Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY LETTERS

Mon. Not. R. Astron. Soc. **401,** L34–L38 (2010) doi:10.1111/j.1745-3933.2009.00780.x

A giant planet in orbit around a magnetic-braking hibernating cataclysmic variable

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Accepted 2009 October 19. Received 2009 October 19; in original form 2009 September 19

ABSTRACT

Detections of Jupiter-like giant planets in orbit around short-period white dwarf binaries should provide insight into the formation and evolution of circumbinary planets (planets orbiting both components of short-period binaries), as well as into the ultimate fate of planets and the late evolutionary stage of binary stars (e.g. the evolution of the common envelope). However, to date no planets have been detected as companions to such close binaries. Here, we report the discovery of a giant planet orbiting the only known hibernating cataclysmic variable (CV), QS Vir, with a period of 7.86 yr. We analysed the variations of the orbital period of the eclipsing white dwarf–red dwarf binary, and a very small-amplitude cyclic change is found to be superimposed on a long-term period decrease. The period oscillation has the smallest amplitude among close binary stars and can be plausibly interpreted as the light-travel time effect via the presence of a third body. We found that the tertiary component is a giant planet with a mass of $\sim$6.4 $M_{\rm Jupiter}$ at a distance of $\sim$4.2 astronomical units (au) from the binary. The continuous decrease is explained as angular momentum loss via magnetic braking which is driving the evolution of the hibernating CV into a normal cataclysmic binary.

Key words: binaries: close – binaries: eclipsing – stars: individual: QS Vir – planetary systems – white dwarf.

1 INTRODUCTION

With an orbital period of about 3.618 h and containing a white dwarf primary and a red dwarf (with spectral type of M3.5–M4) secondary (O'Donoghue et al. 2003), QS Vir (=EC 13471−1258) is the only known hibernating cataclysmic variable (CV) where the red dwarf component is temporarily and marginally detached from its Roche lobe, and no mass transfer or accretion disc is observed in the system. It is therefore important for understanding CV evolution. This binary was discovered during the Edinburgh–Cape blue object survey (e.g. Kilkenny et al. 1997; Stobie et al. 1997) and showed deep and total eclipses (O'Donoghue et al. 2003). Moreover, the well-detached configuration means that the eclipses are not influenced by accretion-driven radiation from other components observed in CVs (e.g. the accretion discs and hotspots). These properties help the determinations of eclipse times to have a high precision, and very small-amplitude orbital period variations can be detected by analysing the 'observed minus calculated' ($O-C$) diagram (constructed by the observed times of light minimum minus those calculated with a given linear ephemeris). Therefore, it is one of the most promising systems for detecting very low-mass companions and providing valuable information on CV evolution through the determination of period changes.

If there is a tertiary companion orbiting an eclipsing binary, the wobble of the binary's barycentre will cause the orbital period and thus the $O-C$ diagram to show a cyclic change. Therefore, extrasolar planets hosted in eclipsing binaries as a tertiary companion can be detected by measuring the $O-C$ variation. This method has been used to detect tertiary brown dwarf companions in the sdB-type eclipsing binaries HW Vir (e.g. Qian et al. 2008; Lee et al. 2009) and HS0705+6700 (Qian et al. 2009), and in the eclipsing white dwarf binary V471 Tau (Guinan & Ribas 2001). It is similar to the radio approach to detecting planets around pulsars (e.g. Wolszczan & Frail 1992; Backer, Foster & Sallmen 1993; Wolszczan 1994). In this Letter, we report the detection of a giant extrasolar planet in orbit around the hibernating CV QS Vir by using this method.

2 NEW OBSERVATIONS AND ORBITAL PERIOD CHANGE OF QS VIR

The white dwarf–red dwarf eclipsing binary QS Vir was monitored from 1992 to 2002 with the South African Astronomical Observatory (SAAO) 0.75- and 1.0-m telescopes, and plenty of

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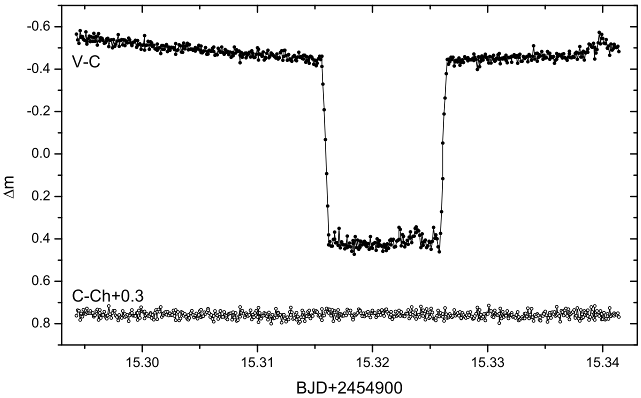

