An Accreting White Dwarf with a Brown Dwarf Donor and a Giant Circumbinary Planet

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Cataclysmic variables (CVs) are short-period binary stars containing a white dwarf and a low-mass donor star that is transferring material to the white dwarf via an accretion disc. Evolutionary theories predict that both the orbital period and the donor's mass are decreasing continuously until the donor is below the hydrogen burning limit[1]. After that point, the donor star becomes a brown dwarf and the orbital period reverses to increase (known as a period bouncer)[2]. It is predicted that about 70% of the current CVs have evolved into period bouncers [3, 4]. However, despite several CVs with substellar donors were detected with orbital

period below or near the minimum[5-8], no orbital bounces were discovered. Where is the missing population predicted by the evolution theory of CVs is still a serious problem in stellar astrophysics. Here we report the period variations of the eclipsing dwarf nova V4140 Sgr with an orbital period of 88.5 minutes. A long-term increase at a rate of 2.69×10^{-12} s/s is found to be superimposed on a cyclic variation. The continuous period increase is opposite to the secular decrease predicted by CV evolution theories and could be explained as the mass accreting of the white dwarf component from a brown dwarf indicating that V4140 Sgr is a period bouncer. Among all of the well observed dwarf novae, the outburst amplitude of V4140 Sgr is the lowest. Both the low accretion rate and the low-amplitude outburst may be the reasons to cause the observed lack of period bouncers. The cyclic change reveals the presence of a giant circumbinary planet.

To keep mass transfer from the donor stars to the white dwarfs in cataclysmic variables (CVs), they must undergo secular angular momentum lose (AML) due to gravitational radiation or magnetic braking of the donor stars[1]. The mass transfer driven by the removal of angular momentum from the binary causes the orbital period to decrease and the donor star shrinks simultaneously. In this way, CVs will evolve from a longer-period binary system with a higher-mass donor star to a shorter-period one with a lower-mass donor. The process continues until the orbital period reaches about 81.8 minimutes[1, 2]. At this point, the donor becomes a brown dwarf (with a mass below the hydrogen burning limit). The internal structure changes (caused by the increasing electron degeneracy) induce the donor star to expand in response to mass loss. At the same time, the orbital period changes from the secular decreasing to increasing. Therefore, in the orbital period distribution of CVs, there is a sharp short-period cut-off around 81.8 minutes (the `period minimum'). The orbital periods of CVs that have evolved past the period minimum should increase (CV period bouncers) and possess brown dwarf donors. It was predicted that about 70% of the current CV population should be CV period bouncers[3, 4]. However, only a few CVs with brown dwarf donor stars were detected[5-8]. No CVs with periods longer than the period minimum have been unambiguously shown a secular increase in their orbital periods.

It is possible that those orbital bouncers are a part of the known CV population, but it is extremely difficult to distinguish them from the background of the relatively brighter systems with higher accretion rates. Their observational properties may be quite different from those of the background CVs. They may consequently be very faint and also lack the frequent outbursts because of low mass transfer rates[9]. To search for the CV period bouncers, we monitored several deeply eclipsing CVs with orbital period below the CV period gap (the apparent scarcity of CVs in the period range from 3 to 2 hours) [10-12]. The mid-eclipse times of those systems could be determined with high precision because of the small size and compact structure ($R \approx 0.01 R_{\odot}$, $R_{\odot}$ is the radius of the Sun) of the white dwarf. Therefore, they are the most promising systems for checking the theories of the CV evolution through the determination of period changes by analyzing the observed-calculated (O-C) diagram (constructed by the observed times of light minimum minus the ones calculated with a given linear ephemeris). The changes of the orbital periods are one of a few key observational properties of the CV population that provides invaluable information on CV evolution.

V4140 Sgr is one of the monitored ultrashort-period eclipsing CVs with an orbital period of 88.46 minutes [13, 14]. It is a faint eclipsing CV with fairly deep eclipses (≈ 1 magnitude). We monitor it since June 2010 by using the 2.15-m Jorge Sahade telescope in Argentina. High-time-resolution photometry of twenty five eclipses between 5 June 2010 and 22 October 2015 were obtained without filters. Mid-eclipse times were determined by averaging the ingress and egress times of the white dwarf component in this CV, while those ingress and egress times are derived by the minimum and maximum of the light curve derivative, respectively [15] (see Supplementary Information for details on those new photometric data and mid-eclipse times). The O-C diagram is constructed by using a linear orbital ephemeris and is shown in Fig. 1.

The most important result is that the variation of the orbital period is more complex than those reported before[16, 17]. An upward parabolic change is found to be superimposed on a cyclic oscillation. To fit the O-C data well, a combination of a linearly period increasing and a cyclic variation is required (solid line in the top panel of Fig. 1),

$$(O - C)_1 = \Delta T_0 + \Delta P_0 E + \alpha E^2 + \tau .$$

In the equation, τ is the cyclic variation, i. e., $\tau = K\sin(2\pi \times E/T - \varphi)$ where E is the cycle number. The explanations of the other parameters and the derived values are listed in Table 1. As shown in the middle panel of Fig. 1, the upward parabolic change is well defined that reveals a long-term increase in the orbital period at a rate of $\dot{P} = 2.69 \times 10^{-12}$ s/s. This is opposite to the secular decrease predicted by CV evolution theories and could be explained as the mass accreting of the white dwarf from a brown dwarf donor, making V4140 Sgr is the first period bouncer of CV evolution. The relation between the period change $\dot{P}$ and the mass loss rate of the donor $\dot{M}_2$ is simply expressing as the following equation [18]:

$$\frac{\dot{P}}{P} = \left(\frac{3\beta - 1}{2}\right)\frac{\dot{M}_2}{M_2},$$

where β is the response of the radius of the donor (R_2) to the mass loss, i.e., $R_2 \propto M_2^{\beta}$. For an increasing orbital period ($\dot{P} > 0$), $\beta < \frac{1}{3}$ is required.

