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Confirmation and revision on the orbital period change of the possible type Ia supernova progenitor V617 Sagittarii

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Abstract

This work reports new photometric results of eclipsing cataclysmic variable V617 Sagittarii (V617 Sgr). We analyzed the orbital period change of V617 Sgr by employing three new (since 2010) CCD eclipse timings along with all the available data from the literature. It was found that the orbital period of V617 Sgr undergoes an obvious long-term increase, which confirms the result revealed by Steiner et al. (2006). The rate of orbital period increase was calculated to be $\dot{P} = +2.14(0.05) \times 10^{-7}$ d yr^{-1}. This suggests the lifetime of the secondary star will end in a timescale of 0.97×10^{6} yr faster than that predicted previously. In particular, a cyclic variation with a period of 4.5 yr and an amplitude of 2.3 min may appear in the $O-C$ diagram. Dominated by the wind-accretion mechanism, high mass transfer from the low mass secondary to the white dwarf is expected to continue in the V Sge-type star V617 Sgr during its long-term evolution. The mass transfer rate $|\dot{M}_{\mathrm{tr}}|$ was estimated to be in the range of about 2.2×10^{-7} to $5.2 \times 10^{-7}\ M_{\odot}$ yr^{-1}. Accordingly, the already massive ($\geq 1.2\ M_{\odot}$) white dwarf primary will process stable nuclear burning, accrete a fraction of the mass from its companion to reach the standard Chandrasekhar mass limit ($\simeq 1.38\ M_{\odot}$), and ultimately produce a type Ia supernova (SN Ia) within about 4–8 $\times 10^{5}$ yr or earlier.

Key words: binaries: close — binaries: eclipsing — stars: evolution — stars: individual (V617 Sgr) — stars: winds, outflows

1 Introduction

V617 Sgr was initially identified as a Wolf–Rayet star, WR 109 in the catalog of van der Hucht et al. (1981), and also once misapprehended as an irregular variable in the General Catalogue of Variable Stars (GCVS: Kholopov et al. 1987). On the basis of some photometric and spectroscopic observations (Steiner et al. 1988, 1999, 2006, 2007; Cieslinski et al. 1999), it was commonly believed that V617 Sgr is a close eclipsing cataclysmic variable binary with an orbital period of 0.207 days (4.98 hr). V617 Sgr was observed to have a median *V* magnitude of 14.7 mag, and its orbital inclination is 72°. Moreover, it was observed to present a double eclipse with minima and maxima in the light curves, strong ionized emission lines (such as He II, NV, OVI, etc.) in the optical spectrum, and high/low photometric states, which are quite similar to those seen in V Sge. So, V617 Sgr was included in a subgroup of several objects, namely the V Sge-type stars [the others are WX Cen, DI Cru, and QU Car, with relatively low orbital inclinations; Hachisu & Kato (2003); Oliveira & Steiner (2004); Steiner et al. (2006); Kafka et al. (2012)]. On account of the striking similarities in the optical spectroscopic and X-ray emission characteristics, the V Sge-type stars were proposed as the galactic counterpart of the Compact Binary Supersoft X-ray Source (CBSS) in the Magellanic Clouds (Steiner & Diaz 1998).

The supersoft X-ray sources are, in principle, thought to be promising candidates for SNe Ia progenitors (van Teeseling & King 1998; Knigge et al. 2000; Parthasarathy et al. 2007; Kato 2010), mostly radiating strong luminosity in the supersoft X-ray spectral range (20 to 80 eV). This emission is attributed to hydrostatic nuclear burning on the surface of a C/O white dwarf. To make this process happen, a high mass-accretion rate (about $10^{-7}\,M_{\odot}\,\mathrm{yr}^{-1}$) is demanded, which may originate from two physical channels in systems with inverted mass ratios. One is mass transfer from a more massive donor onto a less massive white dwarf on a Kelvin–Helmholtz timescale. Then, the orbital period tends to decrease with time (van den Heuvel et al. 1992). The alternative cause for high mass accretion is a very strong wind from the strongly irradiated low-mass donor (i.e., the wind-accretion scenario), which should produce an increase in the orbital period (van Teeseling & King 1998; Oliveira & Steiner 2007).

