A Brown Dwarf Orbiting the Detached White Dwarf-Main Sequence Binary SDSS J143547.87+373338.5

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ABSTRACT

SDSS J143547.87+373338.5 is a detached white-dwarf binary with a short period of 0.1256311 days. The white-dwarf primary has a mass of 0.5 $M_{\odot}$, while the secondary is a fully convective star with a mass of 0.21 $M_{\odot}$. The eclipsing binary was monitored photometrically from March 24, 2009 to April 10, 2015 by using two 2.4-m telescopes in China and in Thailand. The changes in the orbital period are analyzed based on eight newly determined eclipse times together with those compiled from the literature. It is found that the O-C (Observed-Computed) diagram shows a downward parabolic change or a cyclic oscillation with a period of 7.72 years and a small amplitude of $0.^{d}000525$. The downward parabolic variation reveals a continuous period decrease at a rate of $\dot{P} = -2.94 \times 10^{-8}$ days/year. Since the period decrease is too large to be caused by angular momentum loss via magnetic braking or/and gravitational radiation, the cyclic oscillation is more plausible. The cyclic change was explained as the light-travel time effect via the presence of a third body because the required energy for the magnetic activity cycle is much larger than that radiated from the secondary in a whole cycle. The mass of the third body is determined to be $M_3 \sin i' = 0.0189(\pm 0.0016)\, M_{\odot}$ when

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a total mass of $0.71\,M_\odot$ for SDSS J143547.87+373338.5 is adopted. For orbital inclinations $i' \geq 15.9^\circ$, it would be below the stable hydrogen-burning limit of $M_3 \sim 0.072\,M_\odot$, and thus the third body is a brown dwarf. The brown dwarf is orbiting the white dwarf-red dwarf eclipsing binary at a distance of about 3.42 astronomical units (AU).

Subject headings: Stars: binaries : close – Stars: binaries : eclipsing – Stars: individuals (SDSS J143547.87+373338.5) – Stars: whit dwarfs – Stars: low-mass, brown dwarfs

1. Introduction

Short-period white-dwarf (WD) binaries are detached binary systems with orbital periods shorter than one day. Most of them contain a white-dwarf primary and a red-dwarf secondary where both components are well within their Roche lobes. The detached configurations indicate that no mass transfers and accretion discs were taken place in those systems (those are observed in Cataclysmic Variables (CV)), and the eclipses are not influenced by mass transfers and accretion discs. Moreover, because of the small size and compact structure of the white-dwarf component, eclipse times of this type of binary system can be determined with a high precision. They are very good source to search for and to investigate circumbinary substellar objects by analyzing the light travel-time effect. If there is a substellar companion to the white-dwarf eclipsing binary, the wobble of the binary's barycentre will cause the arrival mid-eclipse time to show a cyclic change, and brown dwarfs and planets hosted in those binaries can be detected. To search for substellar objects orbiting white-dwarf binaries, we started to monitor selected eclipsing white-dwarf binaries photometrically since 2009 (e.g., Qian et al. 2009, 2010a, 2012).

SDSS J143547.87+373338.5 (hereafter J 1435) is a detached eclipsing binary with a white dwarf as the primary component (e.g., Eisenstein et al. 2006). Measurements by Rebassa-Mansergas et al. (2007) gave a mass range of $0.35 - 0.58\,M_\odot$ for the WD component. The eclipsing nature was discovered by Steinfadt et al. (2008) and the transit time is about 480 seconds. The WD in J 1435 underwent partial eclipses by an M-type companion every 3.015 hours. The spectral type of the low-mass secondary is M4-M6 that is a fully convective star and contributes less than 4% to the total brightness in the blue band. Time-resolved spectroscopic observations were later published by Pyrzas et al. (2009) and parameters of the system were revised. It is shown that the primary is a He-core white dwarf.

