Interactions between planets and evolved stars

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Abstract. Searching for planetary companions to evolved stars (e.g., white dwarfs (WD) and Cataclysmic Variables (CV)) can provide insight into the interaction between planets and evolved stars as well as on the ultimate fate of planets. We have monitored decades of CVs and their progenitors including some detached WD binaries since 2006 to search for planets orbiting these systems. In the present paper, we will show some observational results of circumbinary planets in orbits around CVs and their progenitors. Some of our findings include planets with the shortest distance to the central evolved binaries and a few multiple planetary systems orbiting binary stars. Finally, by comparing the observational properties of planetary companions to single WDs and WD binaries, the interaction between planets and evolved stars and the ultimate fate of planets are discussed.

1. Introduction

White dwarfs (WD) are the final evolutionary state of low- and medium-mass stars (including our Sun). It is thought that over 97% of the stars in the Milky Way will end their life as white dwarfs [1]. Exoplanets surveys demonstrate that they are prevalent in the Solar neighborhood as well as in the Milky Way [2, 3]. However, little is known about the evolution of planetary systems in orbiting around white dwarfs. Searching for exoplanets around WDs could give some constraints on late stages of stellar evolution (e.g., red giant stars, asymptotic giant branch stars, and planetary nebula). The investigations could provide us more knowledge on the interacting between planets and evolved stars especially on the ultimate fate of planets.

Both the radial velocity and transit methods are extensively used to search for planets around solar-type main-sequence stars. As a WD has a size similar to that of a planet, the transit method could be used to search for earth-like planets or even small objects because the transits would produce strong eclipses [4]. However, the possibility of the transit between a WD and a planet is extremely small. To data, only a minor planet in a debris cloud is detected to transit the metal-rich white dwarf WD 1145+017 that was generated by the disintegration of the planetesimal [5]. As for the other method, the radial velocities of white dwarfs can not be determined in a high precision because of the high surface gravities. Only a brown dwarf circling WD 0137-349 was found by measuring the radial velocities of a WD [6]. No planets were detected to orbit white dwarfs by using this method. When a WD is a member of an eclipsing binary star, eclipses provide a good chance to search for planets. Thanks to the compact structures of the WD component, the eclipse times can be measured in a high precision and therefore its small wobbles caused by the presence of exoplanets can be discovered. By monitoring the changes of eclipse times due to binary wobble, circumbinary planets can be found [7, 8, 9]. We have monitored some WD binaries since 2006 by using several 2.0-m class telescopes and some small telescopes. The hosting binary stars that we interested include detached WD+dM binaries, polars (magnetic cataclysmic variables, MCVs) and total eclipsing normal cataclysmic variables (CVs).

2. Detached white dwarf binary systems

Detached white dwarf binaries (DWDB) are post-common envelope systems with orbital periods from a few hours to a week or so [10]. They usually contain a WD primary and a red dwarf secondary and both components are well within their critical Roche lobes [11]. Because of the detached configurations, they are a good source to search for and to investigate circumbinary substellar objects by analyzing the light travel-time effect. To search for substellar objects orbiting WD binaries, we monitored more than 20 selected eclipsing DWDB photometrically [12, 13, 8]. Some of those targets were later investigated by other authors and the parameters of circumbinary substellar objects were revised [14, 15].

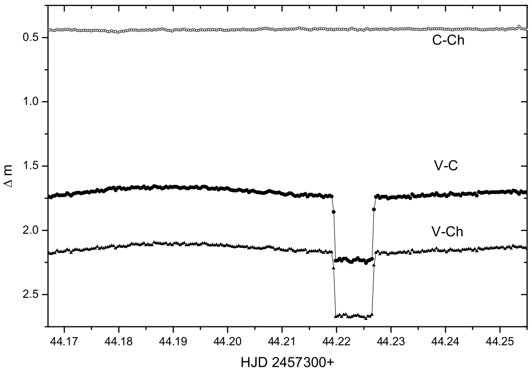

Figure 1. White-light CCD photometric light curve of J 030308 observed on November 17, 2015 by using the 2.4-m TNT telescope in Thailand.