To date, a few white dwarfs accreting material from brown dwarf donor are detected in several CVs[5-7]. However, only SDSS J103533.03+055158.4 (hereafter J1035, P=82.09 minutes) has an orbital period long than the period minimum (81.8 minutes) [7]. Its orbital period should be increasing and thus it is also a period bouncer of CV evolution similar to V4140 Sgr[5]. The donor mass of J1035 was determined as $M_2 = 0.052\ M_\odot$. The orbital period of V4140 Sgr (88.46 minutes) is longer than that of J1035, its donor mass should be lower than that of J1035 because of the mass loss of the donor star during the evolution. By assuming a donor mass of $M_2 = 0.04\ M_\odot$ for V4140 Sgr, different values of β (e. g., $-1 > \beta > -50$) could produce different rates of mass loss ($M_2 \propto 10^{-10} - 10^{-12}\ M_\odot$ per year). A higher transfer rate from the brown dwarf donor would remove the system from the CV population soon because the donor could lose all its mass in a short timescale[9].

The comparison of the eclipse profile of V4140 Sgr to those of the other two ultrashort-period CVs V2051 Oph and OY Car is shown in Fig. 2. One of the double sharp steps in the light curves of V2051 Oph and OY Car represent the ingresses and egresses of the white dwarfs behind the donor stars. The other visible steps are the eclipses of the bright spots, where the gas streams hit the outer edges of the accretion discs. However, the eclipse profile of V4140 Sgr has no trace of a bright spot, suggesting that V4140 Sgr has a lower mass accretion rate and a very low-mass and cool donor star. All of the three CVs have the similar orbital periods. The most plausible explanation is that V2051 Oph and OY Car are normal CVs evolving to the period minimum, while V4140 Sgr is a post-period minimum system. The donor star is below the hydrogen burning limit and has a lower mass transfer rate. The detection indicates that V4140 Sgr is a CV period bouncer that is hidden in the current CV population.

Two outbursts were detected with amplitudes about 1 magnitude during the photometric monitoring. It is confirmed that V4140 Sgr has a small amplitude of regular ourburst[19]. The outburst amplitude distribution of CVs is displayed in Fig. 3 where the mean ourburst amplitudes of 77 dwarf novae are plotted, which were derived based on the data of the American Association of Variable Star Observers (AAVSO). It is shown that

V4140 Sgr has the smallest amplitude of outbursts among all well observed dwarf novae. Previous investigations showed that the outburst of V4140 Sgr occurs mainly by the significant brightness increase in the intermediate and outer disc regions. The temperatures of the disc are usually lower and the radial temperature distributions in both quiescence and outburst are also flatter than the $T \propto r^{-3/4}$ law that is significantly different from those of other short-period dwarf novae of similar orbital period (e.g., OY Car) [19, 20]. Both the lower amplitude of outburst and the peculiar behavior of the disk may be caused by the presence of the brown dwarf donor. An accretion from a brown dwarf usually has a lower rate and material accreting from an electron-degeneracy companion may have different viscosity.

The O-C diagram of V4140 Sgr also shows a cyclic change with a period of 6.69 years that can be explained by wobbles of the binaries' barycentre via the presence of a tertiary component. The explanation of the magnetic activity cycles of the donor could be completely ruled out because it is an extremely low-mass object. Depending on the positions of the eclipsing CV around the barycentre of the triple system, the central dwarf nova is cyclically close to or farther away from the Sun and thus the arrival time of mid-eclipse of the white dwarf periodically advanced or delayed. The same method has been used to detect substellar companions in CVs and some detached white dwarf binaries[21-24]. As shown in the lowest panel of Fig. 1, the data cover about three cycles of the periodic change that support the explanation of the presence of a tertiary companion. The mass of the third body is determined as $M_3 \sin i' = 7.6$ (±1.1) Jupiter mass (M_J) (i' is the orbital inclination of the third body) by assuming a total mass of the dwarf nova as $M_t = 0.82\,M_\odot$. For orbital inclinations $i' \geq 31.7^\circ$, its mass is $M_3 \leq 14\,M_J$ and it should be a giant planet. If the orbital plane of the planetary companion is parallel to the visual line of the observer (i.e., $i' = 90^\circ$), the separation from the circumbinary planet to the central dwarf nova is: d_3=3.3 (±0.7) AU (1 AU is the mean distance between the Earth and the Sun).

Recent investigations suggest that substellar objects orbiting white dwarfs are rare. To date only a few brown dwarfs companion to white dwarf were found [25,26]. The present study together with recent detections may reveal that the incidence of substellar objects in CVs including their progenitors is higher than that in single white dwarfs. This may be caused by the reason that the evolutionary process of evolved binaries is quite different from that of single stars[27]. The original planets orbiting single stars may have been destroyed or escaped during the post main-sequence evolution [28, 29]. However, as for those evolved binaries, they were formed from a common envelope (CE) evolution after the more massive stars in the original binaries evolve into a red giant or an asymptotic giant branch star. The low-mass component stars spiraled in the CE and then its ejection removed a large amount of angular momentum. Finally, CVs and their progenitors were formed. It is possible that the spiraling of the low-mass stars in CE protected those circumbinary planets and brown dwarfs [27]. The other possibility is that they are second generation substellar objects formed during the late evolutionary stages of binary stars (e.g., during the CE) [30].