By using three eclipse times, the orbital period of J 1435 was firstly determined by

Rebassa-Mansergas et al. (2007) who obtained the following linear ephemeris,

$$Min.I = HJD\,2454249.71105 + 0.12562974 \times E. \quad (1)$$

The orbital period of the binary was later revised by Pyrzas et al. (2009) by using their new determined eclipse times together with those determined by Rebassa-Mansergas et al. (2007). They derived a new ephemeris,

$$Min.I = HJD\,2454148.70361 + 0.1256311 \times E, \quad (2)$$

where HJD 2454148.70361 is the initial epoch and 0.1256311 is the orbital period. To understand the properties of the variations in the orbital period of J 1435, it has been monitored since March 24, 2009 with the 2.4-m telescope in Lijiang observational station of Yunnan Observatories. Here we report the discovery of a cyclic change in the O-C diagram of J 1435 that reveals the presence of a tertiary companion, most likely a brown dwarf companion to this binary system.

2. New CCD photometric observations for J 1435

The eclipsing white-dwarf binary, J 1435, was monitored since March 24, 2009 by using the 2.4-m telescope in Lijiang observational station of Yunnan observatories. During the observation in 2009, a VersArray 1300B CCD camera attached to the 2.4-m telescope. The integration time for each CCD image was 8 s. As for the observations in 2012, YFOSC (Yunnan Faint Object Spectrograph and Camera) mounted on the 2.4-m telescope was used that has a 2 K×4 K camera. Four eclipse profiles observed with Lijiang 2.4-m telescope in 2009 and 2012 are displayed in Fig 1. R-band filter was used during the observation on March 24, 2009. However, as we can see in the figure, the data show a large scatter. To improve the precision of the photometric data, no filters were used for later observations. With our observations five mid-eclipse times were obtained and are listed in Table 1.

To obtain more data, the binary star was monitored by using the 2.4-m Thai National Telescope (TNT) of National Astronomical Research Institute of Thailand (NARIT) since December 31, 2014. This telescope is located on one of the highest ridges of Doi Inthanon (about 2457-m high from the sea level), the tallest peak in Thailand. The observing conditions (seeing and photometric conditions) of this site are very good during the dry season that runs approximately from November to April. The TNT is a Ritchey-Chrètien with two Nasmyth focuses. The ULTRASPEC instrument mounted on the telescope was used for the observation on December 31, 2014, while a research-grade $4K \times 4K$ CCD photometer was used for later observations. Two of the eclipse profiles obtained by this telescope are shown in Fig. 2 and the corresponding eclipse times are displayed in Table 1.

