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The quest for companions to post-common envelope binaries

I. Searching a sample of stars from the CSS and SDSS

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ABSTRACT

As part of an ongoing collaboration between student groups at high schools and professional astronomers, we have searched for the presence of circum-binary planets in a bona-fide unbiased sample of twelve post-common envelope binaries (PCEBs) from the Catalina Sky Survey (CSS) and the Sloan Digital Sky Survey (SDSS). Although the present ephemerides are significantly more accurate than previous ones, we find no clear evidence for orbital period variations between 2005 and 2011 or during the 2011 observing season. The sparse long-term coverage still permits O–C variations with a period of years and an amplitude of tens of seconds, as found in other systems. Our observations provide the basis for future inferences about the frequency with which planet-sized or brown-dwarf companions have either formed in these evolved systems or survived the common envelope (CE) phase.

Key words. binaries: close – binaries: eclipsing – planets and satellites: detection

1. Introduction

The detection of circum-binary planets orbiting highly evolved close binary systems has raised many complex questions about the processes by which these companions are formed. These binaries consist of a white dwarf (WD) or a sub-dwarf B star (sdB) in a tight orbit with a low-mass secondary star. They result from the rapid orbital evolution, during which the secondary finds itself immersed in the primary's expanding red giant envelope (Taam & Ricker 2010). This common envelope (CE) phase results in the loss of a significant amount of orbital angular momentum and a large part of the primary's original mass. So far only a handful of post-common envelope binaries (PCEBs) with circum-binary planets have been found (e.g. Lee et al. 2009; Qian et al. 2009, 2010; Beuermann et al. 2010, 2011, 2012), but other PCEBs display similar orbital period variations (e.g. Parsons et al. 2010; Qian et al. 2011), giving the impression that there might be an intimate connection between the evolution of close binaries, the ejection of the CE, and the presence of planets. The case of HU Aqr indicates a far more complex situation, however. Qian et al. (2011) interpreted the O–C variations of this accreting binary as the combined action of two planets moving around the binary, but the implied orbits were subsequently shown to be highly unstable (Horner et al. 2011) and led Wittenmyer et al. (2011) to question their existence. Obviously, a long-term observation program is needed to clarify the nature of the eclipse time variations of PCEBs.

PlanetFinders is a research project conducted by high school teachers and their students in collaboration with professional astronomers. The scientific goal is the measurement of accurate ephemerides of eclipsing PCEBs with the aim of detecting circum-binary companions by the light travel time effect. The didactic goal is to let high school students experience all aspects of authentic scientific work at an early age.

For the first observing season, we chose to survey twelve eclipsing PCEBs, eleven of which are from the list of Drake et al. (2010) drawn from the Catalina Sky Survey (CSS) and the Sloan Digital Sky Survey (SDSS). Our PCEBs include ten with a WD primary, CSS 06833 with an sdB primary, and the double degenerate CSS 41177 (Parsons et al. 2011). All these stars have well-established orbital periods, mostly obtained in the 2005 observing season by Drake et al. (2010). So far, all of them lack known or suspected period variations. Hence, in this respect, the sample is bona-fide unbiased. Obtaining an independent measurement of the binary period in a single second observing season precludes the ready measurement of the orbital period of a putative circum-binary companion, but allows the detection of a period variation. Ultimately, additional eclipse-time measurements will lead to the discovery of any companion that creates a sufficiently large period variation.