The present discovery supports a fundamental and long-standing conclusion of binary evolution theory that a population of orbital bouncers of CV evolution exists. Those orbital bouncers are a hidden population of the known CVs. It is very difficult to find them because they are very faint and have very low-amplitude outbursts due to low mass accretion and different viscosity. It also demonstrates that CVs are planetary hosting stars. The planets orbiting CVs and their progenitors may be “saved” by the low-mass component stars in the original binaries or they may be second-generation planets.

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Supplementary information is linked to the online version of the paper at www.nature.com/nature

Author Contributions Q.S.B. analyzed and interpreted the data from which an accreting white dwarf with a brown dwarf donor and a giant circumbinary planet is discovered. H.Z.T., F.L.E., Z.L.Y., and L.L.J. contributed to the observations and data reduction.

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Table 1 Parameters of the period change and the circumbinary planet [*]

Parameters	Values
Correction on the initial epoch, ΔT_0 (days)	$+8.9(\pm5.9)\times10^{-5}$
Correction on the initial period, ΔP_0 (days)	$+1.05(\pm0.15)\times10^{-8}$
Rate of the linear decrease, 2α (day/cycle)	$+1.65(\pm0.16)\times10^{-13}$
Semi-amplitude[**], K (days)	$1.70(\pm0.26)\times10^{-4}$
Orbital period, T (years)	6.69(±0.12)
The orbital phase, φ (deg)	63.6(±24.4)
Mass function, $f(m)$ [***] ($M_\odot$)	$5.71(\pm0.26)\times10^{-7}$
Mass of the planet companion, $M_3 \sin i'$ ($M_{\rm Jup}$)	7.6(±0.6)
Semi-major axis of the planet, d_3 (AU, $i' = 90^\circ$)	3.3(±0.8)

[*] Our best fit to the O-C diagram reveals that the orbit of planet is circular.

[**] $K = \frac{a_{12}\sin i'}{c}$ ($a_{12} \sin i'$ is the projected semi-major axis of the central binary and c is the speed of the light)

[***] $f(m) = 4\pi^2(a_{12} \sin i')^3 / GT^2 = (M_3 \sin i')^3 / (M_1 + M_2 + M_3)^2$

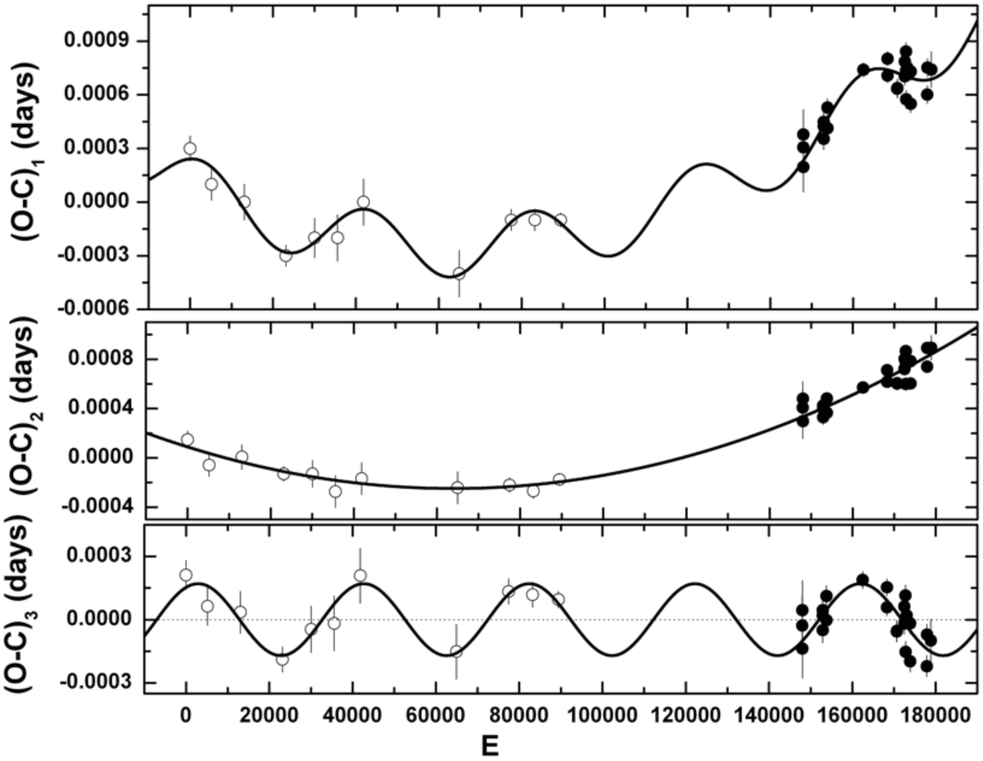

Figure 1 O-C diagrams of V4140 Sgr. The (O-C)1 values are computed by comparing the observed eclipse times with those calculated according to the linear ephemeris: Min.I = BJD 2446261.67145+0.0614296779 × E. To obtain the diagram, eclipse times collected from the literature17 (open circles) and 25 new data (solid dots) were used. The O-C curve in the upper panel shows a combination (solid line) of a small-amplitude cyclic oscillation and an upward parabolic change. The upward parabolic variation in the middle reveals a continuous period increase at a rate of $\dot{P}$ =+26.9(±2.6) ×10-13 s/s (or 8.5s in about 100000 years). The cyclic change is shown in the lowest panel that has an amplitude of 14.6 seconds with a period of 6.69 years.

