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Investigating the low amplitude outbursts of long-orbital period CVs

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Dwarf novae (DNe) outbursts of cataclysmic variables (CVs) typically have asymmetrical outburst profiles, lasting only a week or two. However, we note that long-orbital period DNe have a tendency to exhibit symmetrical light curve (SLC) outbursts with low amplitudes that last for weeks to months. It is not uncommon for DNe to exhibit low amplitude outbursts, however, long durations that can be on the timescale of nova eruptions are what makes them unique and of particular interest. We report on a study to investigate the variety of system properties that can produce SLC outbursts in long-$P_{\rm orb}$ CVs. We confirm V5760 Sgr as a long-$P_{\rm orb}$ DN based on its quiescent light curve and a low amplitude SLC outburst comparable with similar CVs, e.g. GK Per and V1017 Sgr. The donor of V5760 Sgr was also estimated to be a ~G-IV star, based on our detection of a magnetic cycle of $\sim$ 11 years.

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1. Introduction

Binary systems containing a white dwarf (WD) are extremely common, since 95% of all stars end their evolution as WDs [1] and slightly more than 50% of all stars in our Galaxy are in binary (or multiple) systems [2]. Cataclysmic variables (CVs) consist of WDs ($M_1 \sim 0.8 - 1.2$ M$_\odot$; e.g. 3, 4) accreting material from low-mass donors ($M_2 \leq 1$ M$_\odot$ [5]), due to Roche-lobe overflow. The donors are predominately red dwarfs of K or M spectral type, but the CV population also includes degenerate and evolved donors. Most CVs contain accretion discs around the WD [6], however, $\sim$ 36% of CVs are magnetic [7], where the WD has a field of $B_{\rm WD} \sim 1 - 150$ MG. In magnetic CVs, the accretion disc is either disrupted at the Alfvén radius, creating a truncated inner disc (intermediate polars; IPs), or no disc is formed (polars), and accretion occurs onto the WD polar caps via the WD magnetic field lines.

CVs are compact, with binary separations, $a \sim 1$R$_\odot$, and orbital periods mostly in the range 78 min $\leq P_{\rm orb} \leq 12$ hr, although both shorter (e.g. AM CVn systems) and longer periods are known [8]. The currently longest $P_{\rm orb}$ (at 8.7 days) is 3XMM J174417.2–293944 [9]. Systems with $P_{\rm orb} > 9$ hours require larger and hence evolved donors, i.e. sub-giants and even giants, which appear as *symbiotic binaries* [10–12]. Interacting binaries, such as CVs, therefore provide superb laboratories to study the late stages of stellar evolution of low-mass donors [13].

By their nature, CVs are transients. There are four types of weakly (or non-) magnetic CVs (with $B_{\rm WD} < 1$ MG), which are distinguished according to their outburst recurrence times and magnitude ranges: (i) classical novae (CNe); (ii) recurrent novae (RNe); (iii) dwarf novae (DNe); (iv) nova-like (NL) variables (see 5, for full details). All exhibit either sudden increases in brightness due to nova eruptions (CNe and RNe) or DNe outbursts, or have episodes of a prolonged brightness increase due to a sustained high mass transfer rate (NL). A nova eruption is the result of a thermonuclear runaway on the WD surface and causes a brightening of 8 - 20 mag. The peak is reached in just a few days, and the source takes weeks to months to return to quiescence [14, 15]. DNe are the most common CVs known, with outbursts caused by disc instabilities that increase the mass transfer rate ($\dot{M}$) onto the WD, with substantial gravitational energy release. The typical DN outburst has a rapid rise ($\sim$ 1 day) in brightness and brightens by 2 - 8 mag . Normal DNe outbursts return to quiescence within $\sim 2 - 3$ days [5], while superoutbursts (in SU UMa-type DNe), last $\sim 10 - 14$ days [16].

CVs with $P_{\rm orb} \geq 3$ hr typically have $\dot{M} \sim 10^{-9} - 10^{-8}$ M$_\odot$ yr^{-1}. Binary evolution can lead to short-lived situations where $M_2 \geq M_{\rm WD}$ resulting in significantly higher $\dot{M}$, and if $\dot{M} \sim 10^{-7}$ M$_\odot$ yr^{-1} then stable thermonuclear burning on the WD surface can produce extreme supersoft X-ray emission. These are supersoft X-ray sources (SSS) with X-ray luminosities ranging from $L_{\rm X} \sim 10^{36}$ erg s^{-1} up to the Eddington limit $L_{\rm X} \sim 10^{38}$ erg s^{-1} [17].