Secular evolution in eclipsing binary systems can be investigated by means of measuring the change of orbital period from CCD monitoring of timings with high accuracy. For V617 Sgr with an orbital period of 4.98 hr, a long-term increase in the orbital period was found, following the wind-accretion scenario as pointed out by Steiner et al. (2006). To inspect this result, new CCD observations on the eclipsing binary V617 Sgr were implemented during 2010–2013, as shown in section 2. A revised analysis of the orbital period change of V617 Sgr is introduced in section 3. Finally, we discuss the observed period evolution and the mass transfer process that may provide a deeper insight into the nature of the V Sge-type star V617 Sgr and summarize the conclusions in section 4.

2 New observations and reductions

The eclipsing binary V617 Sgr was monitored on 2010 June 8, 2012 April 17, and 2013 April 16 with the 2.15-m Jorge Sahade telescope located at Complejo Astronomico El Leoncito (CASLEO), San Juan, Argentina. A Roper Scientific Versarray 1300B camera system with an EEV CCD36-40 de 1340 × 1300 pix CCD chip was used in the monitoring program. All the CCD photometric observations were carried out in the *I* passband. During the observations, the clock of the control computer was calibrated against UTC time by the GPS receiver's clock. In the same field of view of the target, we chose two nearby stars with similar brightness as the comparison star and the check star, respectively. All images were corrected after subtraction of the bias and flat frames, and reduced by using PHOT (measure magnitudes for a list of stars) in the IRAF aperture photometry package.

Figure 1 shows the corresponding differential light curves with different eclipse depths. This may indicate the presence of high/low states in this source. The averaged value of the eclipse depths is about 0.45 mag. Fluctuations with a timescale of a few tens of minutes and small flickering can be seen throughout the whole process of the eclipse. During the eclipse minimums on the observations of 2012 April 17 and 2013 April 16, the light curves are characterized by brightening, with a small bump superimposed on the flattened-bottom shape (as shown in the middle and bottom panels of figure 1). The width of the flattened bottom shape varies in the two light curves.

By means of the least-squares parabolic fitting method, three new eclipse timings in Heliocentric Julian Day (HJD)

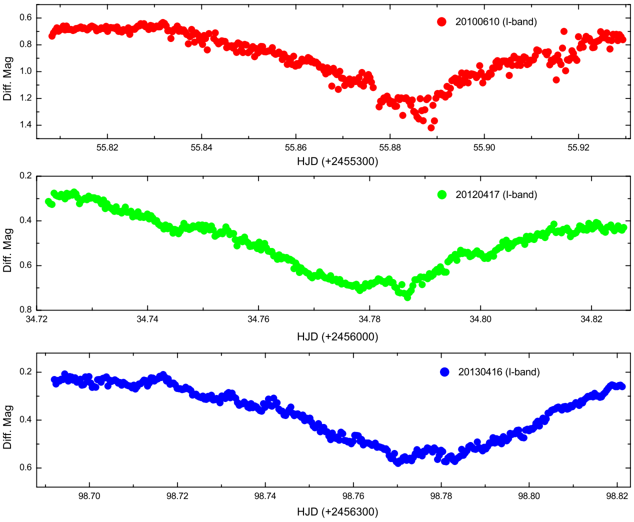

Fig. 1. The differential light curves of V617 Sgr in the *I* band measured on 2010 June 10, 2012 April 17, and 2013 April 16, marked with red, green, and blue points, respectively. (Color online)

Table 1. The new observations of the eclipsing binary V617 Sgr.

Obs. date	State time (HJD)	End time (HJD)	Eclipse timings (HJD)	Method	Filter
	(+2400000)	(+2400000)	(+2400000)		
2010 Jun 10	55355.80825	55355.92935	55355.88437(20)	CCD	I
2012 Apr 17	56034.72212	56034.82578	56034.782305(135)	CCD	I
2013 Apr 16	56398.69203	56398.82116	56398.77636(19)	CCD	I

Table 2. The 39 eclipse timings of the eclipsing binary V617 Sgr.