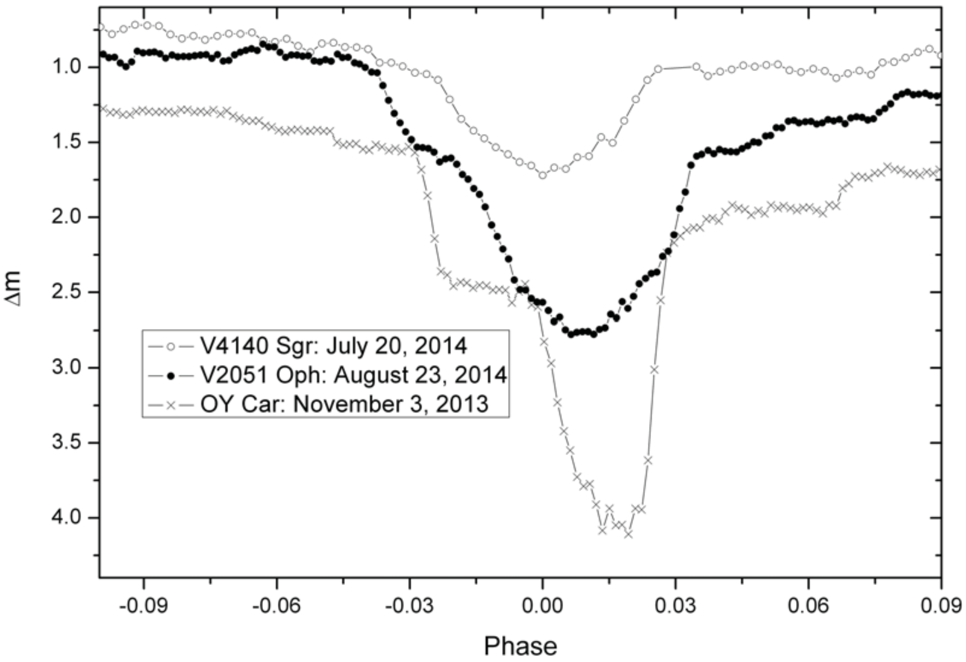

Figure 2 Comparison of eclipse profiles of three dwarf novae with the nearly same orbital periods. Open circles refer to the eclipse profile of V4140 Sgr obtained on July 20, 2014, while solid dots and crosses to those of V2051 Oph (P=88.46 minutes) and OY Car (P=90.88 minutes) observed on August 23, 2014 and November 3, 2013, respectively. Two sharp steps in the light curves are seen for V2051 Oph and OY Car that represent the ingresses and egresses of the white dwarf and the bright spot behind the donor star. However, no obvious sharp steps are visible in the light curve of V4140 Sgr. The lack of steps may reveal that the temperature of the white dwarf is low and no bright spots are formed for V4140 Sgr indicating a low rate of mass accretion from the brown dwarf donor.

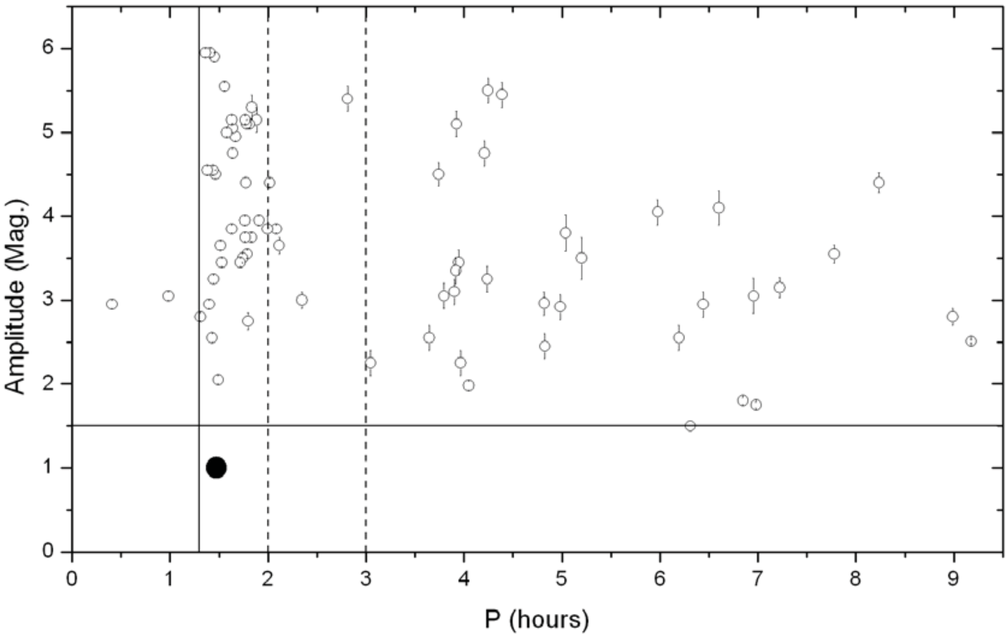

Figure 3 Distribution of outburst amplitude for dwarf novae. The mean outburst amplitudes of 77 dwarf novae were determined by using the AAVSO data in V band. The two dashed lines refer to the well known CV period gap, while the solid vertical line to the period minimum of CVs. The position of V4140 Sgr is plotted as the solid dot that has the lowest outburst amplitude with a post-minimum period. Tow CVs below the period-minimum and the one at the middle of the period gap may be formed directly from a detached white dwarf binary rather than from CV evolution.

