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IS WX CEN A POSSIBLE TYPE Ia SUPERNOVA PROGENITOR WITH WIND-DRIVEN MASS TRANSFER?

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ABSTRACT

WX Cen is one of a few compact binary supersoft X-ray sources (CBSS) in the Galaxy that is a possible Type Ia supernova (SN Ia) progenitor. The supersoft X-ray radiation is explained as hydrostatic nuclear burning on the surface of the white dwarf component that is accreting hydrogen from a stellar companion at a high rate. If the mass donor in this system has a low mass, as has been suggested in the literature, one would expect a high wind-driven mass transfer rate. In that case, the orbital period of the system should increase. To test this theoretical prediction, we have monitored the system photometrically since 2010. By using four newly determined eclipse timings together with those collected from the literature, we discovered that the orbital period is decreasing at a rate of $dP/dt = -5.15 \times 10^{-7}$ days yr^{-1}. The long-term decrease in the orbital period is contrary to the prediction that the system is powered by wind-driven accretion. It therefore seems plausible that the mass donor could be more massive than the white dwarf, and that the mass transfer is driven by the thermal instability of the donor star. This finding suggests that WX Cen is a key object to check the physical mechanisms of mass accretion in CBSS. The corresponding timescale of the period change is about $P/\dot{P} \sim 0.81 \times 10^6$ yr, indicating that WX Cen may evolve into an SNe Ia within one million years in the Galaxy.

Key words: binaries: close – binaries: eclipsing – stars: evolution – stars: individual (WX Cen) – stars: winds, outflows

1. INTRODUCTION

The origin of Type Ia supernovae (SNe Ia) is not fully understood, although two principal scenarios have been proposed, i.e., the single-degenerate model (e.g., Wheeler & Hansen 1971; Whelan & Iben 1973) and the double-degenerate model (the merger of two white dwarfs; e.g., Tutukov & Yungelson 1979; Webbink 1984). In the single-degenerate scheme, mass is transferred from a non-degenerate star onto a C/O white dwarf. The mass of the white dwarf grows slowly and an SNe Ia occurs when it reaches the Chandrasekhar mass limit.

Compact binary supersoft X-ray sources (CBSS) are possible progenitors of SNe Ia that may produce these supernovae through the single-degenerate scenario. Their large luminosity is mostly radiated in the supersoft X-ray spectral range (20–80 eV), and originates from hydrostatic hydrogen burning on the surface of a C/O white dwarf. In order to produce this process, a high mass-accretion rate ($\sim 10^{-7}\ M_\odot\ \mathrm{yr}^{-1}$) is needed. To date, two physical mechanisms have been proposed to produce the high rate of mass accretion. One is mass transfer on a Kelvin–Helmholtz timescale from a more massive donor to a less massive white dwarf, and the orbital period should be decreasing (e.g., van den Heuvel et al. 1992; Kahabka & van den Heuvel 1997). The other is that the mass transfer is caused by wind-driven accretion from a strongly irradiated low-mass donor that produces an increase in the orbital period (e.g., Van Teeseling & King 1998). Therefore, monitoring the orbital period variation could provide a critical test of the two mechanisms (e.g., Oliveira & Steiner 2007).

WX Cen is one of the galactic counterparts of CBSS (e.g., Patterson et al. 1998; Oliveira & Steiner 2007) that is similar to V Sge (e.g., Patterson et al. 1998) and V617 Sgr (e.g., Steiner et al. 1999, 2006). It was identified by Eggen et al. (1968) as the optical counterpart of the X-ray transient Cen XR-2. This identification as well as the classification as a WN-7 star was rejected in the WR stars catalog (van der Hucht et al. 1981). Photometric observations indicated that its colors are typical of cataclysmic variables, i.e., $(B - V) = 0.4$ and $(U - B) = -0.7$, and variability with timescales of a few hours were reported (e.g., Eggen et al. 1968; Munford 1971). This variable was found to be a binary star by Diaz & Steiner (1995) with an orbital period of 10 hr. The light curve has an amplitude of ∼0.32 mag and has a narrow minimum (Oliveira & Steiner 2004), similar to those seen in V Sge and V617 Sgr. It is characterized by strong emission lines of O VI and N V, and He II is at least two times more intense than H_β (Steiner & Diaz 1998). These properties are similar to those of the CBSS seen in the Magellanic Clouds. If the primary component is a white dwarf star ($M_1 < 1.4\ M_\odot$), the analysis by Diaz & Steiner (1995) suggested that the secondary should be a low-mass star with a mass of less than 0.35 solar mass ($M_2 < 0.35\ M_\odot$).