BJD (+2400000)	Errors (d)	E	$O - C$ (d)	Residuals (d)	Reference*
46878.773612	0.001	0	+0.000000	−0.000590	(1)
46947.758615	0.001	333	−0.001109	−0.001710	(1)
46952.731615	0.004	357	−0.000081	−0.000680	(1)
46973.655616	0.001	458	+0.000205	−0.000400	(1)
46974.483616	0.001	462	−0.000457	−0.001060	(1)
47658.754647	0.003	3765	+0.002928	+0.001430	(1)
47721.733648	0.005	4069	+0.003617	+0.001970	(1)
47725.670648	0.002	4088	+0.004472	+0.002820	(1)
48036.829660	0.003	5590	+0.000903	−0.001640	(1)
48069.768660	0.004	5749	+0.000589	−0.002060	(1)
50246.685680	0.006	16257	+0.022535	+0.005750	(1)
50602.595690	0.004	17975	+0.022216	+0.001840	(1)
50671.582704	0.002	18308	+0.023118	+0.002010	(1)
51011.754720	0.001	19950	+0.029383	+0.004450	(1)
51013.615720	0.001	19959	+0.025894	+0.000940	(1)
51040.541721	0.001	20089	+0.020380	−0.004890	(1)
51041.577721	0.001	20094	+0.020552	−0.004730	(1)
51290.806745	0.003	21297	+0.029480	+0.001160	(1)
51292.669745	0.002	21306	+0.027990	−0.000340	(1)
52822.612766	0.001	28691	+0.053794	+0.002980	(2)
52823.646766	0.001	28696	+0.051966	+0.001140	(2)
52824.682766	0.001	28701	+0.052139	+0.001290	(2)
52825.718766	0.001	28706	+0.052311	+0.001450	(2)
52849.748765	0.001	28822	+0.051112	−0.000150	(2)
52873.572764	0.001	28937	+0.051079	−0.000590	(2)
52874.607764	0.001	28942	+0.050251	−0.001430	(2)
52875.645764	0.001	28947	+0.052424	+0.000710	(2)
53211.669752	0.001	30569	+0.053971	−0.003600	(2)
53212.708752	0.001	30574	+0.057143	−0.000450	(2)
53213.744752	0.001	30579	+0.057316	−0.000290	(2)
53564.688738	0.002	32273	+0.062945	−0.001140	(2)
53565.723738	0.001	32278	+0.062117	−0.001990	(2)
53566.552738	0.002	32282	+0.062455	−0.001660	(2)
53566.758738	0.001	32283	+0.061290	−0.002830	(2)
53567.798738	0.003	32288	+0.065462	+0.001310	(2)
53568.621738	0.002	32292	+0.059800	−0.004360	(2)
55355.885124	0.00020	40919	+0.106418	+0.003850	(3)
56034.783081	0.000135	44196	+0.123031	+0.003520	(3)
56398.777152	0.00019	45953	+0.127319	−0.001810	(3)

*(1) Steiner et al. 1999; (2) Steiner et al. 2006; (3) this work.

with high time precision were determined from our CCD photometric data; these are listed in table 1. All available minimum timings of V617 Sgr from 1987–2013, spanning nearly 4.6×10^4 orbital cycles, were collected to construct the $O - C$ diagram. Since the Barycentric Julian Date (BJD) expressed in Barycentric Dynamical Time is a highly accurate time system, we converted all the timings to BJD, as shown in table 2.

3 Analysis of orbital period change

Photometric investigations on the orbital period of V617 Sgr have been performed by several authors (Steiner et al. 1999, 2006; Cieslinski et al. 1999). To calculate the $O-C$ values of all 39 eclipse timings, the linear ephemeris obtained from Steiner et al. (2006) should be converted to BJD:

$$\mathrm{Min.I(BJD)} = 2446878.773612 + 0\overset{\mathrm{d}}{.}20716568 \times E. \qquad (1)$$

The $O-C$ values with respect to the linear ephemeris are listed in table 2. The revised equation is calculated using a least-squares method:

$$\begin{aligned}\mathrm{Min.I(BJD)} &= 2446878.77421(3) + 0\overset{\mathrm{d}}{.}20716569(5) \times E \\ &\quad + 6.07(13) \times 10^{-11} \times E^2, \qquad (2)\end{aligned}$$

with standard deviation $\sigma_1 = 2\overset{\mathrm{d}}{.}327 \times 10^{-4}$. The corresponding fitting curve is displayed in the upper panel of figure 2, while the residuals are shown in the middle panel. The quadratic term in this ephemeris is $+6.07(13) \times 10^{-11}$ d cycle^{-1}, which is nearly 10% larger than the value $+5.5(1) \times 10^{-11}$ reported in equation (2) of Steiner et al. (2006). A revised positive value for the orbital period variation is $\dot{P} = +2.14(0.05) \times 10^{-7}$ d yr^{-1}, leading to an observed timescale of period change $P/\dot{P} = 0.97 \times 10^{6}$ yr.