Figure 1. Light curve of QS Vir in the *V* band obtained with the 2.4-m telescope on 2009 March 24. The coordinates of the comparison star are $\alpha_{2000} = 13^{\rm h}49^{\rm m}58^{\rm s}.1$ and $\delta_{2000} = -13^{\circ}13'57''.6$, while those of the check star are $\alpha_{2000} = 13^{\rm h}50^{\rm m}01^{\rm s}.7$ and $\delta_{2000} = -13^{\circ}16'13''.4$. V − C refers to the magnitude difference between QS Vir and the comparison star, and C − Ch to the magnitude difference between the comparison star and the check star.

times of mid-ingress and mid-egress were determined with those high-speed photometric observations (O'Donoghue et al. 2003). Those data are very useful to investigate the changes of the orbital period. The mid-eclipse times used here were derived by averaging the times of mid-ingress and mid-egress. Apart from the SAAO data, four mid-eclipse times were determined with photometric observations published in the literature (Kawka et al. 2002). However, only two are used for the present analysis, because the other two show large scatters when compared with the general trend formed by the other data points. To get more data for this eclipsing binary, it was monitored with three telescopes (the 2.4-, 1.0- and 0.6-m telescopes) at Yunnan Observatory. Three mid-eclipse times, BJD 245 4915.321 151, 245 4916.225 660 and 245 4945.321 798, were obtained by using a VersArray 1300B CCD camera attached to the 2.4-m telescope, and two mid-eclipse times, BJD 245 4911.401 360 and 245 4915.321 060, were obtained with two DW 436 CCD cameras attached to the 0.6-m and the 1.0-m telescopes, respectively. During the observations, the integration time for each CCD image was 5 s and the readout time of the CCD camera was 1.8 s. Therefore, the time resolution of the photometric data is about 6.8 s. We estimate that the error of the mid-eclipse times is about half of the time resolution, i.e. 0.000 04 d. The light curve observed with the 2.4-m telescope on 2009 March 24 is displayed in Fig. 1.

The $(O-C)_1$ values (see Table 1) of all of the available mid-eclipse times were calculated by comparing the observed mid-eclipse times with those computed according to the linear ephemeris given by O'Donoghue et al. (2003),

$$\text{Min.}\,I = \text{BJD}\,244\,8689.640\,60 + 0.150\,757\,525E, \qquad (1)$$

where E is the cycle. A linear slope in $(O-C)_1$ corresponds to a constant period shorter or longer than predicted by the ephemeris, and a parabola corresponds to a linear period change. To construct the diagram, 29 mid-eclipse times from O'Donoghue et al. (2003) and seven new ones were used. The error of the mid-eclipse times published by O'Donoghue et al. (2003) is about 1 s, while the error of our new observations is about 3.4 s (0.000 04 d). Since Barycentric Dynamical Time (BJD) is a precise time system, which corresponds to coordinated Universal Time (UTC), during the analysis

Table 1. Mid-eclipse times of the white dwarf–red dwarf eclipsing binary star QS Vir.