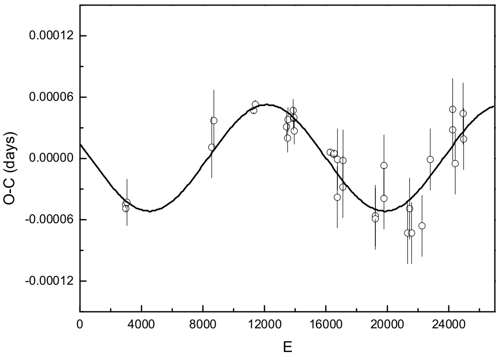

Figure 2. The cyclic variation of the O-C curve for J 030308 after an upward parabolic change is subtracted from the O-C diagram.

SDSS J030308.35+005444.1 (henceforth J 030308) is one of our monitored DWDB that contains a cool (∼ 8000 K) WD and an M4.5 dwarf star with a 3.2 h orbit [16]. The magnetic field strength of the WD is 8 MG and it is a pre-CV that will evolve into an intermediate polar [17]. J 030308 has been monitored for several years by using several 2-m class telescopes. The eclipse profiles shown in Fig. 1 was obtained by using the 2.4-m Thai National Telescope (TNT) of National Astronomical Research Institute of Thailand (NARIT) on November 17, 2015. This telescope is located on one of the highest ridges of Doi Inthanon (about 2457-m high from the sea level). The TNT is a Ritchey-Chrètien with two Nasmyth focuses and A 4K CCD photometer with BVRI filter system was applied. The camera is a cryogenically cooled (liquid nitrogen, -110 C) dewar holding a E2V232-84 thinned, astronomy broadband AR coated, grade one CCD. The O-C diagram was constructed with our new determined eclipse times together with those compiled from literature [17]. A cyclic oscillation with a period of 5.64 years is found to be superimposed on an upward parabolic variation. The cyclic change is shown in Fig. 2 that is explained by the light-travel time effect via the presence of a circumbinary planet with a mass of $M_3 \sin i' = 3.1\, M_{Jup}$. The orbital separation of the planet is only 3.2 AU indicating that it is the shortest distance to the central WD binary among our targets.

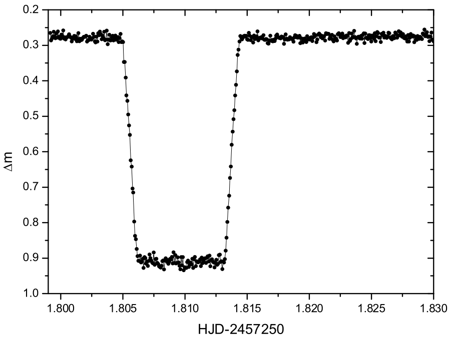

Figure 3. The eclipse profiles of RR Cae obtained with with the 2.15-m Jorge Sahade telescope in Argentina.

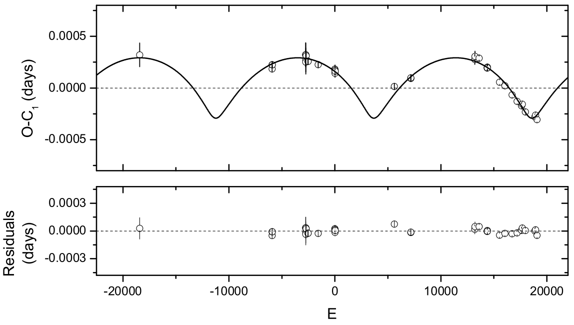

Figure 4. The theoretical light-travel time effect orbit of the circumbinary planet in RR Cae. After both the parabolic variation and the cyclic oscillation are subtracted, the residuals are displayed in the lower panel.