V Sge stars are considered to be galactic counterparts of CBSS (Steiner & Diaz 1998). As one of the three well-known V Sge stars having eclipses, WX Cen provides a good opportunity to measure the changes of the orbital period. Investigations of WX Cen have suggested that it has a low-mass ratio (Diaz & Steiner 1995; Oliveira & Steiner 2004). It was suggested by Oliveira & Steiner (2007) that, similar to the other three long-period systems, CAL 87, QR And, and CAL 83, its orbital period should be increasing. To check this conclusion, we monitored it since 2010 and analyze the period change of the system in the present Letter.

2. NEW CCD PHOTOMETRIC OBSERVATIONS AND ORBITAL PERIOD CHANGES

WX Cen was monitored since 2010 March 21 by using the 2.15 m Jorge Sahade telescope at Complejo Astronomico El

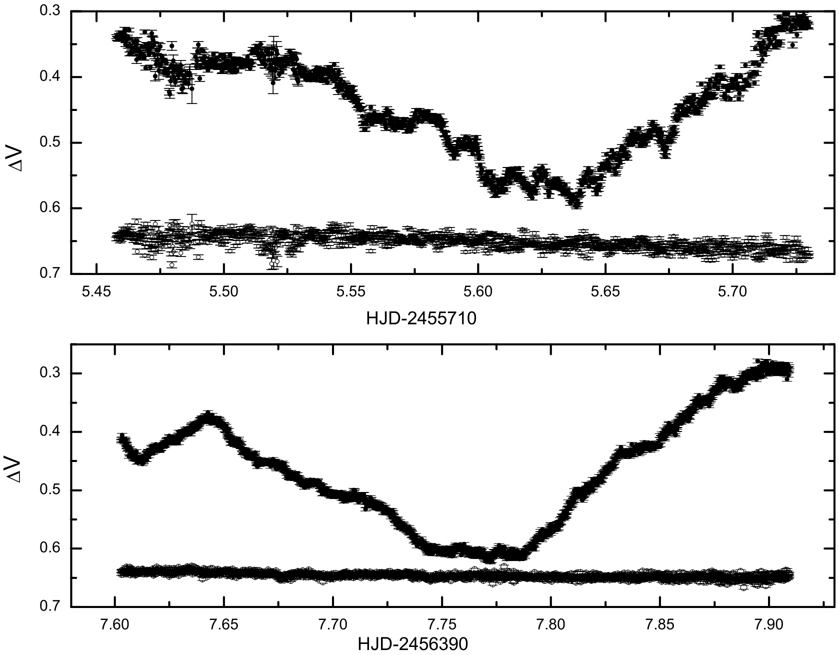

Figure 1. Light curves of WX Cen in the V band obtained by using the 2.15 m Jorge Sahade telescope on 2010 June 2 and on 2013 April 14. Also given in open circles are the magnitude difference between the comparison and check stars (the almost horizontal lines).

Table 1
New CCD Times of Light Minimum

HJD (days)	Errors (days)	Filters
2455276.5775	0.0022	I
2455710.6281	0.0010	N
2455715.6299	0.0003	V
2456397.7677	0.0001	V

Table 2
$O-C$ Values of Times of Light Minimum

HJD (days)	E	$O-C$ (days)	Residuals (days)
2448378.41o	−7869	−0.016	−0.002
2451642.821	−40	+0.014	+0.018
2451643.638	−38	−0.003	+0.001
2451659.485	0	0.0000	+0.004
2451660.711	3	−0.025	−0.021
2451661.579	5	+0.009	+0.013
2452780.668	2689	−0.023	−0.014
2452781.515	2691	−0.010	−0.001
2455276.5775	8675	−0.0364	+0.0021
2455710.6281	9716	−0.0412	+0.0010
2455715.6299	9728	−0.0429	+0.0003
2456397.7677	11364	−0.0518	+0.0001