BJD (d) +240 0000	E	$(O-C)_1$	$(O-C)_2$	Ref.[a]
48715.420 006	171	−0.000 131	+0.000 103	(1)
48715.570 782	172	−0.000 113	+0.000 121	(1)
48721.601 068	212	−0.000 128	+0.000 103	(1)
48723.560 903	225	−0.000 141	+0.000 089	(1)
48770.295 739	535	−0.000 138	+0.000 072	(1)
48771.351 070	542	−0.000 109	+0.000 100	(1)
49043.468 548	2347	+0.000 036	+0.000 139	(1)
49044.523 857	2354	+0.000 042	+0.000 144	(1)
49046.483 702	2367	+0.000 040	+0.000 142	(1)
49097.439 773	2705	+0.000 067	+0.000 151	(1)
49160.305 695	3122	+0.000 101	+0.000 164	(1)
49367.597 318	4497	+0.000 128	+0.000 128	(1)
49421.568 511	4855	+0.000 126	+0.000 112	(1)
49514.435 141	5471	+0.000 121	+0.000 083	(1)
49779.617 550	7230	+0.000 044	−0.000 048	(1)
49782.481 956	7249	+0.000 057	−0.000 035	(1)
49862.232 678	7778	+0.000 048	−0.000 057	(1)
49869.469 049	7826	+0.000 058	−0.000 048	(1)
49870.222 830	7831	+0.000 051	−0.000 055	(1)
50110.530 298	9425	+0.000 025	−0.000 109	(1)
50135.556 050	9591	+0.000 028	−0.000 108	(1)
50138.571 205	9611	+0.000 032	−0.000 105	(1)
50280.283 275	10551	+0.000 028	−0.000 117	(1)
50493.605 178	11966	+0.000 034	−0.000 115	(1)
50575.315 777	12508	+0.000 054	−0.000 093	(1)
51045.227 040	15625	+0.000 111	+0.000 007	(1)
51254.629 180	17014	+0.000 049	−0.000 018	(1)
51311.464 795	17391	+0.000 077	+0.000 022	(1)
52295.609 662	23919	−0.000 179	+0.000 106	(1)
52384.254 978	24507	−0.000 287	+0.000 040	(2)
52386.214 838	24520	−0.000 275	+0.000 053	(2)
54911.401 360	41270	−0.002 298	+0.000 086	(3)
54915.321 060	41296	−0.002 293	+0.000 095	(3)
54915.321 151	41296	−0.002 202	+0.000 186	(3)
54916.225 660	41302	−0.002 238	+0.000 151	(3)
54945.321 798	41495	−0.002 302	+0.000 121	(3)

[a]References: (1) O'Donoghue et al. (2003); (2) Kawka et al. (2002); (3) the present authors.

the 29 previously published mid-eclipse times and our seven new mid-eclipse times were converted to BJD.

The $(O-C)_1$ diagram displayed in the upper panel of Fig. 2 suggests that the period change of the binary is complex. A simple linear decrease cannot fit all of the data satisfactorily, indicating the presence of a cyclic variation. To fit the general trend of the $(O-C)_1$ curve satisfactorily, a combination of a cyclic variation and a long-term rapid period decrease is required (solid line in the upper panel of Fig. 2). A least-squares solution of all available data yields

$$\begin{aligned}(O-C)_1 = & -0.000\,245(\pm 0.000\,010) + 6.75(\pm 0.16) \times 10^{-8}E \\ & - 2.89(\pm 0.04) \times 10^{-12}E^2 \\ & + 0.000\,135(\pm 0.000\,008) \sin[0^{\circ}.018\,91(\pm 0^{\circ}.000\,10)E \\ & + 48^{\circ}.9(\pm 2^{\circ}.6)], \qquad (2)\end{aligned}$$

which suggests a combination of a cyclic oscillation with a very small amplitude of 12 s and a period of 7.86 yr and a linear decrease at a rate of $\dot{P} = -3.8 \times 10^{-11}\,\mathrm{s\,s^{-1}}$ (or 1.2 s in about 1000 yr). The dashed line in the upper panel refers to the linear period decrease, while the solid one represents the combination of the linear decrease

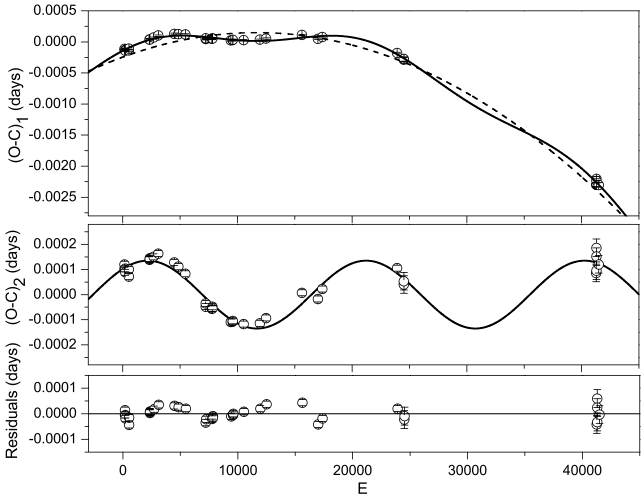

Figure 2. The $(O - C)_1$ curve of QS Vir from the linear ephemeris of O'Donoghue et al. (2003) is shown in the upper panel. The solid line in the upper panel refers to a combination of a long-term period decrease and a cyclic period variation. The dashed line represents the continuous decrease in the orbital period. The $(O - C)_2$ values with respect to the quadratic part of equation (2) are displayed in the middle panel where a cyclic change is more clearly seen. After both the long-term decrease and the cyclic change are removed, the residuals are plotted in the lowest panel.