ASASSN-16oh is an unusual SSS that has symmetrical light curve (SLC) outbursts, and is suspected to be a long ($P_{\rm orb} \sim 5$ days) CV [18, 19]. Its 2016 outburst took over 200 days to reach maximum, with an amplitude of $\Delta V \sim 4$ mag, and X-ray luminosity of $L_{\rm X} \sim 10^{37}$ erg s^{-1} at outburst peak, taking another $\sim$ 200 days to return to quiescence. The cause of the SSS emission at outburst peak is still debated [20, 21]. However, SLC outbursts are similar to those seen in other long $P_{\rm orb}$ CVs, e.g. GK Per [22, 23] and V1017 Sgr [24], with outbursts of low amplitudes ($\Delta V \lesssim 3$ mag), that last for weeks to months. These outbursts are thought to be DNe outbursts triggered by an ionization instability in the inner disc region ("inside-out" outburst) rather than in the outer regions ("outside-in" outburst).

While it is not uncommon for DNe to exhibit low amplitude outbursts, it is very unusual for them to exhibit long durations comparable to nova eruptions, and this makes them of particular interest. This paper is a progress report on our investigation of the properties of three known long-$P_{\rm orb}$ CVs that exhibit SLC DNe outburst, together with preliminary results on a new long-$P_{\rm orb}$ system, V5760 Sgr.

2. DNe outburst light-curves

In most CVs, the accretion disc dominates the optical luminosity during both quiescence and outburst, and is responsible for the DNe outburst phenomenon. The disc viscosity is the main factor that drives DNe outbursts (e.g. 25, 26). During quiescence, the disc is in a cool, low-viscosity state. As material accumulates in the disc, its temperature gradually increases, causing an increase in viscosity, attributed to the magneto-rotational instability [27], which drives disc turbulence and enables angular momentum transport from the inner to outer parts of the disc, thereby increasing the accretion rate onto the WD. This produces a normal DNe outburst [28, 29], during which the inner disc material accretes onto the WD while the outer disc radius expands [30]. After an outburst, the outer part will slowly contract, and in time the disc recovers as material from the donor builds up again.

There are two types of normal outbursts that can occur depending on the disc's surface density distribution prior to the onset of an instability [30, 31]. Most DNe outbursts are Type A – "Outside-in", meaning the disc brightens first in the outer regions and moves inward. These outbursts are due to more material accumulating in the outer parts of the disc, triggering the thermal instability there. The heating wave then travels rapidly inwards, because viscosity causes more material to flow inwards than outwards. The light curves of Type A outbursts have asymmetrical shapes with fast rises to maximum and slower declines to quiescence. Type A outbursts have higher $\dot{M}$ rates than Type B outbursts and occur quasi-periodically.

Type B – "Inside-out" outbursts are less common and are the result of a surface density distribution where the disc instability is triggered within a radius closer to the WD, and therefore propagates both inwards and outwards through the disc. The brightening does not always propagate all the way to the outer edge, which leads to lower amplitude outbursts, and the heating wave propagates very slowly through the disc [32], resulting in symmetrical outburst profiles. It is also not uncommon to observe a pause in the outburst rise before it continues to maximum amplitude. Evans et al. [23] ascribe this to a heating wave encountering a lower surface density in the disc, halting its progress and causing a cooling wave to travel inwards; but it does not completely extinguish the inner region outburst, since the viscous time-scale at the outburst triggering radius outlasts the cooling wave. The outburst is therefore reactivated and rises to peak amplitude.

Actually, DNe can experience both outburst types, as shown in Figure 1 for SS Cyg, a U Gem-type DN of $P_{\rm orb} \sim 6.6$ hours [33, 34]. When the entire accretion disc participates in a Type A outburst, the outburst can be sustained, and can cause the donor to be irradiated, inducing an increase in mass transfer [11]. Sustained outbursts manifest as plateaus at the outburst peaks and are labelled 'P' in Figure 1.