The other monitored example is RR Cae that is a DWDB with a period of 7.3 h. It is a double-lined eclipsing binary containing a cool WD primary with a mass of $0.44\, M_\odot$ and an M_4-type secondary with a mass of $0.182\, M_\odot$[18]. An upward parabolic variation in the O-C curve was found to be superimposed on a cyclic change with a period of 11.9 years and an amplitude of 14.3 s. The cyclic change was explained by the light-travel time effect via the presence of giant planet with a mass of $M_3 \sin i' = 4.2\, M_{Jup}$[8]. This binary was monitored continuously with the 2.15-m Jorge Sahade telescope at Complejo Astronomico El Leoncito (CASLEO), San Juan, Argentina. The eclipse profile observed on August 16, 2015 is shown in Fig. 3. During the observation, no filters were used and a Versarray 1300B camera with a thinned EEV CCD36-40 de 1340 × 1300 pix CCD chip was applied. After the upward parabolic change was removed the cyclic oscillation is plotted in Fig. 4. By considering a general case with eccentricity, the mass of the planet is revised as $M_3 \sin i' = 7.0\, M_{Jup}$. The planet is orbiting the central WD binary in eccentric orbit with an eccentricity of 0.61 at an orbital separation of 5.4 AU.

3. Eclipsing polars

In eclipsing MCVs (polars), the magnetic field of the WD primary is strong enough to prevent materials from the main-sequence companion to form an accretion disc [19]. Therefore, the accretion stream and the hot spot on the WD can be isolated during the eclipses, times of ingress and egress of eclipsing polars can be determined with a high precision. Therefore, they are a good source to search for substellar objects orbiting CVs by analyzing the eclipse times. Some substellar objects were recently discovered to be orbiting the polars [7]. We have selected about ten eclipsing polars (e.g., DP Leo, V2301 Oph, EK UMa, HU Aqr, UZ For, and MN Hya) and monitored them photometrically since 2009 by using the 1.0-m and the 2.4-m telescopes at Yunnan observatories in China, the Danish 1.54-m telescope at La Silla, the 2.15-m "Jorge Sahade" telescope in Argentina, and the 2.4-m telescope in Thailand [20].

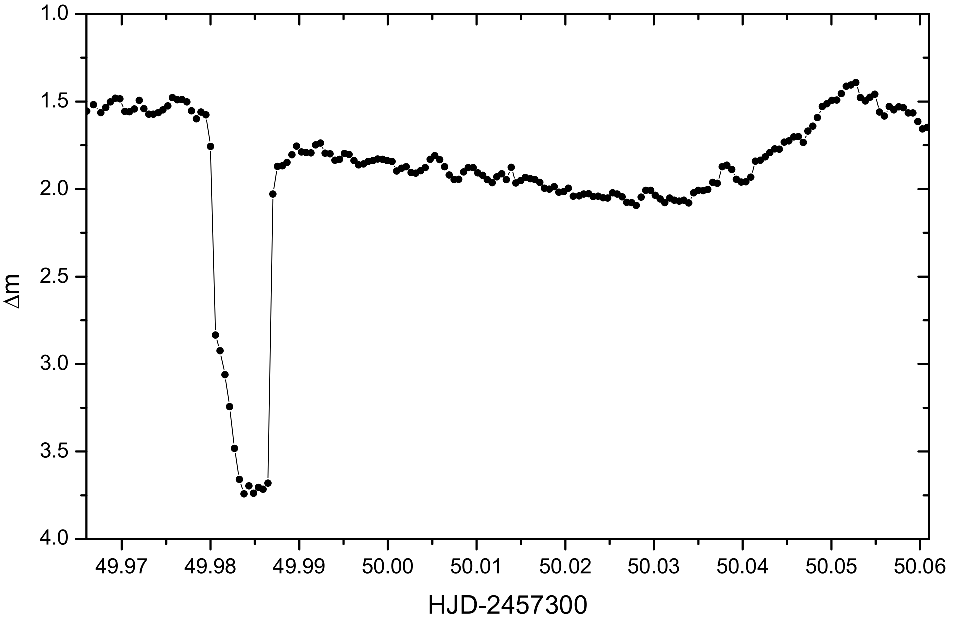

Figure 5. White-light CCD photometric light curve of HU Aqr observed on November 23, 2015 with the 2.4-m telescope in Yunnan observatories.