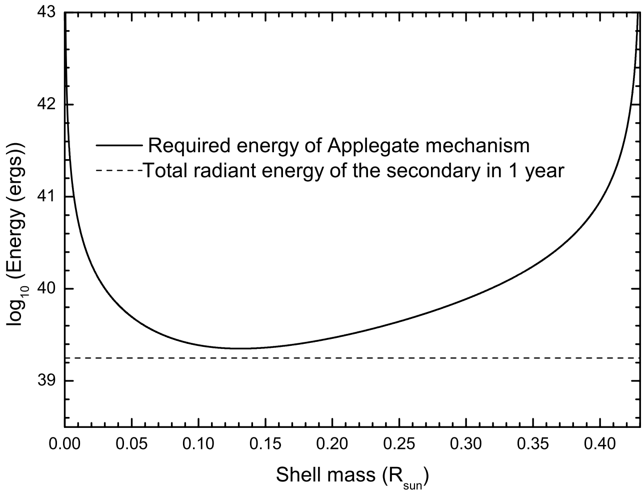

Figure 3. A plot of the energy required to cause the period oscillation of QS Vir by using Applegate's mechanism as a function of the assumed shell mass of the cool component (solid line) (Applegate 1992). The dashed line is the total radiant energy of the secondary component star in 1 yr.

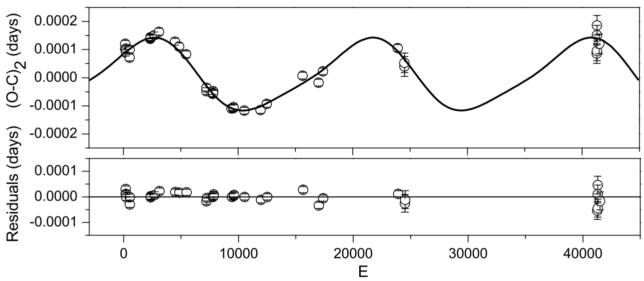

Figure 4. Theoretical light-travel time effect orbit of the giant planet companion in QS Vir with an eccentricity of $e' = 0.37(\pm0.08)$ calculated with the method of Kopal (1959). After the light-travel time effect of the giant planet is subtracted, the residuals are plotted in the lower panel.

and the cyclic period change. After the linear period change is removed, the $(O - C)_2$ values are displayed in the middle panel where a small-amplitude periodic variation can be seen more clearly. The amplitude of the cyclic change is the smallest known among close binary stars (Kreiner, Kim & Nha 2001).

3 DISCUSSION AND CONCLUSIONS

To interpret cyclic period changes in close binaries containing at least one late-type star, a mechanism, based on solar-type activity cycles, was proposed by Applegate (1992). In the mechanism, a certain amount of angular momentum is periodically exchanged between the inner and the outer parts of the convection zone, and therefore the rotational oblateness of the star and thus the orbital period will vary while it goes through its active cycles. This mechanism was supported by the observational fact deduced from the period changes of 101 Algols that all cases of alternating period changes are restricted to binaries with spectral types of the secondary later than F5, and no cyclic variations were detected for systems with spectral types earlier than F5 (Hall 1989). However, as discussed in the literature (e.g. Qian et al. 2008), the period changes of those Algols were mainly based on visual and photographic observations. Some recent investigations have shown that cyclic period variations are also common for early-type binaries, such as BH Cen, V701 Sco (Qian, Liu & Kreiner 2006), TU Mus and V382 Cyg (Qian et al. 2007), which can be plausibly interpreted by the presence of a third body. Moreover, if the cyclic variation is produced by the Applegate mechanism, all close binaries containing at least one cool component star should show cyclic period change, but this is not true. The Applegate mechanism predicted that there is a connection between the variation of the light curve and the change of the orbital period. However, to date, no reliable connections have been found.

