model of CVs, the secular evolution of short-period CVs ($P_{orb} \leq 2$ h) is driven by pure gravitational radiation (GR) (Rappaport et al. 1983; Spruit & Ritter 1983). The period decrease rate due to GR was given by (Kraft et al. 1962; Paczyński 1967)

$$\frac{\dot{P}_{GR}}{P} = -3\frac{32G^3}{5c^5}\frac{M_1 M_2 (M_1 + M_2)}{a^4}. \tag{2}$$

a is the orbital separation, M_1 and M_2 are the masses of gainer and donor stars, respectively. For WZ Sge, $M_1 = 0.85(\pm 0.04)M_\odot$ and $M_2 = 0.078(\pm 0.006)M_\odot$ given by Steeghs et al. (2007), which can be combined with Kepler's third law to yield $a = 0.61R_\odot$. Finally, the period decrease caused entirely by GR is calculated as $\dot{P}_{GR} = -1.78(\pm 0.12) \times 10^{-13}\, ss^{-1}$. The observed period decrease is $\simeq 1.53$ times higher than purely GR-driven decrease rate. To ascertain the evolutionary state of WZ Sge, we have stud-

Table 2. Parameters of the best fitting for $O-C$.

Parameters	Linear ephemeris: $O-C=\Delta T_0+\Delta P_0 E$	Quadratic ephemeris: $O-C=\Delta T_0+\Delta P_0 E+\beta E^2$
Degrees of freedom, ν	147	146
Correction on the initial epoch, ΔT_0 (days)	$1.09(\pm 0.30)\times 10^{-4}$	$2.87(\pm 0.38)\times 10^{-5}$
Correction on the initial period, ΔP_0 (days)	$-3.34(\pm 1.70)\times 10^{-10}$	$+1.96(\pm 0.43)\times 10^{-9}$
Rate of the linear decrease, 2β (days/cycle)		$-1.54(\pm 0.13)\times 10^{-14}$
Adjust R-square, χ^2 for ν	0.019	0.219

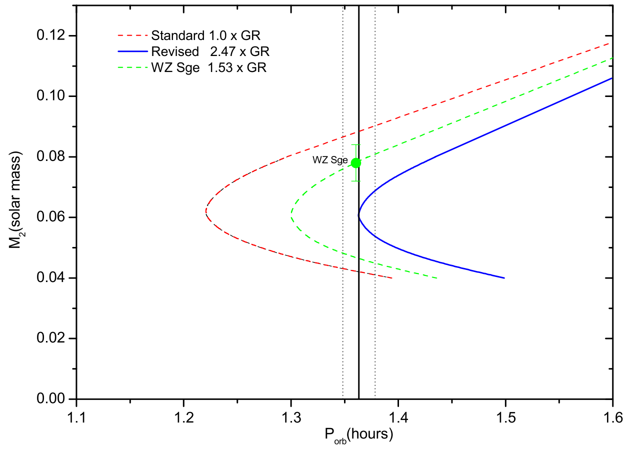

Figure 4. Donor mass (M_2) versus orbital period (P_{orb}) relationship for WZ Sge. The location of WZ Sge is labelled as the solid green circle. The evolutionary track according to the standard model of CV evolution (pure GR driving AML below the gap) is shown with the dashed red line. The solid blue line represents the revised model track from Knigge et al. (2011). The vertical solid black line marks the location of the period minimum ($\sim 81.8\pm 0.9$ min) predicted by the revised model. The dashed green line is the possible evolutionary track of WZ Sge.

ied the relation between donor mass and orbital period (see Fig. 4). The different evolutionary tracks are shown in Fig. 4. The blue track represents the revised model from Knigge et al. (2011) and the red dashed is the standard model track. The revised model showed that AML rates below the gap are $\simeq 2.47$ times higher than pure GR driving. The location of WZ Sge ($\simeq 1.53\times GR$) lies between the revised model and the standard model track. This position corresponds to $M_2 = 0.078 M_\odot$, in agreement with the result of Steeghs et al. (2007). Moreover, we have constructed the possible evolution track of WZ Sge (green dash line) using the method described by Knigge et al. (2011). Along this track, the predicted P_{min} for WZ Sge is $\sim 77.98(\pm 0.90)$ min. Assuming the orbital period decreases at the current rate ($\dot{P}$), then WZ Sge will evolve past its P_{min} after ~ 25.3 Myr.