We pay more attention on the most interesting target HU Aqr. It is a total eclipsing polar with an orbital inclination of $i = 87^\circ$ and has only one accretion pole [21]. The times of mid-egress were used for period investigation because the profiles of the egress are stable. Qian et al. (2011) proposed two planetary objects orbiting the eclipsing polar [22]. Then this polar was monitored continuously. One white-light eclipse profile of HU Aqr is shown in Fig. 5. This eclipse profile was obtained observed on November 23, 2015 by using the 2.4-m telescope in Lijiang observational station of Yunnan observatories. As shown in the figure, the eclipse starts with the limb of the secondary star eclipsing the accretion hot spot and the WD. The accretion stream is then the dominant source of the brightness with a small contribution of the secondary. Finally only the red-dwarf component star is visible and provides a constant contribution. The sequence of the egress is approximately reversed. The O-C diagram is constructed by including new data (see Fig. 6). Details analysis will confirm and revise the parameters of those planets.

4. Total eclipsing normal cataclysmic variables

4.1. Deeply eclipsing dwarf novae

In general, CVs are binary systems with a WD accreting matter from a stellar companion and form an accretion disk around the WD. Dwarf novae are one of the subtypes of CVs that have a very low rate of mass transfer [23]. They are characterized by their recurrent outbursts with $\Delta m \sim$3-5 magnitudes and the typical duration is about 5-10 days. Those outbursts are explained by the structure change of their discs [24]. Some deeply eclipsing dwarf novae (e.g., GY Cnc, EX Dra, V2051 Oph, U Gem, OY Car, Z Cha, HT Cas and V893 Sco) were selected and monitored [25, 26, 27, 28]. One of the good examples is V2051 Oph that is one of a few ultrashort-period dwarf novae [29]. We started to monitor it since 2008 by using the 1.0-m and the 2.4-m telescopes in Yunnan Observatories, the 0.6-m Helen Sawyer Hogg (HSH) telescope and the 2.15-m Jorge Sahade telescope in Argentina. Two eclipse profiles of V2051 Oph obtained in June 2015 with the 2.15-m Jorge Sahade telescope are shown in Fig. 7. As shown in the figure, the eclipse profile is changing with time indicating that both the hot spot and the accretion disc are variable.

To determine the eclipse times of the WD, the derivative technique proposed by Wood et

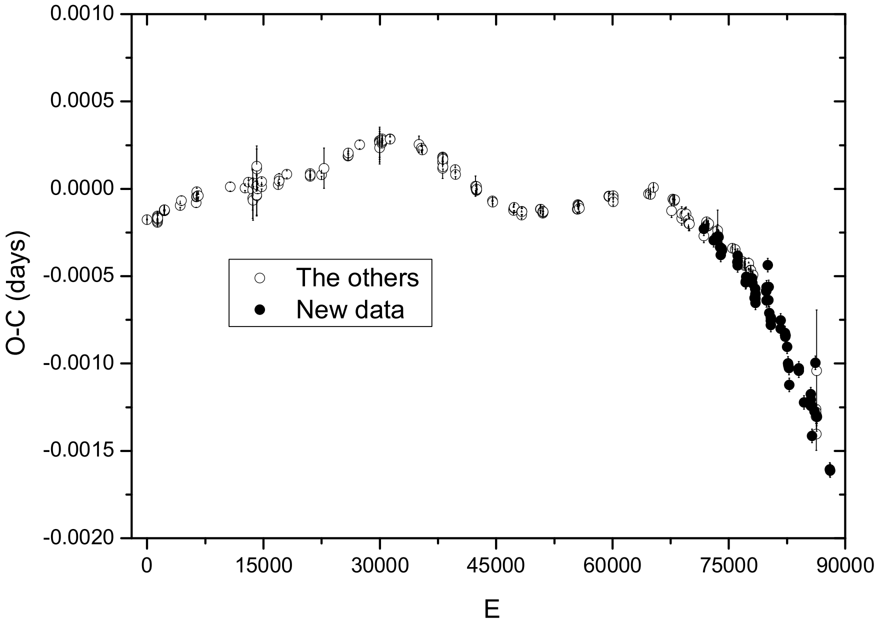

Figure 6. O-C diagram of HU Aqr. Solid dots refer to new observations, while open circles to those data collected from the literature.