Moreover, for QS Vir, the energies required to produce the period oscillation for different shell masses of the secondary have been calculated with the same method as used by Brinkworth et al. (2006) in the case of the pre-CV NN Ser. We discovered that the required energies are larger than the total radiant energy of the M-type component star in 1 yr (see Fig. 3), suggesting that the mechanism of Applegate has difficulty interpreting the cyclic period variation. During the calculation, we chose a temperature of $T_2 = 3100$ K for the M-type component (O'Donoghue et al. 2003) and its luminosity was computed by using $L_2 = (R_2/\mathrm{R}_\odot)^2 (T_2/\mathrm{T}_\odot)^4\,\mathrm{L}_\odot$. Therefore, the cyclic period change in QS Vir is more plausibly interpreted as the presence of a third body. Depending on the position of the QS Vir system around the barycentre of the triple system, the binary is cyclically close to or farther away from the Sun and the time of eclipse periodically advanced or delayed.

By considering a more general case of the tertiary companion with an elliptical orbit, the $(O - C)_2$ curve was described by using the following equation (the solid line in the upper panel of Fig. 4):

$$(O - C)_2 = a_0 + \sum_{i=1}^{2} [a_i \cos(i\Omega E) + b_i \sin(i\Omega E)], \tag{3}$$

where $\Omega = 2\pi/T = 0\overset{\circ}{.}01891$ and T is the orbital period of the third body divided by the binary period. The results are as follows: $a_0 = +0.000\,005(\pm0.000\,003)$, $a_1 = +0.000\,097(\pm0.000\,005)$, $b_1 = +0.000\,076(\pm0.000\,006)$, $a_2 = -0.000\,018(\pm0.000\,006)$ and $b_2 = +0.000\,014(\pm0.000\,001)$. The semi-major axis of the orbit of the binary pair around the barycentre of the triple system, $a'_{12} \sin i' = 0.021(\pm 0.001)$ au (i' is the inclination of the orbital plane formed by the central binary and the third body), and the orbital parameters of the third body, i.e. the eccentricity, $e' = 0.37(\pm 0.08)$, the longitude of periastron from the ascending node, $\omega' = 38\overset{\circ}{.}3(\pm 10\overset{\circ}{.}4)$, and the time of periastron passage, $\tau' = \mathrm{BJD}\,244\,8688.0(\pm 78.3)$ d, were computed by using the formulae given by Kopal (1959). Residuals after subtracting the light-travel time effect of the tertiary component are displayed in the lower panel of Fig. 4. By comparing these residuals with those displayed in the lowest panel of Fig. 2, it is shown that the elliptical orbit fits observations better, especially for the data between $E = 2000$ and 20 000.

With the published absolute parameters given by O'Donoghue et al. (2003), we determined the mass function and the mass of the tertiary companion as $f(m) = 1.58(\pm 0.21) \times 10^{-7}\,\mathrm{M}_{\odot}$ (the mass of the Sun) and $M_3 \sin i = 0.006\,15(\pm 0.000\,27)\,\mathrm{M}_{\odot}$, respectively. When $i \geq 26\overset{\circ}{.}19$, the mass of the third body corresponds to $0.006\,15 \leq M_3 \leq 0.0140\,\mathrm{M}_{\odot}$ – it should be a giant extrasolar planet. However, circumbinary planets were expected theoretically, at least initially, to have a nearly coplanar orbit with the central binary (e.g. Bonnell & Bate 1994). Therefore, by assuming that the tertiary companion in QS Vir is coplanar to the eclipsing binary (i.e. $i = 75\overset{\circ}{.}5$) (O'Donoghue et al. 2003), the mass of the third body is calculated as $M_3 = 0.006\,36\,\mathrm{M}_{\odot}$ which means $M_3 = 6.65\,M_{\mathrm{Jupiter}}$. In this case, the third body would be a giant extrasolar planet at a distance of 4.2 au (1 au is the mean distance between the Earth and the Sun) from the binary.

One of the most interesting things that we have learnt about extrasolar planets during the last 17 years is that they can exist almost anywhere. In the past several years, the quest for Jupiter-like giant planets has been extended to a completely different kind of host star, i.e. white dwarfs (e.g. Debes, Ge & Ftaclas 2006; Farihi, Becklin & Zuckerman 2008; Hogan, Burleigh & Clarke 2009). However, sub-stellar object companions to white dwarfs are rare. To date only four brown dwarfs orbiting white dwarfs have been found (e.g. Becklin & Zuckerman 1988; Farihi & Christopher 2004; Maxted et al. 2006; Steele et al. 2009), and only three white dwarfs are known to be wide companions to stars hosting extrasolar planets (e.g. Mayor et al. 2004; Lagrange et al. 2006; Mugrauer, Neuhäuser & Mazeh 2007). However, no extrasolar planets have been detected as companions to short-period white dwarf binary stars. The detection of the first planet in the white dwarf–red dwarf binary QS Vir will provide us with more knowledge on the formation and evolution of planets.