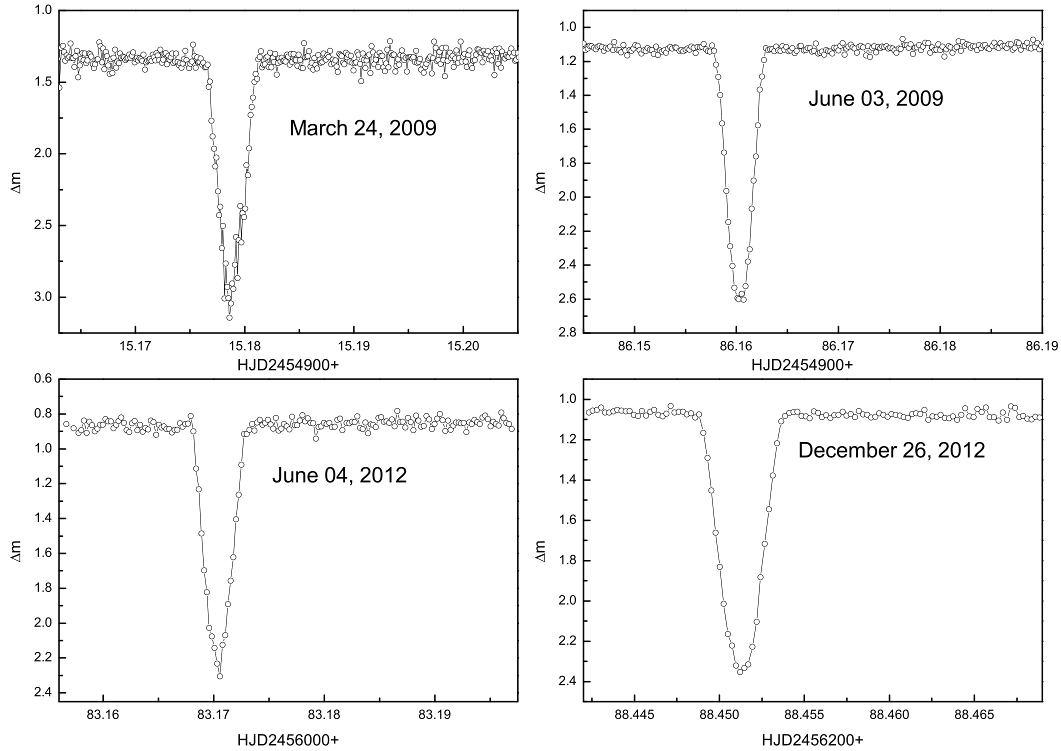

Fig. 1.— Several eclipse profiles of J 1435 observed by using the 2.4-m telescope in Lijiang observational station of Yunnan observatories.

Table 1: New CCD mid-eclipse times for J 1435.

J.D. (Hel.) +2400000 (days)	Errors days	Filters	Telescopes
2454915.17879	0.00003	R	Lijiang 2.4-m
2454978.11992	0.00005	N	Lijiang 2.4-m
2454986.16034	0.00001	N	Lijiang 2.4-m
2456083.17039	0.00002	N	Lijiang 2.4-m
2456288.45127	0.00001	N	Lijiang 2.4-m
2456658.43424	0.00001	N	Thai 2.4-m
2457094.37349	0.00001	N	Thai 2.4-m
2457123.39425	0.00002	N	Thai 2.4-m

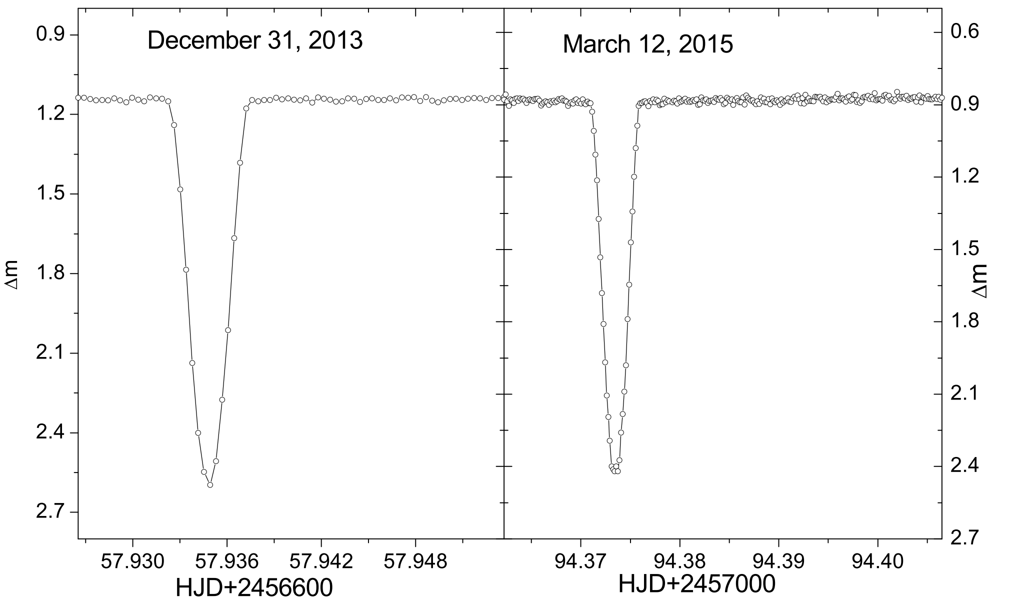

Fig. 2.— Two eclipse profiles of J 1435 observed with the 2.4-m telescope of NARIT. They were obtained on December 31, 2013 and March 12, 2015, respectively.