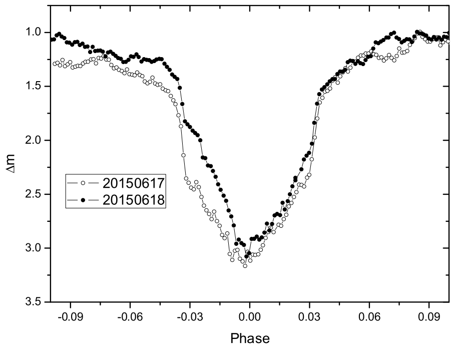

Figure 7. Two eclipse profiles of V2051 Oph obtained with the 2.15-m Jorge Sahade telescope in Argentina.

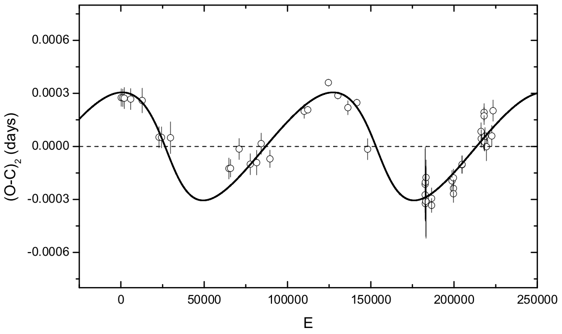

Figure 8. The theoretical light-travel time effect orbit of the circumbinary planet orbiting the dwarf nova V2051 Oph.

al. (1985) was used [30]. By analyzing the O-C diagram, a continuous period decrease was discovered to be superimposed on a cyclic variation with a small amplitude of $0.^d000329$ and a period of 21.64 years [20]. The cyclic oscillation can not be explained by magnetic activity cycles of the secondary (i.e., the Applegate mechanism) because the required energy is much larger than that radiated from the secondary in 10 years [31]. After the continuous period decrease was subtracted from the O-C diagram, the cyclic oscillation is displayed in Fig. 8 that is caused by the presence of a giant planet with a mass of $M_3 \sin i' = 7.3(\pm 0.7)$ Jupiter masses and an eccentricity of $e' = 0.37$. The giant circumbinary planet is orbiting around the dwarf nova at an orbital separation of about 9.0 AU.

4.2. Nova-like cataclysmic variables

Nova-like CVs usually have higher mass-transfer rates and longer orbital periods. We have monitored some deeply eclipsing nova-like CVs (e.g., SW Sex, V363 Aur, QZ Aur, V347 Pup, V348 Pup, LX Ser, PX And, BH Lyn and RW Tri) since 2006 [32, 33]. Here we show the results of one of nova-like CVs, V363 Aur. It is an eclipsing nova-like CV with an orbital period of 7.7 h that The was found by Lanning (1973) as an ultraviolet-bright source during a survey in the galactic plane by using Palomar 48 inch Schmidt [34]. This nova-like CV consists of a WD primary with a mass of $0.90\,M_\odot$ and a G7-type secondary with a mass of $1.06\,M_\odot$ [35]. We started to monitor V363 Aur since January 15, 2007 with the PI 1024 TKB CCD photometric system attached to the 1.0-m reflecting telescope at Yunnan Observatories. The eclipse profiles obtained with the 85-cm telescope is shown in Fig. 9. By using all available eclipse times, the O-C diagram was constructed. After the long-term period decrease was removed from the O-C curve, the cyclic variation is shown in Fig. 10. The preliminary results indicate that the mass of the third body is $M_3 \sin i' = 61.6(\pm 6.6) M_{Jup}$. It is may be a circumbinary brown dwarf orbiting the nova-like CV at a distance of about 9.9 AU.