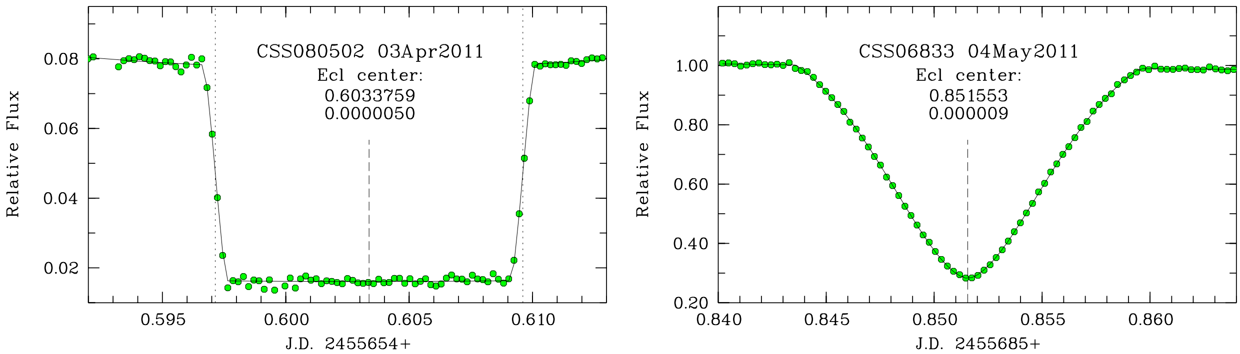

Fig. 1. Eclipse light curves of the WD/dM binary CSS 080502 (SDSS J0908+0604) and the sdB/dM binary CSS 06833 (SDSS J1533+3759). Exposure times are 15 s. The solid lines represent the model fits, the dotted lines in the left panel indicate the FWHM.

2. Observations and data analysis

All data presented here were taken with the remotely controlled 1.2-m MONET/North telescope at the University of Texas' McDonald Observatory via the MONET browser-based remote-observing interface. The teachers and their students usually observed from the classrooms of the participating schools. The photometric data presented here were taken with an Apogee ALTA E47+ 1k × 1k CCD camera in white light. Exposure times were typically 10 s, separated by a 3-s readout for data binned in 2 × 2 pixels, but in some cases exposure times of 15 or 20 s were chosen. The images were corrected for dark current and flatfielded in the usual manner.

The WD binaries show well-defined eclipse light curves with ingress and egress times of about a minute. Usually, we determined the flux of the target relative to an appropriate non-variable comparison star. The high-school students employed a variety of methods for determining the mid-eclipse times $T_{\rm ecl}$ for a given light curve, from graphical ones in the 10th grade to formal fits using a series of concatenated linear functions in the 12th grade. For publication, all data were subjected to more formal fits, which took account of the finite exposure times and yielded formal errors for the mid-eclipse times. The adopted models assume symmetry of the eclipse light curve about mid-eclipse, with ingress and egress taken to be mirror images of each other. In addition, we allowed for a time-dependent multiplicative factor that describes a real or apparent variation of the out-of-eclipse flux by a first- or second-order polynomial. A real effect arises, e.g., from the varying aspect of the illuminated secondary star, an apparent effect from the color-dependent and altitude-dependent atmospheric transmission. For the binaries with WD primary, the eclipsed star was represented by a uniform disk with the ingress/egress time being one of the free parameters. The eclipse light curves of the double degenerate system CSS 41177 and the sdB/dM binary CSS 06833 were fitted by a heuristic model that involves a modified and truncated inverted Gaussian (see Beuermann et al. 2012, Paper II). The Gaussian was modified by replacing the square in the exponential with a free parameter $p_{\rm exp}$, allowing the creation of a more peaked ($p_{\rm exp} < 2$) or broader ($p_{\rm exp} > 2$) light curve, and then truncated at the out-of-eclipse level (one of the other fit parameters). The fits to the light curves of CSS 06833 yield $p_{\rm exp} \simeq 1.70$. Figure 1 shows examples of the observed and fitted light curves.