Leoncito (CASLEO), San Juan, Argentina. The observations in 2010 and 2011 were obtained by using a Versarray 1300B camera with a thinned EEV CCD36-40 of 1340 × 1300 pixel CCD chip, while those in 2013 were acquired by using a new CCD camera, i.e., Versarray 2048B, Roper Scientific. During the observation, the clock of the control computers operating the Versarray 1300B and Versarray 2048B CCD cameras was calibrated against UTC time by the GPS receiver's clock. Two nearby stars that have nearly similar brightness in the same field of view of the telescope were chosen as the comparison star and the check star, respectively. The coordinates of the comparison star are: $\alpha_{2000} = 13^{\rm h}12^{\rm m}35\overset{\rm s}{.}1$ and $\delta_{2000} = -63^\circ22'24\overset{''}{.}8$, while those of the check star are: $\alpha_{2000} = 13^{\rm h}12^{\rm m}36\overset{\rm s}{.}7$ and $\delta_{2000} = -63^\circ24'43\overset{''}{.}6$. All images were reduced by using PHOT (measure magnitudes for a list of stars) of the aperture photometry package of IRAF. The data processing was similar to that used for RR Cae and NY Vir, where two circumbinary planets were discovered (Qian et al. 2012a, 2012b).

The corresponding light curves in the V band obtained on 2010 June 2 and on 2013 April 14 are displayed in Figure 1. As shown in the figure, the eclipse depth is about ∼0.32 mag similar to that observed by Oliveira & Steiner (2004). The light curve observed on 2010 June 2 shows a fluctuation with a timescale of tens of minutes (in the upper panel of Figure 1). However, this fluctuation disappeared when we re-observed it on 2013 April 14 (in the lower panel of Figure 1). By using our data, four times of light minimum were derived which are displayed in Table 1. The third column gives the filters used during the observations where "N" refers to no filters used.

Diaz & Steiner (1995) identified WX Cen as the second binary system with observational properties similar to those of V Sge and derived the orbital period to be 0.417 days. This period was later revised by Oliveira & Steiner (2004). They determined the following linear ephemeris:

$$\text{Min. } I(\text{HJD}) = 2{,}451{,}659.485 + 0\overset{\rm d}{.}4169601 \times E, \qquad (1)$$

where E is the cycle number.

We analyzed the changes in the orbital period by using our times of light minimum together with those collected by Oliveira & Steiner (2004). The $(O-C)$ values with respect to the linear ephemeris derived by Oliveira & Steiner (2004) are listed in Table 2. The corresponding $(O-C)$ curve is displayed in Figure 2 as a function of the epoch number E. As displayed in the upper panel of Figure 2, the general trend of the $O-C$ curve is a downward parabolic variation which indicates a decrease in