Supplementary Materials used in the manuscript

1. New mid-eclipse times and the O-C diagram

V4140 Sgr was monitored photometrically since June 2010 by using the 2.15-m Jorge Sahade telescope (hereafter JST) at Complejo Astronomico El Leoncito (CASLEO), San Juan, Argentina. Until May 2011, observations were made using a Roper Scientific, Versarray 1300B CCD camera. Since Nov 2012, a Roper Scientific, Versarray 2048B camera was used. Fig. 1S shows a finding chart for V4140 Sgr with a nearby comparison star and a number of additional check stars adopted for differential photometry. Because V4140 Sgr is a relatively faint eclipsing dwarf nova (V≈18 mag.), to obtain high precision data and to improve the time resolution of the observations, no filters were applied. All of the CCD images were analysed by using PHOT (measure magnitudes for a list of stars) of the aperture photometry package of IRAF. In all, 25 complete eclipses were observed from June 2010 to October 2015. Two eclipse profiles obtained in 2011 are shown in Fig. 2S. For comparison, two eclipse profiles observed in 2013 are also plotted in the right panel. As shown in the figure, the eclipse profile of the dwarf nova is variable with time from night to night. As in the case of V2051 Oph, some intrinsic and random brightness fluctuations of 0.01-0.15 mag on timescales from seconds to a few minutes (i. e. brightness flickering) are visible.

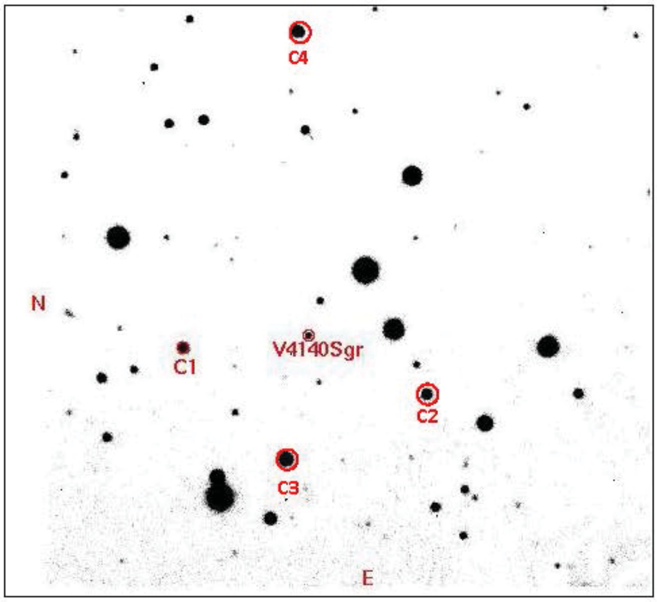

Fig. 1S: Finding chart for V4140 Sgr obtained using the 2.15-m JST in Argentina. C_1 is the comparison star, while C_2, C_3, and C_4 are chosen the check stars.

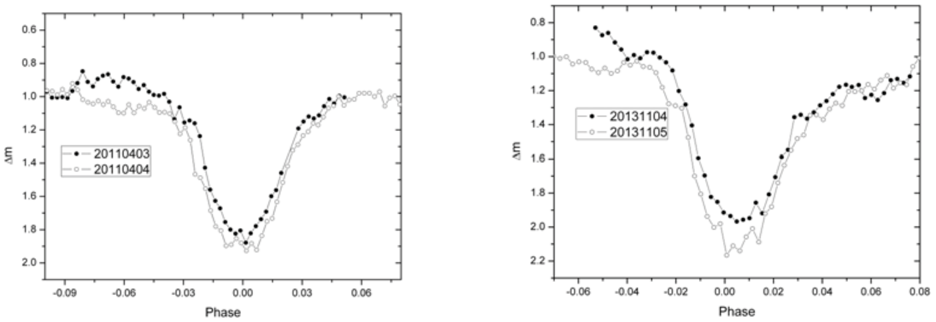

Fig. 2S: White-light eclipse profiles of V4140 Sgr obtained with the 2.15-m JST in Argentina. The two eclipse profiles in the left panel were obtained in two successive nights in April 2011, while those in the right panel were obtained in 2013.

The variation of the eclipse profiles in the panels of Fig. 2S indicates that the accretion disc is varying with time, while the ingress and egress times of the white dwarf are stable. Therefore, we use the mid-eclipse times to investigate the changes of the orbital period that are determined by averaging the mid-ingress and mid-egress times of the white dwarf eclipses. They are derived by using the derivative technique in which the mid-ingress and mid-egress times are corresponding to the minimum and maximum of points in the derivative light curves[15]. Two examples of measuring times of the WD ingress and egress are displayed in Fig. 3S. Those mid-eclipse times in HJD and BJD are listed in Table 1S.

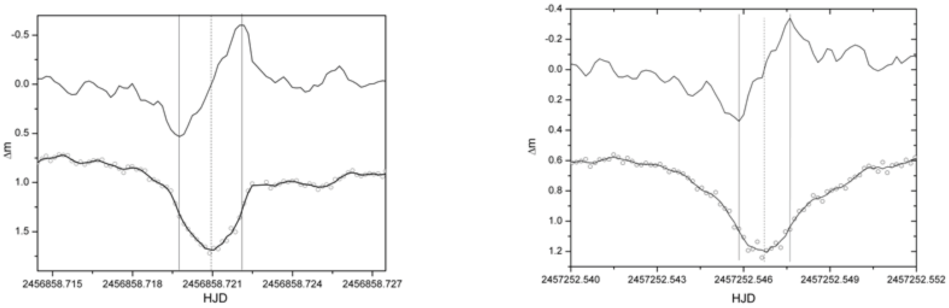

Fig. 3S: Two examples of determining mid-eclipse times. The two solid lines refer to the mid-ingress and mid-egress times of the eclipses of the white dwarf, while dashed line to the mid-eclipse times. The one in the left panel was observed in 2014, while that in the right panel observed in 2015.