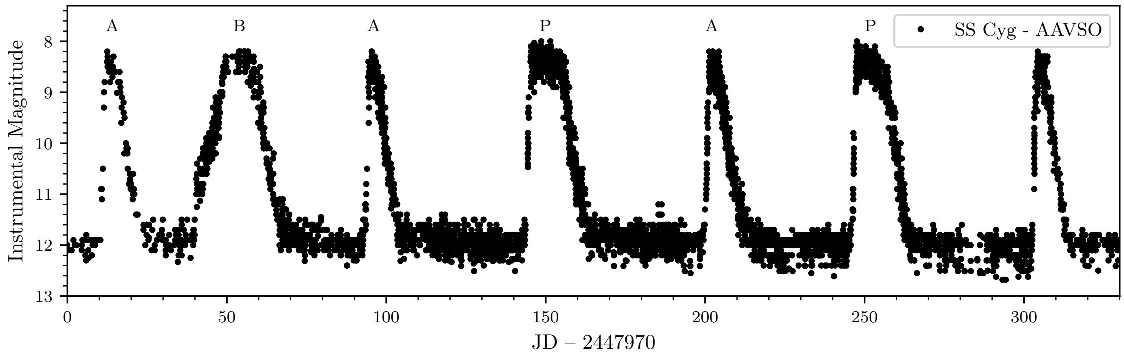

Figure 1: AAVSO light curve of SS Cyg [35]. The different outburst types are labelled: Type A – "Outside-in"; Type B – "Inside-out" and P (Type A with a plateau).

Long-$P_{\rm orb}$ CVs (which we take to have $P_{\rm orb}$ > 10 hours), e.g. X Ser [36], GK Per [37, 38] and V1017 Sgr, show a preference for Type B outbursts, with low amplitudes (~ 3 mag) and long durations (~ months). A possible record for the longest DNe outburst was set by long-$P_{\rm orb}$ CV V1047 Cen [39], with an outburst duration of ~ 400 days. The very long $P_{\rm orb}$ implies an unusually large accretion disc that can sustain such a long outburst. These discs have cooler outer regions and this might be why "inside-out" outbursts are more commonly triggered and long-lasting SLCs observed.

A key property of DNe outbursts is the Bailey relation between $P_{\rm orb}$ and the rate of outburst decline ($\tau_{\rm D}$ [d/mag]) [40], and is independent of outburst duration (Fig. 2). It is clear that long-$P_{\rm orb}$ DNe decline from outburst at a much slower rate than shorter period systems. As Bailey noted, this can be a time-scale possibly associated with the size of the accretion disc.

3. Properties of three long-orbital period CVs

X Ser, GK Per, V1017 Sgr are long-$P_{\rm orb}$ CVs that exhibit SLC DNe ourbursts, as shown in Fig. 3 and Fig. 4. Interestingly, all three sources are post-novae that started to undergo DN outbursts within the first century after their respective nova eruptions. According to the "hibernation" scenario [14], after a nova eruption the system will first evolve to a nova-like, before becoming a DN, a result of donor irradiation by the WD causing an increase in $\dot{M}$. Shara [14] predicted that the WD needs a century to cool sufficiently to stop irradiating the donor, and a few centuries more before DN eruptions begin. However, this remains controversial, and Livio [42] and Hillman et al. [43] have shown that it only occurs for the shortest period CVs. Naylor [44] also argues that nova eruptions are unconnected to mass transfer rates and that a system will be a DN before and directly after a nova eruption, as in the case of V446 Her [45, 46]. Since X Ser, GK Per and V1017 Sgr underwent DN outbursts within the first century after their nova eruptions, they provide further evidence that the "hibernation" scenario does not apply to long-$P_{\rm orb}$ CVs.