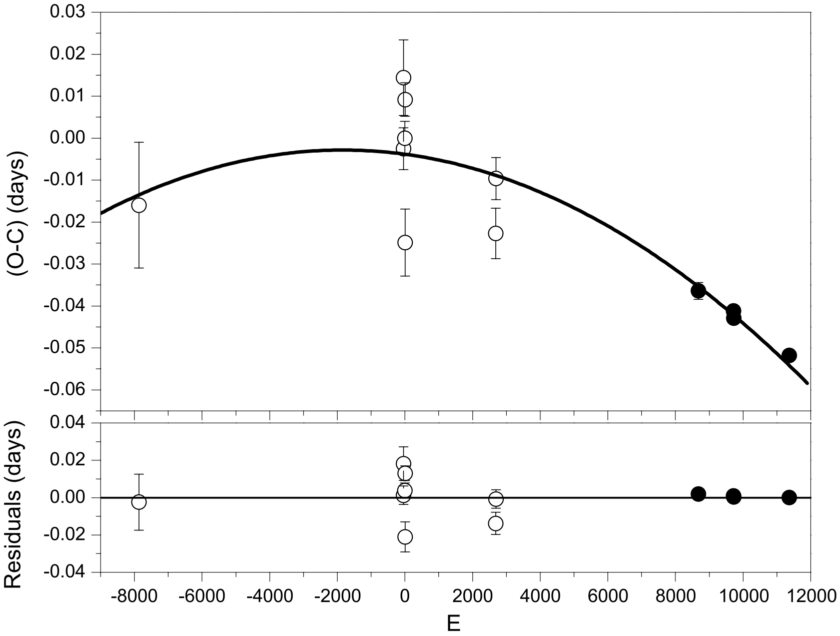

Figure 2. $O - C$ diagram with respect to the linear ephemeris in Equation (1). The downward parabolic change (solid line) reveals a long-term decrease of the orbital period. The open circles refer to observations given by Oliveira & Steiner (2004), while solid circles refer to our new data. The residuals after the long-term decrease was subtracted are shown in the lower panel where no further variations can be seen.

the orbital period. A least-squares fit yielded

$$\begin{aligned}\text{Min. } I = {} & 2{,}451{,}659.4812(\pm 0.0021) \\ & + 0.41695902(\pm 0.00000030) \times E \\ & - 2.94(\pm 0.35) \times 10^{-10} \times E^2. \end{aligned} \qquad (2)$$

The quadratic term in Equation (2) reveals a linear decrease at a rate of $\dot{P} = -5.15(\pm 0.61) \times 10^{-7}$ days yr^{-1} (or 4.4 s in about 100 yr). The solid line in the upper panel of Figure 2 refers to this linear period decrease. The residuals with respect to the downward parabolic variation are displayed in the lower panel of Figure 2 and show that no further changes can be traced, indicating that Equation (2) describes the $O - C$ curve well.

3. DISCUSSIONS AND CONCLUSIONS

As the first counterpart of CBSS in the Galaxy, V Sge has a high-mass ratio of $q = 3.8$ indicating that the mass donor is the more massive one of the binary components. The decrease in the orbital period reveals that the mass transfer from the donor to the white dwarf occurs on the Kelvin–Helmholtz timescale. This process provides a high accretion rate that is required to produce the supersoft X-ray radiation through hydrostatic hydrogen burning on the surface of the white dwarf. However, when the orbital period is shorter than 6 hr (e.g., Oliveira & Steiner 2007), the mass of the donor is expected to be so small that this mechanism is not expected to work. In this case, the mass transfer is expected to be due to a different mechanism, i.e., the wind-driven accretion produced by a strongly irradiated low-mass donor (e.g., Van Teeseling & King 1998). The investigation by Diaz & Steiner (1995) appeared to indicate that the mass donor of WX Cen is a low-mass star ($M_2 < 0.35\ M_\odot$), and these authors suggested that wind-driven accretion does work here which implies that the orbital period should be increasing. The fact that we observe just the opposite, a period decrease, suggests that the wind-driven model is not the correct one for this system. It should be pointed out that the grounds for assuming a low-mass donor are quite doubtful.

The reason for the doubt is that the interpretation of the emission line radial velocities in supersoft X-ray systems like WX Cen is notoriously difficult. The broad emission lines that dominate the spectrum are due to a combination of the spectra of the accretion disk, the wind from this disk, a stream, and the wind from the heated side of the donor star. The spectrum of the donor itself is not seen, and the mass estimate of the donor is based on the amplitudes of the radial velocity exhibited by the emission lines. This was done under the assumption that the wavelengths of the wings of these lines represent the velocity of the accreting white dwarf in the system. In fact, in their paper, Diaz & Steiner (1995) realized that this is a quite uncertain assumption, as they say about the estimate of a mass of 0.35 $M_\odot$ for the companion in WX Cen. The assumption that the radial velocities of the emission line wings reveal the primary orbital motion is based on the idea that such emission lines arise in the inner part of the accretion disk. However, the non-sinusoidal shape of the radial velocity curves in fact indicates that the hypothesis of the wing emission being kinetically associated with the white dwarf is not justified by the observations. For this reason, the conclusion that the secondary star has a low mass ($\sim$0.35 $M_\odot$) and therefore the accretion-driven wind is by no means certain. The discovery of the decreasing orbital period of WX Cen, reported here, seems to confirm that the donor is not a low-mass star, but is more massive than the white dwarf in the system.