3. The orbital period changes of J 1435

By using the eclipse times listed in Table 1 together with those obtained by Rebassa-Mansergas et al. (2007) and by Pyrzas et al. (2009), the $(O-C)_1$ values with respect to the linear ephemeris in Eq. (2) were computed. The corresponding $(O-C)_1$ diagram is shown in the upper panel of Fig. 3. As shown in the panel, the variation of the $(O-C)_1$ curve may show a downward parabolic change indicating a long-term continuous decrease in the orbital period. A least-square solution leads to the following equation,

$$\begin{aligned} Min.I &= 2454148.703602(\pm 0.000007) + 0.^{d}1256311119(\pm 0.0000000003) \times E \\ &\quad -5.05(\pm 0.02) \times 10^{-12} \times E^2. \end{aligned} \tag{3}$$

The quadratic term in this equation reveals a continuous decrease at a rate of $\dot{P} = -2.94 \times 10^{-8}$ days/year (or -8.04×10^{-11} s/s).

J 1435 is a short-period ($P \sim 3$ hours) close binary with a white-dwarf primary and a red-dwarf secondary. The continuous period decrease may be caused by orbital angular momentum loss due to gravitational radiation. By using the following equation (e.g., Kraft 1962; Faulkner 1971),

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

the contribution of the gravitational radiation to the period decrease was computed to be: $\dot{P_{GR}} = -0.0081 \times 10^{-11}$ s/s. P in the equation is the orbital period, M_1 and M_2 the masses of the primary and secondary, a the distance between both components, G the gravitational constant, and c the speed of light. The derived value is about three orders smaller the observed one ($\dot{P} = -8.04 \times 10^{-11}$ s/s). Therefore, the observed continuous decrease in the orbital period could not be explained by angular momentum loss via gravitational radiation. The other possibility that could cause the decrease in the orbital period is angular momentum loss via magnetic braking of the secondary component. However, according to the standard theory of angular momentum loss due to magnetic braking in close compact binaries, magnetic braking ceases when the secondary star becomes fully convective (e.g., Skumanich 1972; Verbunt & Zwaan 1981; Rappaport et al. 1983; Schreiber et al. 2010). The secondary component in J 1435 is fully convective star, the angular momentum loss due to magnetic braking should be too small to cause the period decrease.

Since the angular momentum loss due to magnetic braking and gravitational radiation could not explain the period decrease, we think the O-C curve may show a cyclic variation. By using the least-squares method, we determined,

$$\begin{aligned} Min.I &= 2454148.704123(\pm 0.000039) + 0.^{d}125630992(\pm 0.000000003) \times E \\ &\quad +0.000525(\pm 0.000043) \sin[0.^{\circ}01604(\pm 0.00010) \times E + 257.^{\circ}9(\pm 4.^{\circ}5)]. \end{aligned} \tag{5}$$