The key outburst properties ($P_{\rm orb}$, donor types, etc) of X Ser, GK Per and V1017 Sgr are summarized in Table 1. The SLCs of GK Per, for example, turned on ~ 60 years after the 1901 nova [36] and recur on average every 3 years [23]. These DN outbursts have low amplitudes (~ 3 mag) and the durations (20 – 100 days) are far longer than typical values (~ 2 – 3 days) for shorter

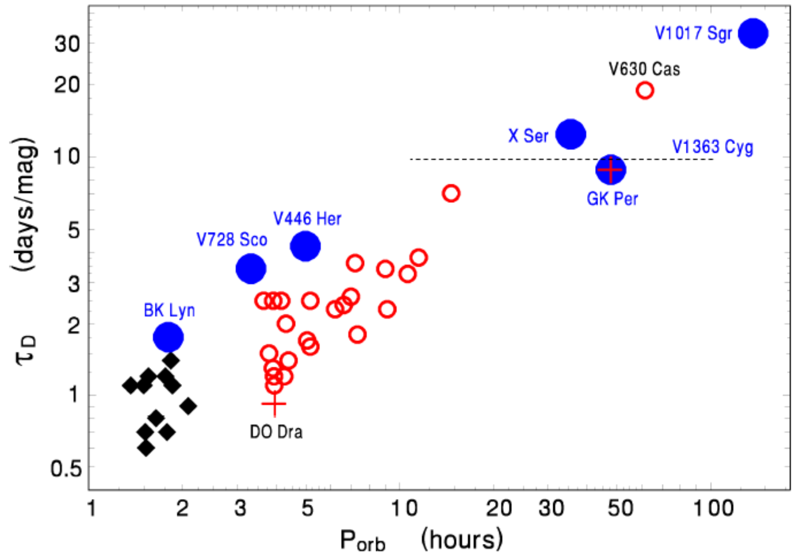

Figure 2: Orbital period ($P_{\rm orb}$)–decline rate ($\tau_{\rm D}$) relation for DNe outbursts. The diagram includes systems that exhibit DNe outbursts, e.g. SU UMa systems (black diamonds), DNe above the period-gap (red open circles), post-novae systems (blue solid circles) and intermediate polars (red crosses). The dashed line represents possible $P_{\rm orb}$ values for post-nova V1363 Cyg (from 41, Fig. 8).

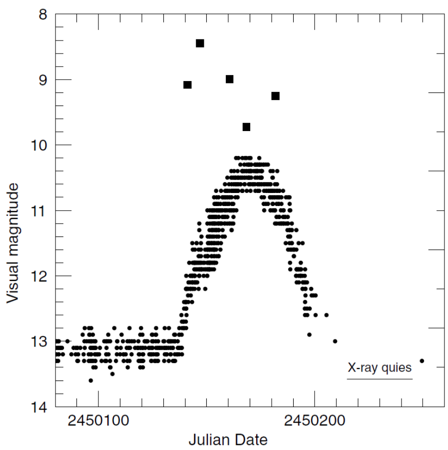

Figure 3: The 1996 outburst light curve of GK Per (from 47, Fig. 1)

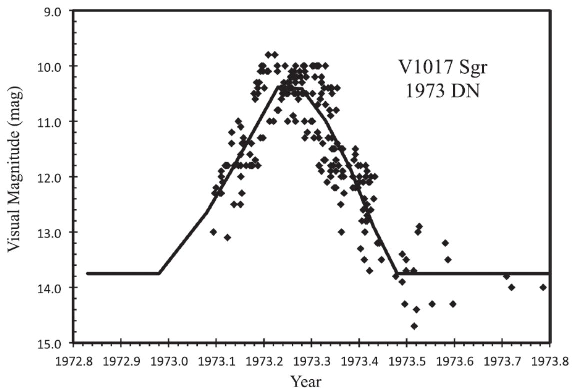

Figure 4: The 1973 outburst light curve of V1017 Sgr (from 24, Fig. 3)

$P_{\rm orb}$ CVs. A correlation between $P_{\rm orb}$, the donor type, the outburst duration and recurrence time are clear in Table 1. For longer $P_{\rm orb}$ the donor star is more massive, and also means larger orbital separations, and hence, larger accretion discs. This is why the outbursts in V1017 Sgr lasted ~ 0.5 year and the longest outburst of X Ser only lasted 80 days. Since these discs are very large, it takes a significant time to recover after outburst. The relation between $P_{\rm orb}$ and outburst recurrence time confirms this. Interestingly, the outburst decline rates of these systems also follow the Bailey relation, as seen in Fig. 2.