3. Results

Between November 2010 and October 2011, a total of 72 eclipse light curves of our twelve targets were secured. The new mid-eclipse times are listed in Table 1 as BJD(TT), i.e., barycentrically and leap-second corrected times in the terrestrial system[1]. The mean statistical 1-σ error of our mid-eclipse times is 1.4 s, with individual values ranging from 0.4 to 4.8 s. The individual eclipse times obtained by Drake et al. (2010) in 2005 have not been published, but we list their epochs converted from HJD to BJD(TT) as representative eclipse times in Table 1. In deriving new ephemerides, we did not include the Drake et al. epochs. Hence, our results are completely independent of theirs. However, we did include additional published mid-eclipse times for CSS 41177 (Parsons et al. 2011), CSS 06833 (For et al. 2010), CSS 03170 (Parsons et al. 2012), SDSS J1548+4057 (Pyrzas et al. 2009), and SDSS J0303+0054 (Parsons et al. 2010). In the case of SDSS J0303+0054, we used the accurate ULTRACAM data of Parsons et al. (2010), but not the less accurate timings of Pyrzas et al., which have almost no influence on the derived ephemeris. The new epochs and periods are given in Table 2 along with those of Drake et al. (2010). The accuracy of the new periods exceeds those of Drake et al. (2010) by one to two orders of magnitude. The χ^2 of the linear fit and the number of degrees of freedom (d.o.f.) are given in the last column.

So far, we find no evidence for a long-term period variation for any of the sources. For our own data, this is not surprising, because we covered only a single observing season. In the case of SDSS J0303+0054, CSS 06833, and SDSS J1548+4057, though, the data cover 5.1, 3.6, and 3.3 years, respectively, and are still consistent with linear ephemerides. In principle, the comparison of the independent ephemerides of Drake et al. (2010) and this work could provide information on a period change between 2005 and 2011 by either a departure of the Drake et al. epoch from the respective new ephemeris or by a difference of the periods measured at the two epochs. The observational situation is illustrated in Fig. 2, where in each panel zero O–C represents our new ephemeris and the dashed lines attached to the Drake et al. points represent the ±1-σ uncertainty in their ephemeris projected 500 days forward in time. The ordinate scales are chosen to incorporate the Drake et al. (2010) epochs. A possible period change is is taking place in CSS 06653, where the epoch and period of Drake et al. (2010) combine to a 2-σ result of an increasing period. The case of WD 1333 is also peculiar and calls for more observations. In summary, period changes that give rise to O–C variations with excursions of several tens of seconds cannot be excluded for any of the sources. The presence or absence of O–C variations

[1] http://astroutils.astronomy.ohio-state.edu/time/

Table 1. New mid-eclipse times and epochs from Drake et al. (2010).

Cycle	BJD(TT) 2 400 000+	Error (days)	O–C (days)	Reference
SDSS J030308.35+005444.1:				
13443	55 798.862876	0.000013	−0.000004	This work
13510	55 807.870189	0.000014	−0.000015	
13533	55 810.962273	0.000012	0.000002	
13874	55 856.805526	0.000011	0.000010	
13897	55 859.897585	0.000011	0.000002	
13926	55 863.796278	0.000010	0.000003	
13948	55 866.753894	0.000013	−0.000010	
CSS 40190 (SDSS J083845.86+191416.5):				
−16141	53 469.720430	0.001300	−0.000427	Drake et al.
0	55 569.862966	0.000009	0.000004	This work
375	55 618.655072	0.000011	−0.000009	
2153	55 849.994786	0.000016	−0.000000	
2214	55 857.931650	0.000013	0.000013	
2276	55 865.998586	0.000015	−0.000015	
CSS 03170 (SDSS J085746.18+034255.3):				
−31709	53 464.720527	0.000900	−0.000020	Drake et al.
0	55 528.866640	0.000026	−0.000020	This work
755	55 578.014506	0.000030	−0.000040	
1841	55 648.709375	0.000011	−0.000011	
1932	55 654.633181	0.000009	0.000010	
4887	55 846.993443	0.000026	0.000004	
4948	55 850.964311	0.000020	−0.000017	
5178	55 865.936535	0.000019	0.000003	
CSS 080502 (SDSS J090812.03+060421.2):				
−14073	53 466.830927	0.001400	−0.003100	Drake et al.
0	55 569.876004	0.000010	−0.000008	This work
47	55 576.899608	0.000013	0.000006	
94	55 583.923204	0.000016	0.000013	
514	55 646.687183	0.000011	0.000002	
521	55 647.733251	0.000005	0.000003	
527	55 648.629867	0.000005	−0.000009	
561	55 653.710777	0.000012	0.000006	
567	55 654.607405	0.000005	0.000006	
1968	55 863.970136	0.000006	−0.000001	
1981	55 865.912837	0.000007	0.000004	
1995	55 868.004964	0.000005	−0.000002	
CSS 38094 (SDSS J093947.95+325807.3):				
−6320	53 495.954128	0.003300	−0.000078	Drake et al.
0	55 587.808817	0.000035	−0.000006	This work
84	55 615.611957	0.000010	0.000003	
202	55 654.668723	0.000021	−0.000011	
774	55 843.994813	0.000019	−0.000003	
795	55 850.945601	0.000013	0.000002	
CSS 41631 (SDSS J095719.24+234240.7):				
−14145	53 470.764125	0.001500	0.000612	Drake et al.
0	55 604.830127	0.000029	0.000003	This work
72	55 615.692822	0.000008	0.000005	