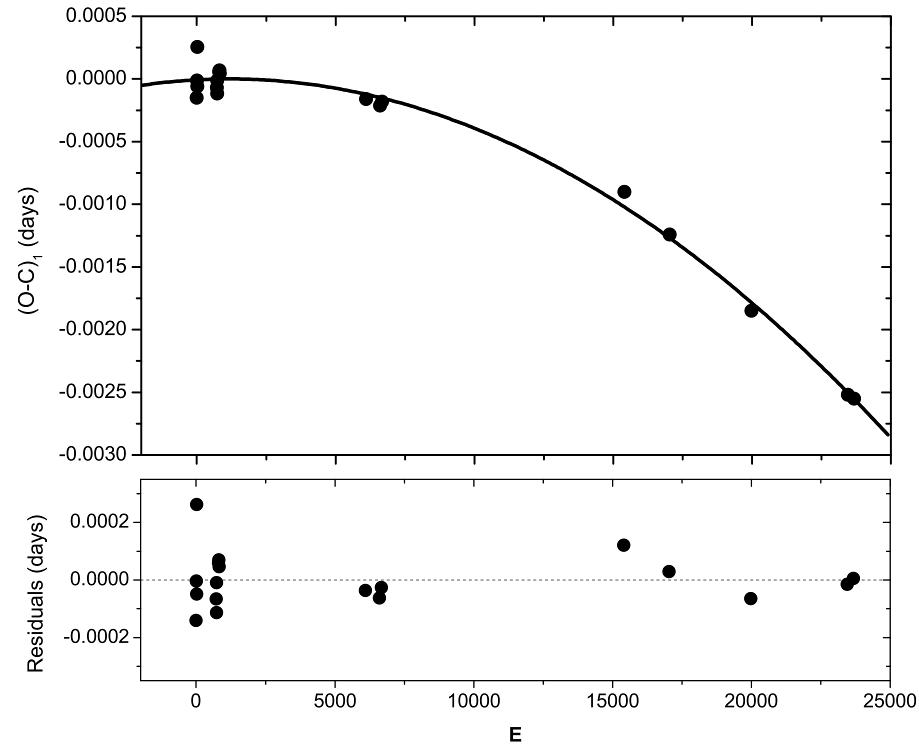

Fig. 3.— A plot of the $(O-C)_1$ diagram of J 1435 with respect to the linear ephemeris given by Pyrzas et al. (2009) is shown in the upper panel. The solid line in the panel indicates a downward parabolic change revealing a continuous decrease at a rate of $\dot{P} = -2.94 \times 10^{-8}$ days/year. After the period decrease was removed, the residuals are shown in the lower panel.

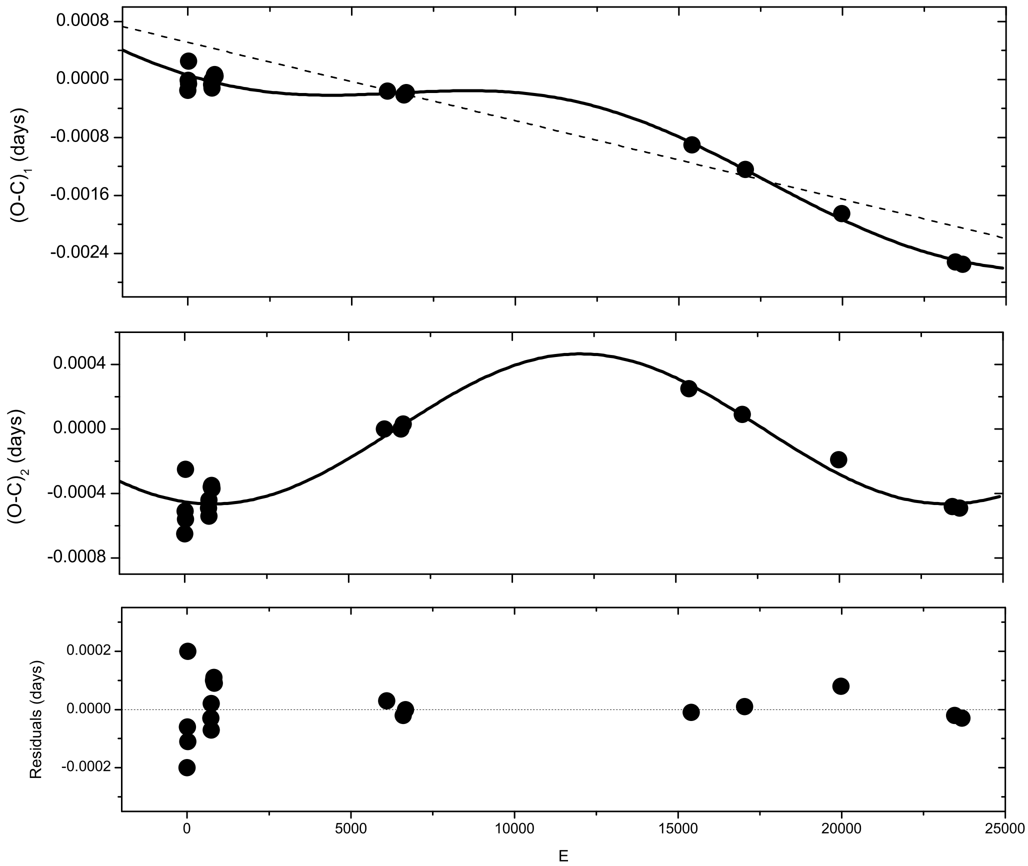

Fig. 4.— The solid line in the upper panel suggests a combination of a cyclic change and a revision in the orbital period, while the dashed line refers to the revised linear ephemeris. The theoretical light-travel time effect orbit of the brown dwarf companion with respect to the new ephemeris in Eq.(4) is shown in the middle panel where the cyclic variation can be seen more clearly. After the all of the variations were removed, the residuals are shown in the lower panel.