Based on all available eclipse times, the O-C diagram is constructed and shown in Fig. 4S. To describe the general trend of the O-C diagram well, it is found that the combination of an upward parabolic change (solid line in Fig. 4S) and a cyclic oscillation is required. The upward parabolic change reveals a long-term increase in the orbital period that is cause by a mass accretion of the white dwarf from a brown dwarf donor. The cyclic oscillation of the O-C curve is caused the light-travel time effect via by the presence of a giant planet (see next paragraph for details). Firstly, we analyse the light-travel time effect by considering a general case with an eccentric orbit of the third body [31-33]. However, the eccentricity was determined to be close to zero but with a larger error indicating that the orbit of the third body is circular. Therefore, final solutions were obtained by assuming a circular orbit for the third body. Residuals, after both of the two kinds of variations are removed, are plotted in the lower panel. As displayed in the panel, no changes can be traced indicating that the fit is well.

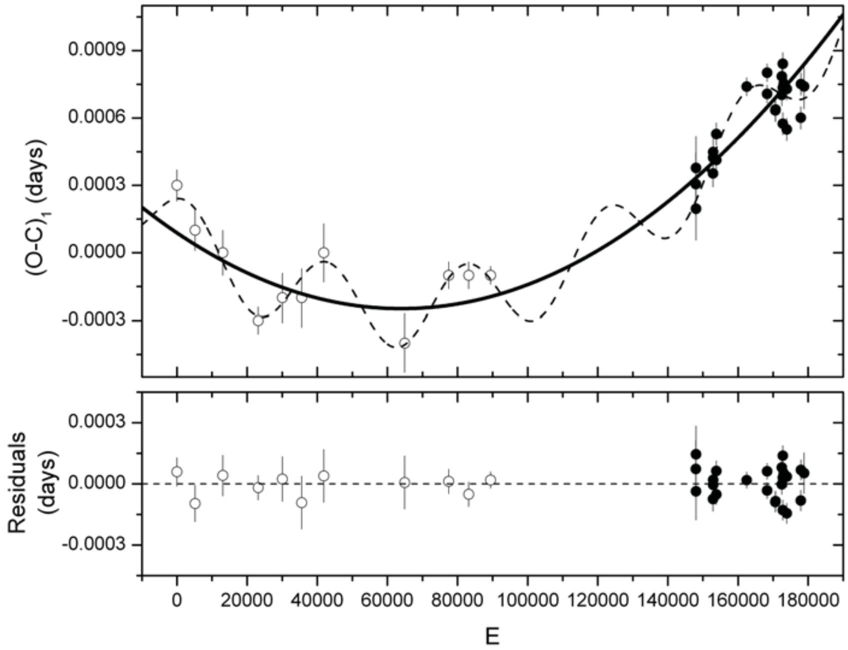

Fig. 4S: O-C diagram of V4140 Sgr. The symbols are the same as those in Fig. 1. The solid line refers to the continuously increasing in the orbital period, while the dashed line to the combination of the increase and a cyclic change. After both the continuous increase and the cyclic variation were subtracted, the residuals are displayed in the lower panel.

The cyclic variation is detected in the O-C diagram of V4140 Sgr with a cycle length of 6.69 years and an amplitude of 14.6 seconds. One of the possibilities to cause this type of cyclic changes is the mechanism of magnetic activity cycles of the cool component (the mechanism of Applegate) [34]. Since the mass donor in V4140 Sgr is a brown dwarf, this mechanism could be completely ruled out. However, we also investigated this mechanism by considering a higher donor mass, i.e., M_2=0.092(± 0.016) $M_\odot$[19]. The required energies to produce the period oscillations for different shell masses of the donor are calculated with the same method used by previous investigators[35]. We discovered that the required energies are larger than the total radiant energy of the donor in a whole cycle (see for details see Fig. 5S). This suggests that the mechanism of Applegate could not explain the cyclic period variations even we assume the donor is a completely fully convective star with a mass of 0.092$M_\odot$. During the calculation, the parameters: $M_1 = 0.73\ M_\odot$ and R_2=0.0136$R_\odot$ were used[19]. We chose a temperature of $T_2 = 2400\ K$ for the donor star and its luminosity was computed by using $L_2 = \left(\frac{R_2}{R_\Theta}\right)^2 \left(\frac{T_2}{T_\Theta}\right)^4 L_\Theta$. These results suggest that the cyclic period change is caused by the light travel-time effect via the presence of a circumbinary giant planet.

The orbital separation between V4140 Sgr and the giant planet is about 3.3 AU when the orbital inclination equals 90 degrees indicating that the orbit is very tight. The progenitor of the central dwarf nova was formed from a common envelope (CE) evolution after the more massive component star in the original binary evolves into a red giant or an AGB star. The low-mass star spiraled in the CE and its ejection removed a large amount of angular momentum. Then the short-period close binary was formed[36, 37]. It is possible that the giant circumbinary planet was saved by the spiraling process of the low-mass stars because it caused the ejection of the CE. The other possibility is that the planet in the tight orbit was formed during the CE evolution and it may be a second generation planet[27, 30].

Table 1S: New mid-eclipse times of V4140 Sgr.