Table 1. continued.

Cycle	BJD(TT) 2 400 000+	Error (days)	O–C (days)	Reference
CSS 41631 continued:				
325	55 653.863107	0.000009	−0.000007	
370	55 660.652293	0.000015	−0.000005	
1678	55 857.991223	0.000009	−0.000002	
1691	55 859.952549	0.000010	0.000005	
CSS 41177 (SDSS J100559.10+224932.2):				
−18521	53 470.704027	0.001700	−0.000528	Drake et al.
116	55 632.884239	0.000014	0.000003	This work
252	55 648.662338	0.000009	0.000003	
355	55 660.611914	0.000019	−0.000011	
1996	55 850.993250	0.000021	−0.000005	
2125	55 865.959247	0.000010	−0.000000	
CSS 21616 (SDSS J132518.18+233808.0):				
−11198	53 470.804327	0.001900	−0.000054	Drake et al.
0	55 653.954195	0.000011	0.000008	This work
138	55 680.858500	0.000014	−0.000017	
215	55 695.870287	0.000056	−0.000067	
783	55 806.607031	0.000031	0.000014	
CSS 06653 (SDSS J132925.21+123025.4):				
−26458	53 466.817520	0.000400	0.000499	Drake et al.
0	55 609.022163	0.000005	−0.000002	This work
37	55 612.017920	0.000009	0.000003	
1034	55 692.741265	0.000006	−0.000008	
1059	55 694.765440	0.000007	0.000011	
1060	55 694.846403	0.000012	0.000008	
2391	55 802.612475	0.000010	−0.000004	
WD 1333+005 (SDSS J133616.05+001732.6):				
−17605	53 464.891227	0.000600	−0.001316	Drake et al.
0	55 611.976665	0.000010	−0.000002	This work
679	55 694.786674	0.000010	0.000003	
1563	55 802.598220	0.000013	−0.000002	
CSS 06833 (SDSS J153349.44+375928.0):				
−13173	53 480.923730	0.000800	−0.000671	Drake et al.
0	55 611.926569	0.000010	−0.000011	This work
260	55 653.986899	0.000009	0.000002	
439	55 682.943820	0.000009	0.000011	
457	55 685.855660	0.000009	−0.000017	
488	55 690.870566	0.000009	0.000006	
1204	55 806.698204	0.000010	−0.000001	
1537	55 860.567775	0.000012	0.000009	
SDSS J154846.00+405728.7:				
−5745	53 526.785031	0.002700	−0.002547	Drake et al.
5920	55 690.823510	0.000012	0.000013	This work
5942	55 694.904830	0.000010	−0.000003	
5947	55 695.832395	0.000016	−0.000015	
6507	55 799.720977	0.000023	0.000002	
6512	55 800.648543	0.000011	−0.000009	
6523	55 802.689237	0.000015	0.000017	

caused by planet-sized or brown-dwarf companions orbiting the binaries of the present sample remains an open question.