The linear ephemeris refers to the revisions of the initial epoch and the orbital period (dashed line in the upper panel of Fig. 4). The cyclic oscillation has an amplitude of 45.4 seconds and a period of 7.72 years. The $(O-C)_2$ values calculated with the linear ephemeris in the equation are plotted in the middle panel of Fig. 4 where the cyclic change is seen more clearly. After the revision of the orbital period and the cyclic change were subtracted from the $(O-C)_1$ curve, the residuals are displayed in the lowest panel.

4. Discussions and conclusions

As discussed in previous section, the most plausible description of the O-C diagram is a cyclic variation. The cyclic changes of the O-C diagram for close binaries containing at least one cool component could be explained by the solar-type magnetic activity cycles, i.e., the Applegate mechanism (Applegate 1992). In the mechanism, a certain amount of angular momentum is assumed to be periodically exchanged between the inner and the outer parts of the convection zone, and therefore the rotational oblateness and thus the orbital period will vary when the cool component goes through its activity cycles. The secondary in J 1435 is a fully convective star that rotates mainly as a rigid body, and lacks the thin interface layer between a radiative core and a convective envelope, where dynamo processes are thought to concentrate at for solar-type stars (e.g., Barnes 2005). To check whether this mechanism could explain the cyclic variation or not, the required energies to produce the cyclic oscillation for different shell masses of the secondary have been calculated with the same method used by Brinkworth et al. (2006) in the case of the pre-CV NN Ser. It is found that the required energies are larger than the total radiant energy of the M4.5-type component star in one whole cyclic change (see Fig. 5). During the calculation, the parameters given by Pyrzas et al. (2009) were used, i.e., $M_1 = 0.50\,M_{\odot}$, $M_2 = 0.21\,M_{\odot}$, and $R_2 = 0.23\,R_{\odot}$. By using Kepler's third law,

$$(M_1 + M_2) = 0.0134a^3/P^2, \tag{6}$$

the orbital separation of the two component stars was computed as $a = 0.94\,R_{\odot}$. We choose a temperature of $T_2 = 3200\,K$ for the M4.5-type star and its luminosity was calculated by using $L_2 = (\frac{R_2}{R_{\odot}})^2(\frac{T_2}{T_{\odot}})^4\,L_{\odot}$. The result suggests that the mechanism of Applegate has difficulty to interpret the cyclic variation.

Therefore, we analyzed the O-C diagram of J 1435 for the light-time effect that arises from the gravitational influence of a third body. By assuming that the orbit of the third body is circular, its orbital and physical parameters were estimated. The projected orbital radius of J 1435 rotating around the barycenter of the triple system is computed with the