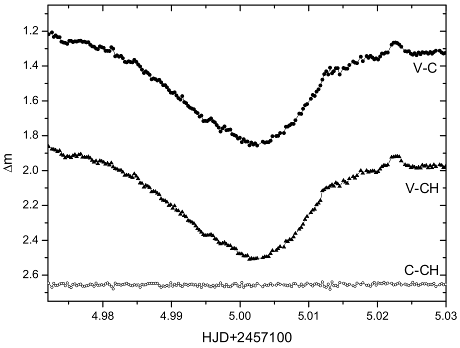

Figure 9. The eclipse profile of V363 Aur obtained with the 85-cm telescope in Xinglong observational station of national astronomical observatories (NAOs). "V" refers to V363 Aur, "C" to the comparison star, and "Ch" to the check star. Magnitude differences between V363 Aur, the comparison and the check stars are also shown in the figure.

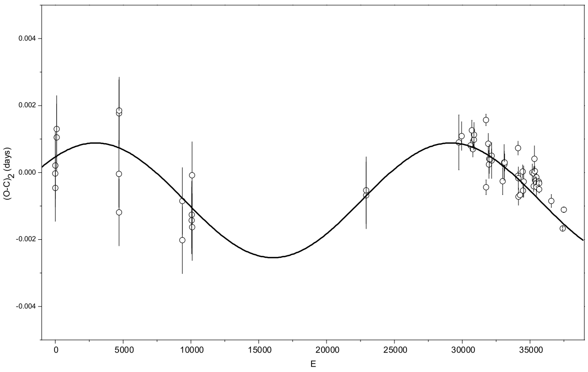

Figure 10. The cyclic variation of V363 Aur with an amplitude of 0.00172 days and a period of 23.0 years. The solid line refers to the light travel-time effect orbit caused by the presence of a brown dwarf with a mass of $M_3 \sin i' = 61.6\,M_{Jup}$.

5. Discussions and conclusions

Cyclic variations in the O-C diagrams were found for different types of WD binaries. Most of them can not be explained by the Applegate mechanism because of the energy problem. The plausible mechanism to cause those cyclic oscillations is the light-travel time effect via the presence of circumbinary planets. For some systems, e.g., J 030308 and RR Cae, the upward parabolic changes may be only a part of a long-period cyclic variation indicating that there is another planet in the systems. As shown by other investigators [36, 37, 38], our studies suggest that planets can exist in a completely different kind of host stars, i.e., WD binaries. Several exoplanets are found to be orbiting several kinds of WD binaries. However, substellar objects orbiting single white dwarfs are very rare. To date, only a few brown dwarfs companion to WD were found [39, 40, 41, 42, 6]. The project of direct imaging searching for exoplanets around white dwarfs also obtained null results [43]. The reasons for lack of detections may be (i) those methods are not very suitable (or not sensitive) or have a low efficiency to detect plants orbiting white dwarfs and (ii) the original planets may have been destroyed or escaped during the post main-sequence evolution [44, 45].

A very interesting question is why are the exoplanets orbiting WD binaries so common? Those WD binaries have undergone the common envelope (CE) evolution. The low-mass stars in the original binaries spiraled in the CE after the more massive stars evolve into a red giant or a AGB star. The ejection of the CE removed a large amount of angular momentum, and then the short-period WD binaries were formed. It is possible that the spiraling process of the low-mass stars in CE protected those circumbinary exoplanets [46]. The other possibility is that they are second generation exoplanets formed during the late evolution of binary stars [47]. Apart from searching for exoplanets, those long-term photometric data could provide valuable information on CV evolution and outburst [32, 48, 20, 28, 49]. One of the good examples is that the long-term period decrease in the eclipsing dwarf nova V2015 Oph. It indicates that the orbital evolution of short-period CVs is about 5 times faster than that predicted by the standard CV theory. This result suggests that additional angular momentum loss is required for CVs below the period gap [20].

Acknowledgments

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