4. Discussion

In recent years, several PCEBs have been found (or suspected) to host circum-binary substellar objects. The host compact binary stars are two pulsars, PSR 1257 and PSR B1620, and a small number of post-CE binaries with either an sdB star or a white-dwarf as primary, both of the detached and the semi-detached variety. The best cases apart from the pulsars are probably the detached systems HW Vir (Lee et al. 2009), NN Ser (Beuermann et al. 2010), HS0705+67 (Qian et al. 2009, Paper II), and the cataclysmic variable DP Leo (Qian et al. 2010; Beuermann et al. 2011). The origin of the suggested companions is uncertain. Either they are of primordial origin and survived the CE evolution of the host binary or they formed as second-generation object (Perets 2010) from the expelled envelope of the compact object (see, e.g., the discussion in Beuermann et al. 2010). Any theory of such a scenario will require information on the frequency of incidence of circum-binary planets. Obtaining this information requires that a larger number of binaries are searched for the presence of companions.

The third-body hypothesis lingered in the background for decades because of the possibility of inducing real or apparent orbital period variations by other mechanisms. In detached

Table 2. Ephemerides for the binaries of Table 1, with the epoch quoted as BJD in the terrestrial time system.

CSS name	SDSS name	Drake et al. (2010) BJD(TT) 2 400 000+	Drake et al. (2010) P (days)	This work BJD(TT) 2 400 000+	This work P (days)	χ^2/d.o.f.
	J030308.35+005444.1			53 991.617287(2)	0.1344376696(4)	6.5/8
CSS 40190	J083845.86+191416.5	53 469.72043(130)	0.13011225(40)	55 569.862961(7)	0.130112320(5)	3.2/3
CSS 03170	J085746.18+034255.3	53 464.72053(90)	0.06509654(3)	55 528.866660(1)	0.065096538(2)	9.0/14
CSS 080502	J090812.03+060421.2	53 466.83093(140)	0.1494385(25)	55 569.876012(3)	0.149438072(3)	8.2/9
CSS 38094	J093947.95+325807.3	53 495.95413(330)	0.3309896(2)	55 587.808823(10)	0.330989655(21)	0.4/3
CSS 41631	J095719.24+234240.7	53 470.76412(150)	0.15087065(15)	55 604.830124(6)	0.150870740(6)	1.3/4
CSS 41177	J100559.10+224932.2	53 470.70403(170)	0.1160154(1)	55 619.426445(6)	0.116015436(6)	3.9/6
CSS 21616	J132518.18+233808.0	53 470.80433(190)	0.1949588(5)	55 653.954186(9)	0.194958909(42)	2.2/1
CSS 06653	J132925.21+123025.4	53 466.81752(40)	0.08096622(2)	55 609.022166(4)	0.080966254(4)	4.9/4
WD 1333+005	J133616.05+001732.6	53 464.89123(60)	0.12195874(5)	55 611.976667(9)	0.121958769(11)	0.2/1
CSS 06833	J153349.44+375928.0	53 480.92373(80)	0.16177052(8)	55 611.926580(3)	0.1617704531(9)	16.9/17
SDSSJ1548	J154846.00+405728.7	53 526.78503(270)	0.1855162(15)	54 592.572944(56)	0.185515296(9)	4.6/10