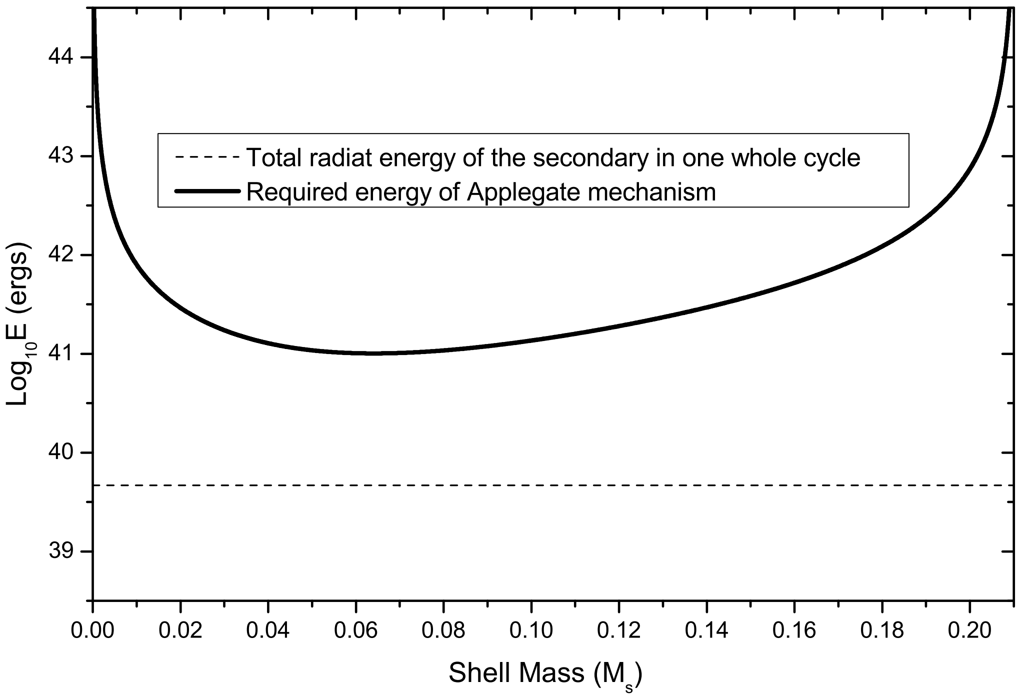

Fig. 5.— A plot of the energy required to cause the period oscillation of J 1435 by using Applegate's mechanism as a function of the assumed shell mass of the cool component (solid line). The dashed line represents the total radiant energy of the secondary component star in a whole cyclic change of the O-C variation.

equation,

$$a'_{12} \sin i' = K \times c, \tag{7}$$

where K is the amplitude of the cyclic variation and c is the speed of light. Then, by using the absolute parameters determined by by Pyrzas et al. (2009), a calculation with the following equation,

$$f(m) = \frac{4\pi^2}{GP_3^2} \times (a'_{12} \sin i')^3 = \frac{(M_3 \sin i')^3}{(M_1 + M_2 + M_3)^2}, \tag{8}$$

yields the mass function and the mass of the tertiary companion as: $f(m) = 1.26(\pm 0.31) \times 10^{-5}\,M_{\odot}$ and $M_3 \sin i' = 0.0189(\pm 0.0016)\,M_{\odot}$=19.8(±1.7) M_{Jup}, respectively. G and P_3 in this equation are the gravitational constant and the period of the $(O-C)_2$ oscillation. If the orbital inclination of the tertiary companion is larger than 15.9°, the mass of the third body corresponds to: $M_3 \leq 0.072\,M_{\odot}$, and thus it should be a brown dwarf. Therefore, with 82.3% probability, the third body is a brown dwarf (by assuming a random distribution of orbital plane inclination). The orbital radius d_3 of the tertiary component is about 3.42 AU when the orbital inclination equals 90°.

Substellar objects orbiting white dwarfs are rare. To date only a few brown dwarfs companion to white dwarf were found (e.g., Becklin & Zuckerman 1988; Farihi & Christopher 2004; Dobbie et al. 2005; Burleigh et al. 2006; Maxted et al., 2006). As for white-dwarf binary stars, a few exoplanets or brown dwarfs were reported to be orbiting V471 Tau (Guinan & Ribas 2001), QS Vir (Qian et al. 2010a; Almeida & Jablonski 2011), NN Ser (Marsh et al. 2014), and RR Cae (Qian et al. 2012). The detection of a brown dwarf companion to the white dwarf-red dwarf binary J 1435 will provide us more knowledge on the formation and evolution of Sub-stellar objects. However, the observational span for J 1435 is only 8.1 years that is comparable to the period of the O-C cyclic oscillation (7.72 years). To confirm the presence of the brown dwarf in the J 1435, more eclipse times are needed.

J 1435 is a pre-CV system with an orbital period of 3 hours that is just at the upper edge of the period gap of CVs. It is formed through a common-envelope evolution and will evolve into normal cataclysmic variables (CV) by secular angular momentum loss via gravitational radiation (e.g., Shimansky et al. 2006). The detection of a brown dwarf orbiting J 1435 suggests that some short-period CVs should contains substellar companions. A possible giant planet was found to be orbiting the eclipsing dwarf nova V893 Sco (Bruch 2014). A few planetary candidates orbiting the two magnetic CVs, DP Leo (Qian et al. 2010b; Beuermann et al. 2011) and HU Aqr (Qian et al. 2012; Goździewski et al. 2015), were reported. To check this conclusion, photometric monitoring of some deeply eclipsing CVs is required.

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