The quest for companions to post-common envelope binaries

1. 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 orbits 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 (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 circumbinary 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 similar pre-CEs serve 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 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.
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\text{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 \( \exp(\frac{y}{\sigma}) \) or broader (\( \exp(\frac{y}{\sigma^2}) \)) 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 \( p_{exp} \approx 1.70 \). 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., barycentric- 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 (Pyraz 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 Pyraz 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 \( \chi^2 \) 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

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\(^1\) http://astrotools.astronomy.ohio-state.edu/time/
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 circumbinary 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 caused by planet-sized or brown-dwarf companions orbiting the binaries of the present sample remains an open question.

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## 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) | P (days) | This work BJD(TT) | P (days) | $\chi^2$/d.o.f. |
|--------------|---------------|-----------------------------|----------|-------------------|----------|-----------------|
| J030308.35+005444.1 |              | 2400000+                   |          | 2400000+          |          | 3.8            |
| CSS 40190    | J080812.03+600421.2 | 53 469.7204(130)           | 0.13011225(40) | 53 991.617287(2)  | 0.1344376696(4) | 6.5/8          |
| CSS 03170    | J080812.03+600421.2 | 53 464.7205(90)            | 0.06509654(3)  | 53 528.86666(11)  | 0.065096538(2)  | 9.0/14         |
| CSS 080502   | J080812.03+600421.2 | 53 466.8309(140)           | 0.1494385(25)  | 53 587.678612(3)  | 0.149438072(3)  | 8.2/9          |
| CSS 38094    | J080812.03+600421.2 | 53 495.9541(330)           | 0.3309896(2)   | 53 587.808823(10) | 0.330989526(21)| 4.5/3          |
| CSS 41631    | J080812.03+600421.2 | 53 764.12(150)             | 0.15807065(15) | 53 604.8301(6)    | 0.158070740(6) | 1.3/4          |
| CSS 41177    | J080812.03+600421.2 | 53 7040(170)               | 0.1160154(1)   | 53 619.4264(5)    | 0.116015436(6) | 3.9/6          |
| CSS 21616    | J080812.03+600421.2 | 53 8043(190)               | 0.194588(5)    | 53 653.954186(9)  | 0.19458909(4)  | 2.2/1          |
| CSS 06653    | J080812.03+600421.2 | 53 617852(40)              | 0.08096622(2)  | 53 609.022166(4)  | 0.080966254(4) | 4.9/4          |
| WD 1333+005  | J080812.03+600421.2 | 53 69123(60)               | 0.12195874(5)  | 53 611.976667(9)  | 0.121958769(11)| 0.2/1          |
| CSS 06833    | J080812.03+600421.2 | 53 92373(80)               | 0.16770752(8)  | 53 611.926580(3)  | 0.167704531(9) | 16.9/17        |
| SDSSJ1548    | J154846.00+005728.7 | 53 526.78503(270)           | 0.1855162(15)  | 53 592.572944(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 SDSSJ1548+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 06833, and SDSSJ1548+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).

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**Footnote:**

2 [http://www.sdss-obs.org](http://www.sdss-obs.org)
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