The residuals related to the parabolic fit still show a small fluctuation, and may present a cyclical characteristic. It can be described as:

$$\begin{aligned}\mathrm{Min.I(BJD)} &= 2446878.77439(12) \\ &\quad - 0.0013(6)\cos(0.0008 \times E) \\ &\quad + 0.0009(6)\sin(0.0008 \times E), \qquad (3)\end{aligned}$$

with standard deviation $\sigma_2 = 2\overset{\mathrm{d}}{.}023 \times 10^{-4}$. The relevant fitting curve is plotted in the bottom panel of figure 2. The χ^2 value is ~ 1, far less than the value 9.77 in the parabolic fit. Based on the F-test proposed by Pringle (1975), $F(3,36) = 5.24$ are obtained, which reveals a confidence level above 99.58% for the sinusoidal ephemeris. Since the sinusoidal fit is significant, a periodic component added to the orbital period increase plausibly exists in the $O-C$ variations. The cyclic variation yields an amplitude of about 2.3 min and a timescale of about 4.5 yr.

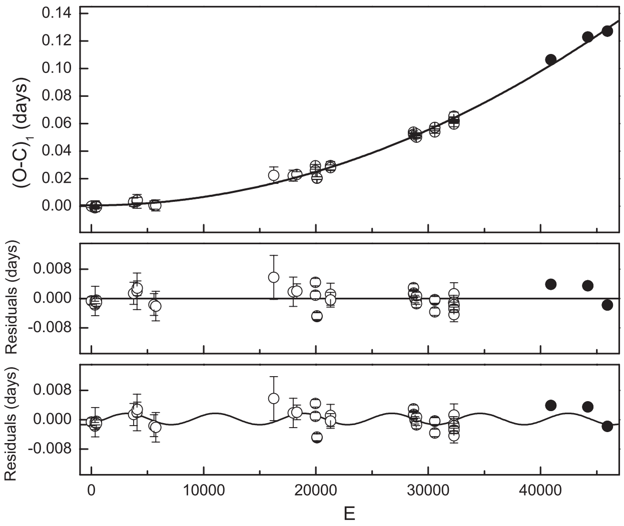

Fig. 2. Upper panel: The upward parabola fitting curve of the $O-C$ variations (open circles represent the old data from the literature and solid circles represent the new data in this work). Middle panel: The residuals of the $O-C$ values. Bottom panel: The sine fitting curve for the residuals based on equation (3).

4 Discussion and conclusions

In this work, we present an orbital period analysis of V617 Sge by adopting three new eclipse timings together with data from the literature. The long-term general trend of its orbital period shows a clear continuous increase, confirming the result of Steiner et al. (2006). A revised orbital period change is obtained at a rate of $\dot{P} = +2.14(0.05) \times 10^{-7}$ d yr^{-1}, which is larger than that derived before. The previous $O-C$ analysis only covers about 3.2×10^{4} cycles, while that reported here contains all the data from 1987–2013, spanning about 4.6×10^{4} orbital cycles. The positive rate of the orbital period change deduced from the $O-C$ analysis can describe a secular variation of the orbital angular moment in V617 Sgr. It should be noted that the observed timescale of orbital period variation is estimated to be 0.97×10^{6} yr. Thus, the secondary star of the binary V617 Sgr will accomplish its evolution faster than the predicted result in Steiner et al. (2006).

The V Sge-type stars are regarded as a counterpart of the CBSS in the Galaxy. The prototype V Sge has a high mass ratio of $q = 3.8$ and an orbital period of 12.3 hr. The detected decrease in its orbital period is due to mass transfer from the more massive donor to the less massive white dwarf primary on the Kelvin–Helmholtz timescale. This can produce a high mass-accretion rate leading to supersoft X-ray radiation via hydrostatic nuclear burning on the surface of the white dwarf. However, for systems with a period shorter than 6 hr, this mechanism does not work (Oliveira & Steiner 2007). Instead, the mass transfer is driven by the wind accretion produced by the irradiated low-mass donor (van Teeseling & King 1998). As a member of the V Sge-type stars, V617 Sgr has an orbital period of 4.98 hr, shorter than 6 hr. The binary system is thought to be composed of a massive ($\geq 1.2\,M_{\odot}$) white dwarf primary and an evolved low-mass (about $0.5\,M_{\odot}$) secondary star (Steiner et al. 2006). With the observed long-term increase in its orbital period, the wind-accretion evolution scenario is particularly appropriate for V617 Sgr.