Hydrodynamic simulations of the formation and evolution of giant planets in a circumbinary disc showed that for a binary with orbital separation $a_{\mathrm{b}} = 1$ au, eccentricity $e_{\mathrm{b}} = 0.1$ and mass ratio $q_{\mathrm{b}} = 0.2$, the eccentricity damping provided by the disc can enable planetesimal accretion to take place in the regions located less than 4 au from the central binary (Scholl, Marzari & Thébault 2007; Pierens & Nelson 2008). This physical process may have occurred for the giant planet in QS Vir. However, theoretical investigations revealed that post-common envelope binaries like QS Vir come from the evolution of the common envelope after the hydrogen in the cores of the primary components runs out and they expand into red giant stars (Paczynski 1976; Iben & Livio 1993). It is possible that the orbit of the giant planet in QS Vir has been changed during this evolutionary stage.

Planets more massive than two Jupiter masses around low-mass stars survive the planetary nebula stage down to orbital distances of about 3 au (Villaver & Livio 2007). The distance between the giant planet companion and QS Vir is about 4.2 au, and thus it would survive the common envelope evolution of the parent binary. The survival of a giant planet orbiting the sdB star V391 Peg was recently reported (Silvotti et al. 2007). However, the situation of QS Vir seems to be more complex. The progenitor of the QS Vir system is composed of at least three components; after the evolution of the common envelope stage, both the M-type component and the giant planet survive, which could give some constraints on stellar evolution in such systems and the interactions between red giants and their companions.

QS Vir is the only known hibernating CV where the secondary component is temporarily detached from the critical Roche lobe, the mass transfer is shut off between both components and no CV phenomena are observed. How the hibernating CV formed is an unsolved problem. By using the equation (Kraft, Matthews & Greensten 1962; Faulkner 1971)

$$\frac{\dot{P}}{P} = -3\frac{32G^3}{5c^5}\frac{M_1 M_2(M_1 + M_2)}{d^4}, \tag{4}$$

where P is the orbital period, M_1 and M_2 the masses of the primary and secondary, d the distance between both components, G the gravitational constant and c the speed of light, the contribution of the gravitational radiation to the period change was computed to be $\dot{P_{\mathrm{GR}}} = -0.016 \times 10^{-11}\,\mathrm{s\,s^{-1}}$. This is about two orders smaller than the observed value ($\dot{P} = -3.8 \times 10^{-11}\,\mathrm{s\,s^{-1}}$). Therefore, the observed continuous decrease in the orbital period can be explained by angular momentum loss (AML) via magnetic braking of the secondary component. A calculation with the equation (given by Tout & Hall 1991)

$$\frac{\dot{P_{\mathrm{MB}}}}{P} = -2\left(\frac{R_{\mathrm{A}}}{d}\right)^2 \frac{M}{M_1 M_2}\dot{M}_{\mathrm{MB}}, \tag{5}$$

where R_{A} is the Alfvén radius, yields $R_{\mathrm{A}}^2 \dot{M}_{\mathrm{MB}} = -\,1.62 \times 10^{-8}$ in units of $\mathrm{R}_{\odot}^2\,\mathrm{M}_{\odot}\,\mathrm{yr}^{-1}$. If we take the Alfvén radius to be the same as that of the Sun (i.e. $R_{\mathrm{A}} = 15\,\mathrm{R}_{\odot}$), the required mass-loss rate should be $\dot{M}_{\mathrm{MB}} = -\,7.2 \times 10^{-11}\,\mathrm{M}_{\odot}\,\mathrm{yr}^{-1}$. The secular AML will drive the evolution of the binary system into a normal CV.

The evolution of long-period ($P > 3$ h) CVs is driven by AML via magnetic braking, and CVs are expected to evolve from a higher mass secondary with longer period to a lower mass secondary with shorter period (Andronov, Pinsonneault & Sills 2003). However, details of the CV evolution are still open. The detection of evidence for magnetic braking in the only known hibernating CV can provide new clues on CV evolution.