P_{min} is closely connected to the natures of CV donors. Base on the mass-radius and period-density relation for CV donors, the period evolution equation was derived as (Robinson et al.1991; Knigge et al. 2011)

$$\frac{\dot{P}}{P}=\frac{3\zeta-1}{2}\frac{\dot{M}_2}{M_2}, \tag{3}$$

where ζ is the mass-radius index. If the orbital period decrease ($\dot{P}<0$), $\zeta<\frac{1}{3}$ is required. When $\zeta=\frac{1}{3}$, $P_{orb}=P_{min}$. Revised model fit to the mass-radius relation of CV donors provides the relevant parameters including mass-radius index (Knigge et al. 2011). For WZ Sge, the donor mass corresponds to $\zeta \simeq 0.559$. Plugging these parameters into equation (3), we find $\dot{M}_2 \simeq 4.04\times 10^{-11} M_\odot yr^{-1}$. The position of WZ Sge-type stars is marked on $\dot{M}_2$ versus P_{orb} diagram of CVs by Zharikov et al. (2013), corresponding to the mass transfer range from $\sim 2\times 10^{-11} M_\odot yr^{-1}$ to $\sim 8\times 10^{-11} M_\odot yr^{-1}$. Our $\dot{M}_2$ value is compatible with this limit. The decreasing of orbital period of WZ Sge is accompanied by the decline in the mass transfer rate. After reaching a lower mass transfer rete ($\dot{M}_2 \leq 2\times 10^{-11} M_\odot yr^{-1}$), it eventually enters the period bouncer regime.

5 CONCLUSIONS

We have presented the photometric results of an eclipsing CV WZ Sge. Seven new mid-eclipse times were determined and the updated ephemeris has a significant improvement to ascertain the evolutionary state of WZ Sge. Our analysis reveals that the orbital period of WZ Sge is undergoing a secular decrease at a rate of $\dot{P}=-2.72\times 10^{-13}\, ss^{-1}$. Secular decrease is opposite to the expected increase in period bouncers. This together with a L2-L5 type donor detected by Harrison (2016) suggest that WZ Sge is a pre-bounce system. To study its evolution further, we find that the observed $\dot{P}$ is about 1.53 times larger than pure GR driving decrease. Moreover, we investigate whether WZ Sge is indeed a system still evolving toward its P_{min} by studying the $M_2 - P_{orb}$ relation. We constructed the evolution track of WZ Sge, and compare with the standard model and revised model track from Knigge et al. (2011). The location of WZ Sge in Fig. 4 would match to $M_2 = 0.078 M_\odot$, in consistent with Steeghs et al. (2007). Its evolution track predicts a $P_{min} \simeq 77.98(\pm 0.90)$ min. Supposing the orbital period decreases at the present rate, then WZ Sge will become a bounce-back CV after ~ 25.3 Myr. Using the period evolution equation, the mass transfer rate is derived as $\dot{M}_2 \simeq 4.04\times 10^{-11} M_\odot yr^{-1}$, which is compatible with the conclusion of Zharikov et al. (2013).

WZ Sge-type stars were regarded as the dominant CVs at P_{min} (Zharikov et al. 2013; Zharikov 2014). Indeed, these systems have ultrashort orbital periods of ~ 80 min and undergo rare super-outbursts but absence of normal outbursts. This implies that there are an extremely low viscosity parameter ($\alpha \sim 0.01-0.001$) and a very low mass transfer rate (a few$\times 10^{-11} M_\odot yr^{-1}$) (Smak 1993; Osaki 1994). There are already some authors to study the properties of accretion disk of the bouncer candidates (e.g. Zharikov et al. 2013; Zharikov 2014). In addition, a few eclipsing CVs with substellar donors were detected (e.g. Littlefair et al. 2006, 2008; Savoury 2011; McAllister et al. 2015). In fact, their eclipsing properties offer important clues concerning the long-term evolution of orbital periods and the identification of period bouncers. However, so far, the discussion in this aspect is very rare. This paper provides a good example but much work remains to be done.

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