Detection of the Supercycle in V4140 Sagittarii: First Eclipsing ER Ursae Majoris-like Object

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Abstract
We observed the deeply eclipsing SU UMa-type dwarf nova V4140 Sgr and established the very short supercycle of 69.7(3) d. There were several short outbursts between superoutbursts. These values, together with the short orbital period (0.06143 d), were similar to, but not as extreme as, those of ER UMa-type dwarf novae. The object is thus the first, long sought, eclipsing ER UMa-like object. This ER UMa-like nature can naturally explain the high (apparent) quiescent viscosity and unusual temperature profile in quiescence, which were claimed observational features against the thermal-tidal instability model. The apparently unusual outburst behavior can be reasonably explained by a combination of this ER UMa-like nature and the high orbital inclination and there is no need for introducing mass transfer bursts from its donor star.

Key words: accretion, accretion disks — stars: novae, cataclysmic variables — stars: dwarf novae — stars: individual (V4140 Sagittarii)

1 Introduction
Dwarf novae are a class of cataclysmic variables which show outbursts, SU UMa-type dwarf novae are a subclass of dwarf novae which show superhumps during long-lasting outbursts called superoutbursts [for general information of CVs, dwarf novae and SU UMa-type dwarf novae and superhumps, see e.g. Warner (1995)]. The origin of superhumps and superoutbursts are widely believed as a consequence of the 3:1 resonance between the rotation in the accretion disk and the secondary star (Whitehurst 1988; Osaki 1989; Hirose and Osaki 1993; Lubow 1992).

This thermal-tidal instability (TTI) model by Osaki has long been debated and challenged by an alternative theory of dwarf nova outbursts — the enhanced mass-transfer (EMT) model.1 The degree of challenge varies from SU UMa-type dwarf novae in general (Smak 1991; Smak 2004, Smak 2008); applications to WZ Sge-type dwarf novae, which are a subtype of SU UMa-type dwarf novae (e.g. Patterson et al. 2002; Buat-Ménard and Hameury 2002) and to applications to special objects (e.g. Baptista and Bortoletto 2004; Baptista 2001; Baptista et al. 2016). In SU UMa-type in general, the detection of variation of frequencies of negative superhumps, which are considered to arise of a tilted disk, in the high precision Kepler data led to the strongest support to the TTI model.

1 Although there is another pure thermal instability model Cannizzo et al. (2010), details of this model has not yet been published in a solid paper, we do not discuss it further in this Letter.
(Osaki and Kato 2013; see also Osaki and Kato 2014 for the final answers to Smak’s criticism).

This Letter deals with the object (V4140 Sgr) in the final category. This object was studied by Baptista et al. (2016) by eclipse mapping and flickering analysis. Baptista et al. (2016) concluded that the temperature distribution in quiescence and the estimated high viscosity parameter are in contradiction with the prediction of the TTI model, and proposed that the outbursts in this object are powered by mass transfer bursts from its donor star.

2 Observation and Analysis

The observations were carried out as a part of a campaign led by the VSNET Collaboration (Kato et al. 2004). F.-J. Hambusch obtained snapshot observations (typically two points a few minutes apart per night, between 2017 March 7 and 2017 November 26) and L. Cook obtained time-resolved photometry on two nights (2017 May 4 and 7) immediately following one of superoutbursts. Both observers used standard de-biasing and flat fielding and extracted magnitudes by aperture photometry. The times of all observations are expressed in barycentric Julian days (BJD). This object is renowned as a deeply eclipsing cataclysmic object and we used the eclipse ephemeris by Baptista et al. (2016) after confirming that this ephemeris expresses our observations well.

3 Results and Discussion

3.1 Long-term Light Curve

The resultant light curve is shown in figure 1. Observations around eclipses (orbital phases between −0.07 and 0.07) were removed from this figure. Since the object is relatively faint for amateur instruments, individual estimates have relatively large errors. We selected observations (good, reliable estimates) with errors less than 0.2 mag as large symbols with error bars. Other observations (not very reliable estimates) are shown with small filled circles without error bars to avoid complexity of the figure. Although errors of “not very reliable estimates” reached 0.9 mag in extreme cases, typical errors were 0.3–0.5 mag when the object was below 18 mag.