ACKNOWLEDGMENTS

This work is partly supported by the Chinese Natural Science Foundation (No.10973037, No.10903026 and No. 10778718), the National Key Fundamental Research Project through grant 2007CB815406, the Yunnan Natural Science Foundation (No. 2008CD157) and the Special Foundation of President and West Light Foundation of the Chinese Academy of Sciences. The authors thank the referee for useful comments and suggestions that helped them to improve the original manuscript. New CCD photometric observations of the system were obtained with the 60-cm, the 1.0-m and the 2.4-m telescopes in Yunnan Observatory.

REFERENCES

Andronov N., Pinsonneault M., Sills A., 2003, ApJ, 58, 2358
Applegate J. H., 1992, ApJ, 385, 621
Backer D. C., Foster R. S., Sallmen S., 1993, Nat, 365, 817

Becklin E. E., Zuckerman B., 1988, Nat, 336, 656
Bonnell I. A., Bate M. R., 1994, MNRAS, 269, L45
Brinkworth C. S., Marsh T. P., Dhillon V. S., Knigge C., 2006, MNRAS, 365, 287
Debes J. H., Ge J., Ftaclas C., 2006, AJ, 131, 640
Farihi J., Christopher M., 2004, AJ, 128, 1868
Farihi J., Becklin E. E., Zuckerman B., 2008, AJ, 681, 1470
Faulkner J., 1971, ApJ, 170, 99
Guinan E. F., Ribas I., 2001, ApJ, 546, L43
Hall D. S., 1989, Space Sci. Rev., 50, 219
Hogan E., Burleigh M. R., Clarke F. J., 2009, MNRAS, 396, 2074
Iben I. J., Livio M., 1993, PASP, 105, 1373
Kawka A., Vennes S., Koch R., Williams A., 2002, AJ, 124, 2853
Kilkenny D., Koen C., O'Donoghue D., Stobie R. S., 1997, MNRAS, 285, 640
Kopal Z., 1959, Close Binary Systems. Chapman & Hall, London, p. 111
Kraft R. P., Matthews J., Greensten J. L., 1962, ApJ, 136, 312
Kreiner M. J., Kim C.-H., Nha I.-S., 2001, An Atlas of O–C Diagrams of Eclipsing Binaries. Pedagogical University Press, Krakóv
Lagrange A.-M., Beust H., Udry S., Chauvin G., Mayor M., 2006, A&A, 459, 955
Lee J. W., Kim S.-L., Kim C.-H., Koch R. H., Lee C.-U., Kim H.-I., Park J.-H., 2009, AJ, 137, 3181
Maxted P. F. L., Napiwotzki R., Dobbie P. D., Burleigh M. R., 2006, Nat, 442, 543
Mayor M., Udry S., Naef D., Pepe F., Queloz D., Santos N. C., Burnet M., 2004, A&A, 415, 391
Mugrauer M., Neuhäuser R., Mazeh T., 2007, A&A, 469, 755
O'Donoghue D., Koen C., Kilkenny D., Stobie R. S., Koester D., Bessell M. S., Hambly N., MacGillivray H., 2003, MNRAS, 345, 506
Paczynski B., 1976, in Eggleton P., Mitton S., Whelan J., eds, Proc. IAU Symp. 73, Structure and Evolution of Close Binary Systems. Reidel, Dordrecht, p. 75
Pierens A., Nelson R. P., 2008, A&A, 483, 633
Qian S.-B., Liu L., Kreiner J. M., 2006, New Astron., 12, 117
Qian S. B., Yuan J. Z., Liu L., He J. J., Fernández L. E., Kreiner J. Z., 2007, MNRAS, 380, 1599
Qian S.-B., Dai Z.-B., Zhu L.-Y., Liu L., He J.-J., Liao W.-P., Li L.-J., 2008, ApJ, 689, L49
Qian S.-B. et al., 2009, ApJ, 695, L163
Scholl H., Marzari F., Thébault P., 2007, MNRAS, 380, 1119
Silvotti R. et al., 2007, Nat, 449, 189
Steele P. R., Burleigh M. R., Farihi J., Gänsicke B. T., Jameson R. F., Dobbie P. D., Barstow M. A., 2009, A&A, 500, 1207
Stobie R. S. et al., 1997, MNRAS, 287, 848
Tout C. A., Hall D. S., 1991, MNRAS, 253, 9
Villaver E., Livio M., 2007, AJ, 661, 1192
Wolszczan A., 1994, Sci, 264, 538
Wolszczan A., Frail D., 1992, Nat, 355, 145

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