HJD (days)	BJD(days)	Errors (days)	E	O-C （days）
2455352.89476	2455352.895507	0.00014	147994	0.000305868
2455353.8777075	2455353.878454	0.00014	148010	0.000378022
2455353.938955	2455353.939702	0.00014	148011	0.000196343
2455654.883095	2455654.883851	0.00006	152910	0.000353311
2455655.866065	2455655.866821	0.00006	152926	0.000448465
2455709.739855	2455709.740613	0.00005	153803	0.000412947
2455710.784275	2455710.785033	0.00005	153820	0.000528422
2456243.502625	2456243.503411	0.00004	162492	0.000739674
2456600.53197	2456600.532761	0.00004	168304	0.000801719
2456601.57618	2456601.576971	0.00004	168321	0.000707194
2456745.81299	2456745.813781	0.00005	170669	0.000633485
2456747.8401725	2456747.840964	0.00005	170702	0.000637115
2456857.7379325	2456857.738724	0.00005	172491	0.000703351
2456858.72089	2456858.721681	0.00005	172507	0.000785505
2456874.7540925	2456874.754883	0.00005	172768	0.000841573
2456875.67543	2456875.676221	0.00005	172783	0.000734405
2456876.658145	2456876.658936	0.00005	172799	0.000574558

2456889.55855	2456889.559341	0.00005	173009	0.000747199
2456892.56861	2456892.569401	0.00005	173058	0.000752982
2456944.537915	2456944.538705	0.00005	173904	0.000549479
2456944.599525	2456944.600315	0.00005	173905	0.000729801
2457190.80955	2457190.810335	0.00005	177913	0.000600778
2457192.77545	2457192.776235	0.00005	177945	0.000751085
2457249.720740	2457249.721536	0.00040	178872	0.000740671
2457252.546645	2457252.547440	0.00015	178918	0.000879488
2457317.540163	2457317.539370	0.00020	179976	0.00100000

Explanations of the columns:

Col. 1: Mid-eclipse times in Heliocentric Julian Date (HJD).

Col. 2: Mid-eclipse times in Barycentric Dynamical Time (BJD).

Col. 3: Errors of those mid-eclipse times.

Col. 4: The cycle numbers.

Col. 5: O-C values computed with the linear ephemeris: Min. I = BJD 2446261.67145 +0.0614296779×E.

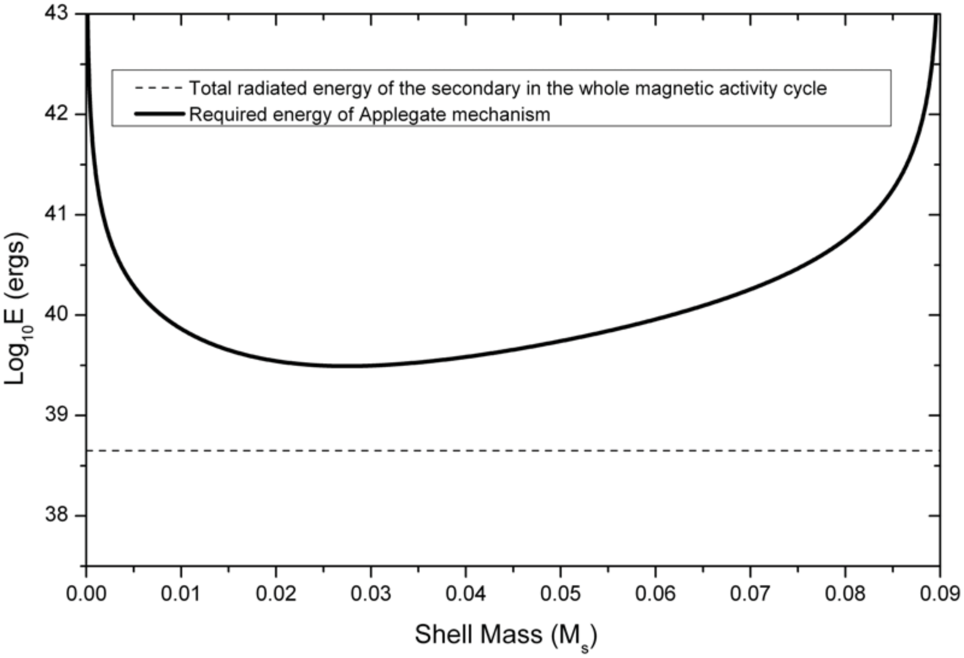

Fig. 5S: The energy required to produce the cyclic oscillation of the O-C curve by using Applegate's mechanism (solid line). M_S is the assumed shell mass of the mass donor. The dashed line refers to the total energy that radiates from the cool component in a whole cycle of the O-C oscillation.

2. Light-term brightness changes and outbursts

The mean out-of-eclipse brightness is determined by averaging the observations outside the eclipse and is shown in Fig. 6S. Apart from normal brightness state changes, two dwarf nova outbursts were taking place in May 2011and in July 2014 with an amplitude of about 1 magnitude. A typical brightness state change is shown in Fig. 7S where the comparison of eclipse profiles in different brightness states is plotted. They were obtained in three successive nights in June 2015. The eclipse profile observed on June 17 indicates that V4140 Sgr is at a low state, while it then goes to a high brightness state on June 18. Finally, it goes back to low state again on June 19 indicating that the timescale of this brightness state change is about two days. As seen in the figure, the high-frequency flickering disappeared in the light curve at high state. This supports the idea that the high-frequency flickering is produced in the accretion disk that shows a radial distribution.