We can see from this figure that there were very distinct four outbursts labelled with SO1–SO4. These outbursts typically reached 16.6 mag and linearly faded for ∼10 d. The properties of these outbursts exactly match the category of superoutbursts (cf. Warner 1995). Although we did not perform time-resolved photometry during these long outbursts, superhumps were almost certainly present since superhumps were detected during a similar long outburst in 2004 September–October (Kato et al. 2009).

The most striking point is the shortness of the interval (supercycle) between these superoutbursts. A Phase Dispersion Minimization (PDM, Stellingwerf 1978) analysis yielded a supercycle of 69.7(3) d. Another striking point is the small amplitudes (1.5 mag) of superoutbursts.

In addition to these superoutbursts, there were normal outbursts indicated by vertical ticks in figure 1. Normal outbursts were difficult to detect since they are fainter than superoutbursts and have shorter (usually 1–2 d) durations. We consider that not all normal outbursts were detected. This was partly due to the periodic interference by the bright Moon since V4140 Sgr is located close to the ecliptic. We, however, consider that the interval between SO2 and SO3 was best observed, when many of observations were classified as “good, reliable estimates”. We note the clear presence of at least four normal outbursts (labelled with ticks) in this interval. The shortest intervals were 8 d (between SO2 and SO3) and 6.4 d (between SO1 and SO2). Considering that not all normal outbursts could be detected, the number of normal outbursts within a supercycle must have been relatively large (five or more). The gradually brightening trend of peaks of normal outbursts between superoutbursts is also similar to other SU UMa-type dwarf novae (Osaki 1989; Osaki and Kato 2013). In Kato et al. (2017), we reported our preliminary result about the apparent absence of normal outbursts in V4140 Sgr. We update the result here.

3.2 Nature of V4140 Sgr

Observations indicate that V4140 Sgr has all the characteristics of an SU UMa-type dwarf nova: presence of superhumps during superoutbursts, long-lasting superoutbursts occurring relatively regularly and frequent occurrence of normal outbursts. The only points different from ordinary SU UMa-type dwarf novae are the shortness of the supercycle and low outburst amplitudes.

We know SU UMa-type dwarf novae with very short (19–45 d) supercycles, known as ER UMa-type dwarf novae (Kato and Kunjaya 1995; Robertson et al. 1995; Patterson et al. 1995; Nogami et al. 1995). Although the supercycle 69.7(3) d in V4140 Sgr is somewhat longer than those in “classical” ER UMa-type dwarf novae supercycles in ER UMa-type dwarf novae vary both secularly and sporadically (Zemko et al. 2013; Otulakowska-Hypka and Olech 2013) the supercycle in V4140 Sgr is only slightly longer than the longest “snapshot” supercycles in classical ER UMa-type dwarf novae [the known limit being 59 d
Otulakowska-Hypka and Olech (2013). Although there exist SU UMa-type dwarf novae with supercycles intermediate between ER UMa-type dwarf novae and ordinary SU UMa-type dwarf novae, these objects have much longer orbital periods (the examples are such as SS UMi, V503 Cyg, V344 Lyr and V1504 Cyg, see Otulakowska-Hypka and Olech 2013 for the references). V4140 Sgr has a short orbital period of 0.06143 d, which would more naturally qualify it an object analogous to ER UMa-type dwarf novae which are known to occupy the short-period end of the distribution of orbital periods. Thus, we consider V4140 Sgr as the first, and long sought, eclipsing ER UMa-like dwarf nova. We should note, however, that durations of superoutbursts in V4140 Sgr are shorter than those in classical ER UMa-type dwarf novae. V4140 Sgr probably has the properties similar to classical ER UMa-type dwarf novae, but with a slightly smaller mass-transfer rate.