All three systems have low amplitude outbursts. In post-nova systems this is attributed to the

Target	Nova	P_{orb} (d)	d (kpc)	Donor	ΔV (mag)	t_{out} (yr)	t_{recur} (yr)	References
X Ser	1903	1.479(16)	> 3	K-type?	∼ 3	0.1 – 0.2	∼ 1	36, 41
GK Per	1901	1.9968	0.47	K2 IV	∼ 2 – 3	0.1 – 0.3	∼ 3	23, 47, 48
V1017 Sgr	1919	5.7863	1.21	G IV	∼ 3.3	0.5	∼ 20	24

Note: d = distance, ΔV = outburst amplitude, t_{out} = outburst duration, t_{recur} = outburst recurrence.

Table 1: Outburst properties of three long-P_{orb} CVs that display low-amplitude symmetrical outbursts.

inner disc regions being irradiated by the WD, and kept in a high-viscosity state. Therefore, low amplitude outbursts are observed when only the outer discs participate in the outbursts [49]. Of the three sources, only GK Per is a confirmed IP, but hard X-rays detected for V1017 Sgr suggest that it might also be an IP. The fact that these both exhibit the same low amplitude outbursts as X Ser, but have a very small or no inner disc, indicates that similar outer disc regions participated in the "inside-out" outbursts, producing low amplitude SLCs.

4. V5760 Sgr

Following its discovery by OGLE (Optical Gravitational Lensing Experiment) [50] V5760 Sgr (= OGLE-2004-BLG-081 and OGLE BLG-DN-673) was identified as a possible CV based on its light curve[1] [51, 52]. OGLE has been operational from the early 1990s and is aimed at detecting microlensing events that mostly have symmetrical light curves. In order to do this, it regularly monitors millions of stars in the Galactic Bulge and Magellanic Cloud regions. It also detects other transients, such as supernovae, novae and CV outbursts [53, 54] and is therefore the ideal archive to mine for SLC CVs.

V5760 Sgr is located in the Galactic Bulge and has a Gaia determined distance of $d \sim 8 \pm 3$ kpc [55][2]. It is associated with the X-ray source, 2XMM J180540.5-273427 [56], which has $L_X \sim 6 \times 10^{31}$ erg s^{-1} [57], typical for non-magnetic CVs. Mróz et al. [52] determined $P_{orb} = 3.97$ days from OGLE light curves, and suggested that it is a post-nova DN.

The 22-year OGLE light curve (from OGLE-III and OGLE-IV data in the I-band) is shown in Fig. 5, and is mostly in quiescence at $I \sim 17.1$. There is an offset between the OGLE-III and OGLE-IV light curves, which sometimes occurs between different phases of the OGLE project [58]. It was corrected by calculating the average magnitudes for the OGLE-III and IV data separately, and adding the difference of the average values (∼ 0.094 mag) to the OGLE-III data.

An underlying modulation is visible in the off-set corrected quiescent light curve. This light curve was binned (mean magnitudes calculated in bins with widths equal to P_{orb}) and fitted with a sine function, yielding a period of ∼ 10.7 years (Figure 6). This is similar to the solar cycle and comparable to the magnetic cycles detected in G-type stars [59]. Magnetic cycles have also been detected in other CVs, e.g. U Gem and GK Per [11, 60] and provides a good indication of the donor's spectral type. We therefore estimate that V5760 Sgr has a G subgiant donor, similar to that of V1017 Sgr.

The data in Figure 6 were detrended by removing the long-term modulation, and then phase-folded (100 bins) on the published $P_{orb} = 3.97$ days, using HJD2451438.93 as the time zero point,

[1] https://ogle.astrouw.edu.pl/ogle4/transients/
[2] http://gea.esac.esa.int/archive/