Supposing that the orbital period increase in V617 Sgr wholly results from the consecutive mass transfer and/or mass loss of the low-mass secondary star, an experiential relationship between period change and mass transfer and/or loss is given by the formula

$$\frac{\dot{P}}{P} = \frac{3\varsigma - 1}{2}\frac{\dot{M}_2}{M_2}, \tag{4}$$

from equation (6) of Knigge, King, and Patterson (2000). Here, ς is the effective mass–radius index of the secondary and $\dot{M}_2$ is the mass change rate. We adopt $\varsigma = -1/3$ (van Teeseling & King 1998; Knigge et al. 2000) for the low-mass secondary of V617 Sgr. Thus, an averaged mass change rate of the secondary $\dot{M}_2 = \dot{M}_{\rm tr} + \dot{M}_{\rm w2} \simeq -5.2 \times 10^{-7} M_{\odot}\,{\rm yr}^{-1}$ is required to produce such a high variation in the orbital period of V617 Sgr. This also reveals an upper limit of $|\dot{M}_{\rm tr}| = |\dot{M}_2|$ for the long-term mass transfer from the secondary to the white dwarf, when the mass loss of the secondary disappears or can be neglected.

Considering the largest wind loss for the irradiated secondary by the X-ray source (the wind is almost fully ionized), a maximum rate of wind loss $\dot{M}_{\rm w2,max} \simeq 3.0 \times 10^{-7}\,M_{\odot}\,{\rm yr}^{-1}$ is derived from equation (11) of van Teeseling and King (1998):

$$\dot{M}_{\rm w2,max} \simeq -6 \times 10^{-6}\sqrt{M_2 R_2}\;M_{\odot}\;{\rm yr}^{-1}. \tag{5}$$

Here, R_2 can be calculated to be $R_2 = R_{\rm L2} \simeq 0.53 R_{\odot}$, on the assumption of a Roche-lobe geometry for the secondary star (King & van Teeseling 1998). This maximum rate of wind loss is dependent on the basic parameters of the secondary, and tends to a gradual decrease with the evolution of the binary system. It should be noted that it may be overestimated to some extent, because of the possible existence of an very young disk and the actual variation of wind loss in different evolutionary states. Then, we obtain a quite critical lower limit of $|\dot{M}_{\rm tr}| \simeq 2.2 \times 10^{-7}\,M_{\odot}\;{\rm yr}^{-1}$ for the long-term mass transfer. Hence, following the wind-accretion channel, the white dwarf primary in V617 Sgr will experience stable nuclear burning and accumulate mass efficiently from the irradiated donor star. After about 3.5–8.2 × 10^5 yr or less, the white dwarf of V617 Sgr will grow in mass to the Chandrasekhar mass limit $1.38\,M_{\odot}$, exploding as a SN Ia in the Galaxy.

Of particular interest, a cyclic component with an amplitude of 2.3 min and a timescale of 4.5 yr may exist in the $O - C$ diagram of V617 Sgr, which is reported in this system for the first time. To comprehend this characteristic, two kinds of mechanisms are possible. One is the solar-type magnetic activity of the secondary star known as Applegate's mechanism (Applegate 1992; Lanza et al. 1998). In this model, the fractional period change of V617 Sgr $\Delta P/P$ can be calculated to be 6.17×10^{-6}. It is noted that this object has behaviour similar to that of cataclysmic variables above the period gap in the diagram of period versus amplitude (Baptista et al. 2003). The other mechanism is the light-travel-time effect via the presence of a tertiary component. These two explanations for cyclical period change in the $O - C$ analysis of eclipsing cataclysmic variables are still under discussion (Baptista et al. 2003; Qian et al. 2007, 2009; Dai et al. 2009, 2010). However, neither can be totally ruled out. In the future, more long-term monitoring and more CCD eclipse timings are, in particular, expected to confirm this preliminary result and to investigate the nature of V617 Sgr.

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