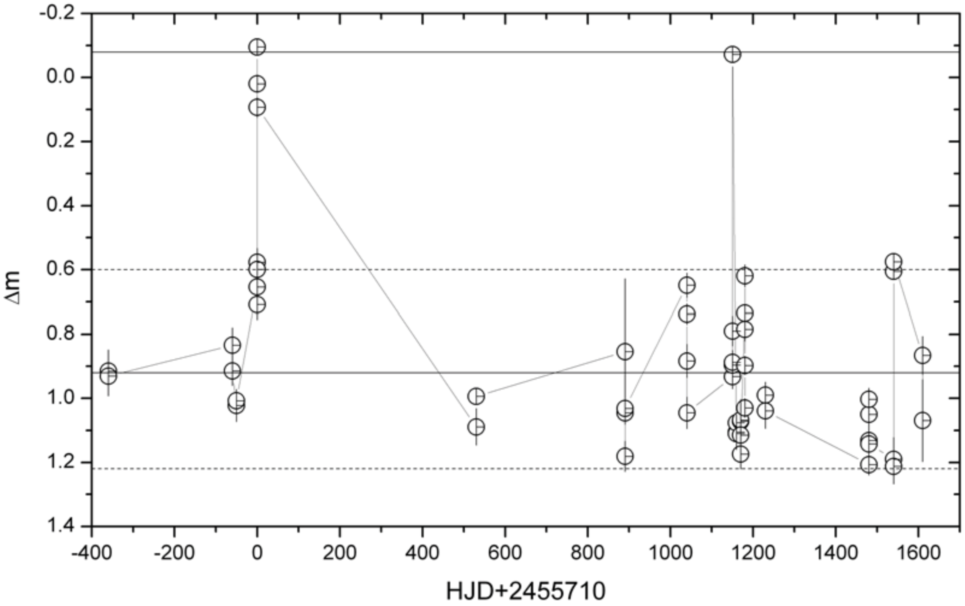

Fig. 6S: Variation of the out-of-eclipse brightness from 2010 to 2015 for V4140 Sgr. Apart from normal brightness state changes (between the two dashed lines), two outbursts occurred in May 2011and in July 2014 (as shown by the two solid lines), respectively.

The comparison of the eclipse profiles in outburst and quiescence is displayed in Fig. 8S in which the light curves in the left panel were obtained in May 2011, while those in right were observed in July 2014. It is shown that the light curves in quiescent are narrow and deep, while those in outburst are wider and shallower. These properties confirm that the brightness distributions in quiescent are smooth with maximum light at disc centre with a slightly brighter of the hot spot at disc rim. However, during outburst, the brightness was increasing in the outer parts of the accretion disc and asymmetries at the hot spot position are larger. The properties support the conclusion that the outbursts of V4140 Sgr occurs mainly with a significant brightness increase in the intermediate and outer disc regions[19]. Among all of the well observed dwarf nova outbursts, the amplitude of V4140 Sgr is the lowest one. The long-term period increase, the lowest-amplitude outbursts, and some other peculiar properties, all suggest that V4140 Sgr is the first orbital bounce of CV evolution.

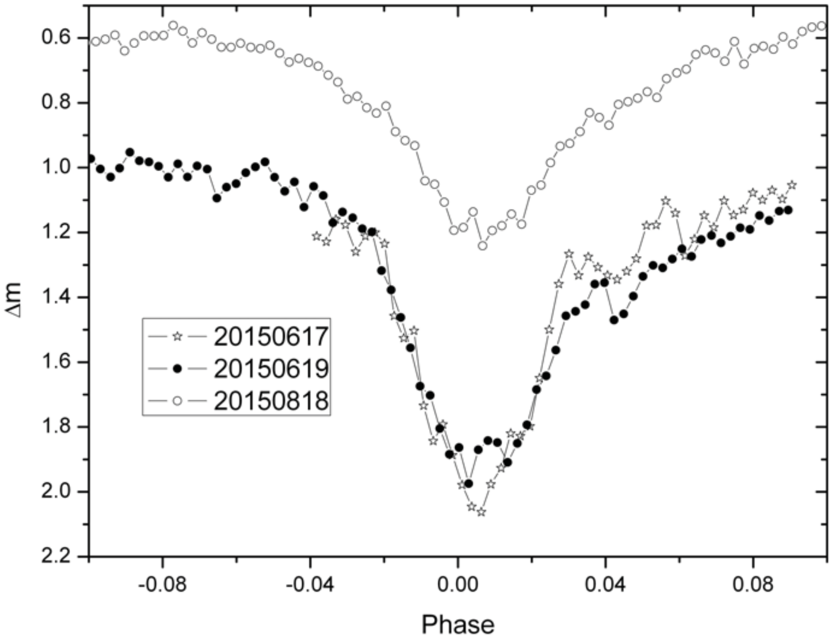

Fig. 7S: Comparison of the eclipse profiles at high and low brightness states. All of the light curves were obtained in three successive nights in June 2015.

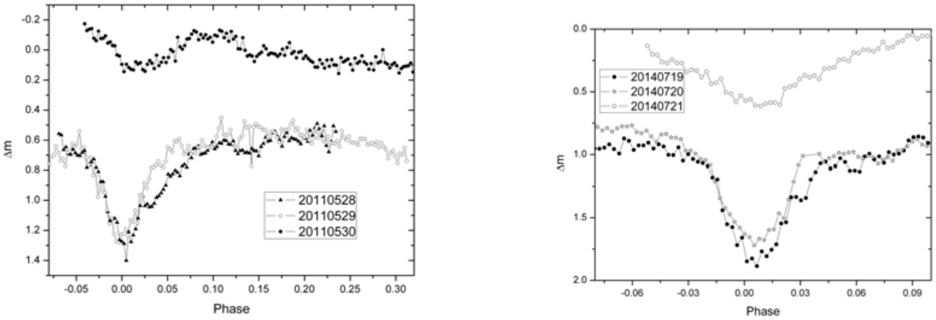

Fig. 8S: Comparison of the eclipse profiles in outburst and quiescence. The light curves in the left panel were obtained in May 2011, while those in right were observed in July 2014.

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