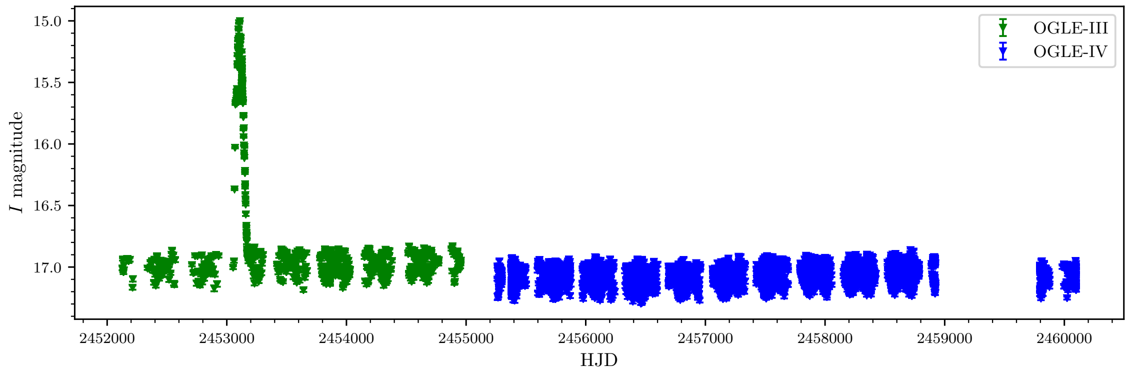

Figure 5: OGLE-III and OGLE-IV light curves of V5760 Sgr (Aug 2001 – June 2023) in the *I*-band.

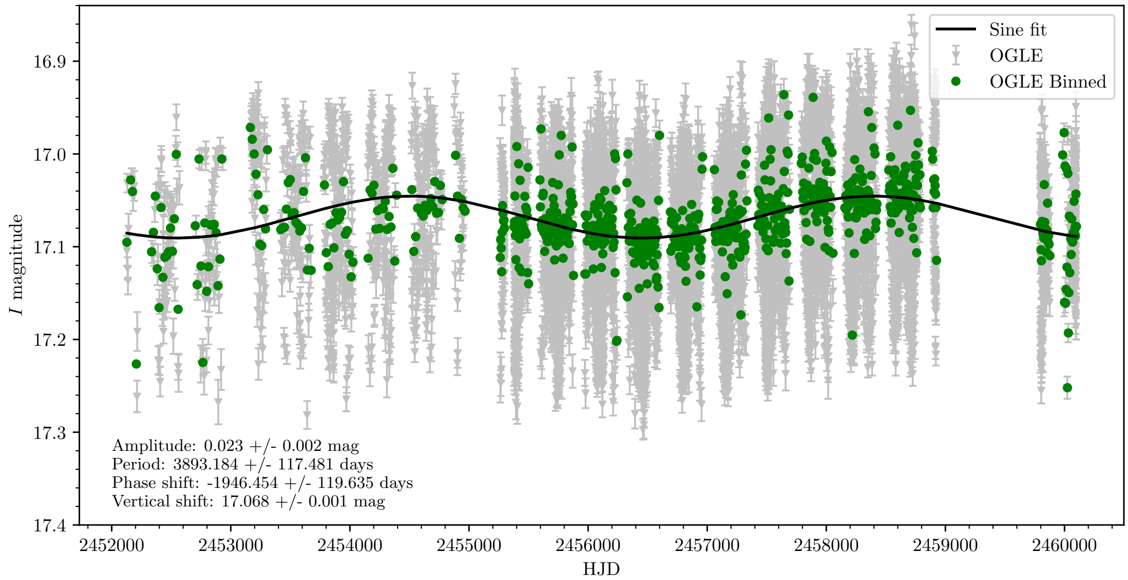

Figure 6: Binned quiescent OGLE light curve of V5760 Sgr, fitted with a sine function. The outburst data points (2453052 < HJD < 2453170) have been removed and the bin widths are equal to $P_{\rm orb}$.

T_0, yielding the orbital, folded light curve shown in Figure 7. The shape of the folded light curve shows why it was flagged as an eclipsing binary system. We also performed a Lomb-Scargle analysis of the detrended OGLE light curve and determined $P_{\rm orb}$ = 3.9663 ± 0.0005 days, which is in agreement with that of Mróz et al. [52].