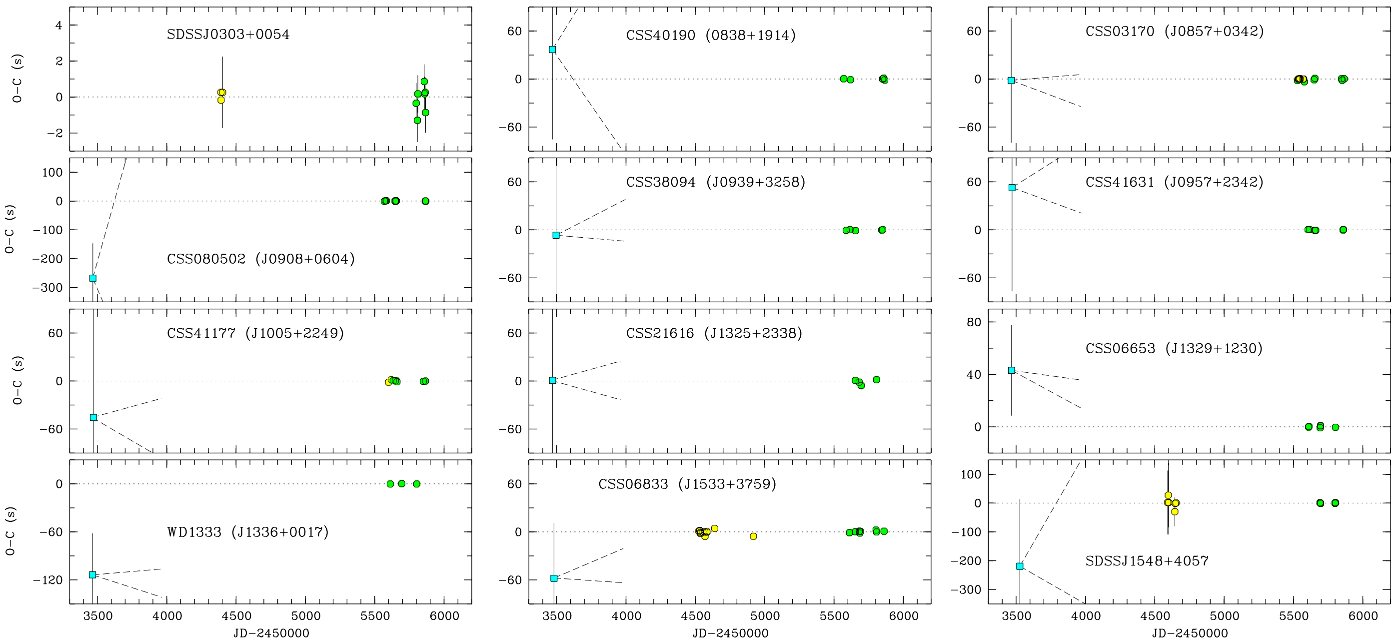

Fig. 2. O–C residuals for the new mid-eclipse times of Table 1 (green dots) and other published times for SDSS J0303+0054, CSS 41177, CSS 06833, and SDSS J1548 +4057 (yellow dots) relative to the new ephemerides of Table 2, Cols. 5 and 6. The cyan-blue square indicates the Drake et al. (2010) epoch (see text).

binaries, these include spin-orbit coupling induced by variations in the internal constitution of the secondary star (Applegate 1992) and apsidal motion of an eccentric binary orbit (Todoran 1972). The former is generally thought to be too weak to produce the observed amplitudes (Brinkworth et al. 2006; Chen 2009; Potter et al. 2011), but this may not be the last word (Wittenmyer et al. 2011). Apsidal motion can be excluded if the expected shift of the secondary eclipse is found to be absent (e.g. Beuermann et al. 2010, 2012). The high frequency of exoplanets around normal stars has resulted in a re-consideration of the third-body hypothesis, starting with a series of papers by the group of Qian et al. (2009, 2010, and references therein). However, the interpretation of the results is still controversial and it is not clear whether the same explanation will apply to all PCEBs that show eclipse time variations.

Here we studied twelve eclipsing PCEBs, mostly identified by Drake et al. (2010), for apparent period variations, which could indicate the presence of a third body. None were found so far, primarily because the Drake et al. (2010) ephemerides lack sufficient accuracy. Our substantially more accurate results provide the basis, however, for a future detection of companions orbiting these binaries. The sample studied here is a mixed bag that contains systems with a white dwarf primary, the double degenerate CSS 41177, and CSS 06883 with an sdB primary. The first group includes systems with a He white dwarf and a CO white dwarf as shown by the masses derived from SDSS spectra (Rebassa-Mansergas et al. 2012)[2]. Although members of all subgroups went through a CE phase, their progenitors and evolutionary histories differ (e.g. Zorotovic et al. 2011) and the incidence of circum-binary planets may differ, too. Elucidating these connections will require substantially more observational and theoretical work.

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[2] http://www.sdss-wdms.org

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