In view of the relatively "long" orbital period of this system in which the donor fills its Roche lobe, this is in fact a quite "natural" solution, and this would at once explain why the orbital period of this system is decreasing. The period changes of the three well-known V-Sge-type binary stars are listed in Table 3. As shown in this table, V617 Sgr has the shortest period (4.98 hr) and should have a low-mass donor (Steiner et al. 1999). Therefore, a strong radiation should cause a high rate of wind-driven accretion. The period increase discovered for this system by Steiner et al. (2006) is in agreement with the prediction. On the other hand, some of the properties of WX Cen are similar to

Table 3
Orbital Period Changes of Three V Sge-type Binary Stars

Name	P (days)	q (M_2/M_1)	$\dot{P}$ (days yr^{-1})	$P/\dot{P}$ (yr)	Ref.
V617 Sge	0.207166	0.4	$+1.9 \times 10^{-7}$	1.1×10^{6}	(1), (2)
WX Cen	0.416960	0.35	-5.2×10^{-7}	0.8×10^{6}	(3), (4), (5)
V Sge	0.514197	3.8	-1.3×10^{-7}	4.0×10^{6}	(5), (6)

References. (1) Steiner et al. 1999; (2) Steiner et al. 2006; (3) present paper; (4) Oliveira & Steiner 2004; (5) Oliveira & Steiner 2007; (6) Patterson et al. 1998.

those of V Sge. Both systems have a longer orbital period and their periods are decreasing. These properties support the idea that the period decrease of WX Cen is caused by mass transfer from the donor to the white dwarf as in the case of V Sge. If one would assume the white dwarf to be more massive, say 1.2 $M_\odot$, and the donor to have a mass of, for example, 1.32 $M_\odot$, one finds that the radius of the donor (=Roche lobe) is 1.355 $R_\odot$, which is perfect for a slightly evolved donor which started out at a somewhat higher mass, say 1.4 or 1.5 $M_\odot$, at the beginning of the mass transfer.

Similar to WX Cen, CAL 87 is also a long-period CBSS, with a period of 10.62 hr. In the same way, the inference that the companion of CAL 87 is only 0.34 $M_\odot$ is in our opinion equally uncertain (e.g., Oliveira & Steiner 2007). This period increase of the binary system can be explained by mass transfer from a slightly evolved donor with a mass of 0.9 or 1.0 $M_\odot$ to the massive white dwarf (∼1.35 $M_\odot$). The CAL 87 system could have started Roche lobe overflow with a donor mass larger than the 1.35 $M_\odot$ white dwarf in this system. After some time of mass transfer, the donor in such a system will have become the less massive star, and will continue mass transfer by Roche overflow, which will make the orbital period increase. Therefore, the observed orbital period increase in the case of CAL 87 can equally well be explained by thermal-timescale mass transfer from a Roche lobe-filling donor, and the orbital period increase of this system is therefore no proof for the wind-driven model, with a very low-mass donor star.

The finding of the period decrease for WX Cen makes it an important target to test the physical mechanisms of mass accretion in CBSS, i.e., wind-driven models and thermal-timescale Roche lobe overflow-driven mass transfer in supersoft X-ray binaries. We conclude that the mass accretion in long-period supersoft X-ray binaries is likely to be driven by thermal-timescale Roche lobe overflow mass transfer rather than by wind-driven mass transfer produced by a strongly irradiated donor. The timescale of the period change is about $P/\dot{P} \sim 0.8 \times 10^{6}$ yr suggesting that it may evolve into an SNe Ia within one million years. To check this conclusion and to investigate the period change of the binary star, more photometric data are required in the future.

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