The transient event that occurred February – June 2004, was detected by OGLE and the Microlensing Observations in Astrophysics (MOA) group[3]. However, this was not a microlensing event as the light curve could not be fitted with a standard lensing model [51, 56]. It reached a maximum amplitude of ∼ 2 mag and lasted ∼ 100 days (Fig. 8) with a symmetrical shape and similar properties to the outburst light curves of X Ser, GK Per and V1017 Sgr. It also has a pause in the rise before it continues on to the peak, and a decline rate of 30 d mag^{-1} that satisfies the

[3]https://www.massey.ac.nz/~iabond/alert2000/moa-2004-blg-3.html

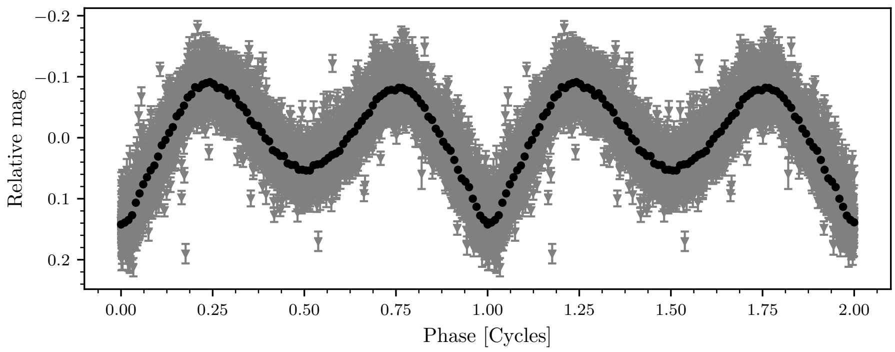

Figure 7: The detrended OGLE light curve of V5760 Sgr, phase-folded on $P_{\rm orb}$ = 3.96659 days [52] and binned into 100 phase bins.

Bailey relation (Fig. 2). We therefore confirm that V5760 Sgr is a long-$P_{\rm orb}$ DN that had a Type B outburst in 2004. The similarities between V5760 Sgr and the earlier mentioned long-$P_{\rm orb}$ sources displaying SLCs, are remarkable. However, we do not know if it is a post-nova system which can only be confirmed by the detection of a nova shell.

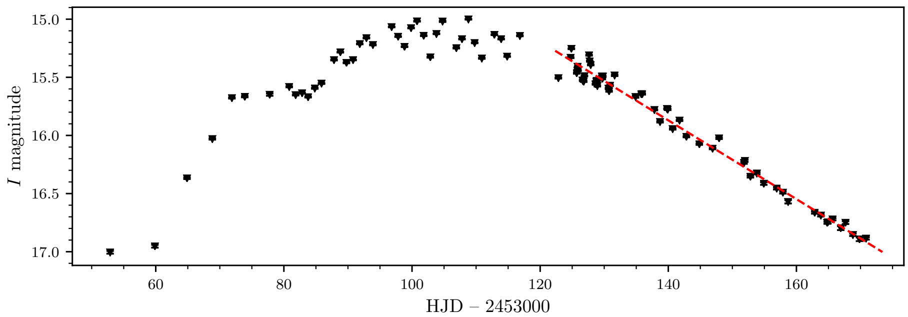

Figure 8: OGLE-III outburst light curve of V5760 Sgr (Feb – Jun 2004). The red dashed line represents the decline rate of 30 d mag^{-1}.

We roughly estimated the binary parameters for V5760 Sgr by assuming it has a G IV donor (M_2 = 1 $M_\odot$) of $T_2 \sim 5000$ K. Two sets of binary parameters were calculated for two different WD masses (M_1 = 0.8 $M_\odot$ and M_1 = 1.1 $M_\odot$), and are given in Table 2.

The size of the donor's Roche lobe, R_2, was calculated with Eggleton's analytical approximation [61]:

$$\frac{R_2}{a} = \frac{0.49q^{2/3}}{0.6q^{2/3} + \ln\left(1 + q^{1/3}\right)} \quad \text{for} \quad 0 < q < \infty, \tag{1}$$

where $q = M_2/M_1$ is the mass ratio. By replacing q with q^{-1}, the equation was used to calculate the WD's Roche lobe radius, R_1. The circularization radius of the accretion disc was determined from the expression in Warner [5]:

$$R_{\rm circ} = a\,(1 + q)\,(0.500 - 0.227 \log q)^4\,. \tag{2}$$

Binary Parameter	$M_1 = 0.8\ M_\odot$	$M_1 = 1.1\ M_\odot$
M_2 ($M_\odot$)	1	1
q ($= M_2/M_1$)	1.25	0.91
R_1 ($R_\odot$)	4.6	5.2
R_2 ($R_\odot$)	5	5
R_{circ} ($R_\odot$)	1.5	1.7
$\dot{M}$ ($M_\odot$ yr^{-1})	4×10^{-9}	4×10^{-9}
$\dot{M}_{acc}$ ($M_\odot$ yr^{-1})	7×10^{-12}	3×10^{-12}