Regarding the low outburst amplitudes, we consider it a combination of low outburst amplitudes in ER UMa-type dwarf novae (cf. Osaki 1996), resulting in low outburst amplitudes. The high inclination ($i$) produces the small ($\propto \cos i$) projected surface area of the disk and effectively reduces the outburst amplitude. The inclination of V4140 Sgr is reported to be 80.2(5)$^\circ$ (Borges and Baptista 2005). If the apparent brightness of the disk is indeed proportional to $\cos i$, it should be 0.23 times that of ER UMa with $i=43^\circ$. Let’s assume an extreme case that the quiescent brightness is dominated by the hot spot$^2$. This would lead to the same apparent quiescent brightness regardless of the inclination. An inclination effect alone leads to a reduction of outburst amplitude 0.23 times that of ER UMa in this extreme assumption. Since the disk is expected to significantly contribute to the quiescent brightness of ER UMa-type dwarf novae and it will also suffer from the inclination effect, this ratio should be considered to be the lower limit of the amplitude ratio. In any case, it would be easy to produce a low amplitude of superoutbursts (1.5 mag), which is 0.5–0.6 times that of ER UMa.

$^2$Although an orbital hump is not prominent in V4140 Sgr, The light curve in Baptista et al. (1989) indicated the clear asymmetry of the eclipse, particularly the long-lasting trailing feature of the egress phase. This is a signature of a geometrically broad hot spot. We consider that there is a significant contribution from the hot spot.
3.3 Implication to Outburst Mechanism

Such low outburst amplitudes of superoutbursts can be easily confused with normal outbursts. This was indeed the case in Baptista et al. (2016), who described the “long (80–90 d) time interval” which was meant to refer to the cycle length of normal outbursts rather than the supercycle. A similar confusion was already in the past, namely Mason et al. (2001) for the eclipsing SU UMa-type dwarf nova V893 Sco, and was corrected by Kato et al. (2002). This incorrect identification in Baptista et al. (2016) led to an assumption of long-lasting quiescent phase and a low quiescent viscosity parameter $\alpha \sim 0.01$, which contradicted their observation. When we consider the ER UMa-like properties of V4140 Sgr correctly, normal outbursts occur shortly after the disk reaches full quiescence, and it is likely that the disk is still turbulent following the outburst or the hot part remaining in the (almost) quiescent disk when Baptista et al. (2016) made observations, resulting high $\alpha$ values.

The temperature structure is also expected to be different from those of ordinary SU UMa-type dwarf novae, in which the entire disk reaches the low state. A contribution from the hot part in the (almost) quiescent disk alters the temperature structure and it would appear closer to that of a steady-state ($T \propto R^{-3/4}$) disk, where $T$ and $R$ are the temperature and the radius, respectively, since the essence in the disk instability in ER UMa-type dwarf novae is that the disk is almost always close to the steady-state and only weak heating/cooling waves travel in such a disk (Osaki 1996). We conclude that the two important observational results by Baptista et al. (2016) for V4140 Sgr are no longer contradictions to the TTI model. Rather it strengthens our interpretation. Proper understanding of the apparent contradiction with the claimed low mass-transfer rate reported in Baptista et al. (2016) probably should await an accurate parallax measurement [see e.g. the case of SS Cyg (Miller-Jones et al. 2013)].

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$^3$ Another possible interpretation of an anomalous temperature distribution and high $\alpha$ is a result of a disk tilt (as already proposed in Kato et al. 2017). It has been shown that many high-mass transfer systems frequently show negative superhumps, particularly in ER UMa itself (e.g. Ohshima et al. 2014), which are believed to arise from a tilted disk (Wood and Burke 2007). On a tilted disk, the accretion stream hits the inner part of the disk, resulting a high temperature in the inner part. Although there was no direct observational evidence, it may have been that V4140 Sgr spent a similar phase when observed by Baptista et al. (2016).
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