Table 2: Rough estimates of V5760 Sgr binary parameters for two WD masses (see text for explanation of parameters)

where a (in cm) is the orbital separation, also given by Warner [5]:

$$a = 3.53 \times 10^{10} M_1^{1/3} (1+q)^{1/3} P_{orb}^{2/3}, \tag{3}$$

and M_1 is in $M_\odot$ and P_{orb} is in hours.

The mass transfer rate, $\dot{M}$, was calculated by considering the distance between the donor's photosphere and the L1 funnel through which material flows. In this context, the mass transfer rate was determined by

$$-\dot{M} \approx \frac{1}{4\pi} \rho_{L1} c_s^3 P_{orb}^2, \tag{4}$$

where ρ_{L1} is the average density in the L1 region given by

$$\rho_{L1} = \frac{1}{\sqrt{e}} \rho_{phot} \exp \frac{-(R_2 - R_*)}{H_p}, \tag{5}$$

with ρ_{phot} representing the photospheric density of a late-type star ($\sim 10^{-6}$ g cm^{-3}; 5, 62). Applying the methodology of Meintjes [63] for late-type dwarfs, the mass transfer rate was calculated using a scale height factor (α) of

$$\alpha = \frac{R_2 - R_*}{H_p} = 10, \tag{6}$$

where R_* is the secondary's photospheric radius, and $H_p = c_s^2 R_*^2 / G M_2$ is the stellar scale height. We selected a scale height factor of 10 to ensure a large distance between the photosphere and L1, representing a donor under-filling its Roche lobe.

The observed $L_X \sim 6 \times 10^{31}$ erg s^{-1} was used to calculate the accretion rate $\dot{M}_{acc}$ from Frank, King & Raine [62]:

$$L_X \approx L_{acc} = \frac{G M_1 \dot{M}_{acc}}{R_*}, \tag{7}$$

where L_{acc} is the accretion luminosity, and $R_* \sim 7.5 \times 10^8$ cm and $\sim 5.0 \times 10^8$ cm for WDs with masses $M_1 = 0.8\ M_\odot$ and $1.1\ M_\odot$, respectively [64].

The mass transfer rates of $\dot{M} \sim 10^{-9}\ M_\odot$ yr^{-1} and the accretion rates of $\dot{M}_{acc} \sim 10^{-12}\ M_\odot$ yr^{-1} are in agreement with typical values for DNe in quiescence. An evolving G-type donor under-filling its Roche lobe is therefore a good approximation. The large $R_{circ} > 1\ R_\odot$ also confirms that it will take a significant time for the surface density to increase in the large accretion disc, and explains why only one outburst has been detected for V5760 Sgr in the last 22 years.

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5. Future work

The SLC outburst, decline rate, and approximated mass transfer and accretion rates of V5760 Sgr are in agreement with long-$P_{\rm orb}$ CVs such as X Ser, GK Per and V1017 Sgr. However, we still have to confirm if it is a disc or discless system containing an evolved G-type donor. We are, therefore, planning spectroscopic observations with the Southern African Large Telescope (SALT) at SAAO to confirm this. These observations will also enable us to produce radial velocity curves and constrain the stellar masses. The behaviour of V5760 Sgr is very similar to GK Per, and it is of interest to determine if it is an IP. Small scale variability is visible in the quiescent OGLE light curve of V5760 Sgr (Fig. 7), and so high-speed photometry will enable us to determine if the variability is due to a WD spin period, magnetic interactions or flickering from an observable hot spot. We are, therefore, planning high-speed photometry observations with the UFS-Boyden 1.5-m and SAAO 1.0-m telescopes. OGLE continues to monitor this source, and intensive follow-up observations are planned to follow the next outburst.

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