ULTRA-SHORT PERIOD BINARIES FROM THE CATALINA SURVEYS


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ABSTRACT

We investigate the properties of 367 ultra-short period binary candidates selected from 31,000 sources recently identified from Catalina Surveys data. Based on light curve morphology, along with WISE, SDSS and GALEX multi-colour photometry, we identify two distinct groups of binaries with periods below the 0.22 day contact binary minimum. In contrast to most recent work, we spectroscopically confirm the existence of M-dwarf+M-dwarf contact binary systems. By measuring the radial velocity variations for five of the shortest-period systems, we find examples of rare cool-white dwarf+M-dwarf binaries. Only a few such systems are currently known. Unlike warmer white dwarf systems, their UV flux and their optical colours and spectra are dominated by the M-dwarf companion. We contrast our discoveries with previous photometrically-selected ultra-short period contact binary candidates, and highlight the ongoing need for confirmation using spectra and associated radial velocity measurements. Overall, our analysis increases the number of ultra-short period contact binary candidates by more than an order of magnitude.

Subject headings: galaxies: stellar content — Stars: variables — Galaxy: stellar content

1. INTRODUCTION

The study of eclipsing binaries provides the opportunity of determining stellar parameters with a high degree of accuracy using constraints on the geometry and motions of the system (Southworth 2012 and refs therein). Amongst other things, eclipsing binaries can be used to probe various stages of stellar evolution via the determination of system parameters such as the orbital period, inclination, radii and masses.

Types of eclipsing binaries are generally defined by the degree of separation of the components. These include over-contact, contact, semi-detached and detached systems that can often be discerned from light curve shapes. Eclipsing contact binaries are referred to as W Ursae Majoris (W UMa’s) stars (or EW variable types). Such systems allow mass to flow from one star to the other, and both stars usually have similar temperatures and types. Here the depth of the eclipses is most dependent on the system geometry, while in contrast, the depth of the eclipses reflects the relative effect temperatures in detached binaries (Rucinski 2001). Nevertheless, slight differences in the eclipse depth still occur in contact systems due to differences in the temperature of the component stars.

For many years it has been suspected that there is a minimum period for contact binaries at $P \sim 0.22$ days (Rucinski et al. 1992, 1997). Numerous explanations have been put forth to explain the observed abrupt cut off. For example, Stepiew (2006) proposed that the limit was due to the decrease in the efficiency of angular momentum loss with decreasing mass on the main sequence. In such cases the current age of the systems comprising the binary population produces the limit. More recently, Jiang et al. (2012) investigated mass transfer in low-mass binaries, and found this to be unstable. They suggest that systems with the lowest mass might quickly coalesce, leading to their observational absence.

In the past few years, increasing numbers of eclipsing binary candidates have been discovered with periods less than 0.22 days. For example, the detached binary, OGLE-BW03-V038 was discovered with a period of 0.1984 days by Maceroni & Rucinski (1997), and a similar detached eclipsing binary system with main-sequence stars was found with a period of 0.1926 days by Norton et al. (2007) and confirmed by Dimitrov & Kjurkchieva (2010). However, as detached systems are not in the process of mass transfer, they exist in different evolutionary state than contact systems.

Recently, Norton et al. (2011) identified 14 new eclipsing systems with periods $P < 0.22$ days among 30 million SuperWASP sources. Their results include a number of possible contact systems with periods in the 0.2 to 0.22 day range. Similarly, Nefs et al. (2012) discovered 14 eclipsing binary candidates with periods less than 0.22 days. Among these systems Nefs et al. (2012) spectroscopically confirm a detached system with a 0.18 day period containing an M-dwarf. However, they did not attempt to measure radial velocities. In contrast, Denport et al. (2013) discovered a likely contact binary system with a period of 0.19856 days. They confirm the presence of a M-dwarf and find radial velocity variations
that are consistent binary M-dwarf system. Nevertheless, despite the increasing evidence for short period contact binary systems below the 0.22 day period cutoff, only a handful of candidates have so far been spectroscopically confirmed, and fewer still have had their component masses determined via radial velocities measurements.

In this analysis we will investigate both the spectral types and radial velocities for ultra-short period binary systems discovered during the compilation of the Catalina Surveys periodic variable stars catalog (Drake et al. 2014).

2. OBSERVATIONAL DATA

The Catalina Sky Survey\(^9\) uses three telescopes to cover the sky between declination $\delta = -75$ and $+65$ degrees in order to discover Near-Earth Objects (NEOs) and Potential Hazardous Asteroids (PHAs). Catalina observations do not cover regions within 15 degrees of the Galactic plane because of blending in crowded stellar regions. All the images are taken unfiltered, and photometry is carried out using the apertures photometry program SExtractor (Bertin & Arnouts 1996). These measurements are transformed to an approximate V magnitude ($V_{\text{CSS}}$) using fiducial 2MASS colour-selected G-dwarf stars as outlined in Drake et al. (2013).

In this paper, we select and analyze the ultra-short period systems ($P < 0.22$ days) among the 31,000 contact binary candidates discovered by Drake et al. (2014) from data in the Catalina Data Release-1 (CSDR1; Drake et al. 2012). The CSDR1 dataset itself consists only of data taken with the Catalina Schmidt Survey telescope. This includes an average of 250 observations per position spanning six years for 198 million discrete sources. The CSDR1 sources have $12 < V < 20$, and lie in the region $-360^\circ < \alpha < 360^\circ$ and $-30^\circ < \delta < 65^\circ$. The lightcurve data for all CSDR1 sources (including those presented here) is publicly available online\(^{10}\).

3. SHORT PERIOD BINARIES

The Drake et al. (2014) variable catalog contains 367 systems with periods less than 0.22 days, and of these 73 have periods less than 0.2 days. The eclipsing systems were selected based on the morphological classification from among 61,000 periodic variables in the catalog. Additional confirmation of the variable classifications in the catalog was performed by Drake et al. (2014) using colour information derived by combining CSS, WISE and SDSS photometry. Spectroscopic parameters were also derived from SDSS data and confirm the separation between the eclipsing binaries and pulsating stars such as RR Lyrae stars. As the photometry spans many years we do not expect contamination by spotted variable stars (such as RSCVns), since such objects exhibit clear changes in the average brightness, amplitude and phase of flux variations (eg. see Drake 2006, figure 2 and Drake et al. 2014, figure 18).

In Figure 1, we present the period distribution of the 31,000 Drake et al. (2014) contact binary candidates. Here we see there is indeed a very sharp decline in the number of short period systems below $\sim 0.27$ days. Given the large number of contact systems in CSDR1, the fraction of ultra-short period objects amounts to only $\sim 0.26\%$ of the total number. This result in itself very strongly supports the scarcity of short period systems. However, we note that past surveys for such systems have had a clear observational bias against finding such systems. That is to say, the stars that comprise short-period systems are much fainter than the dG and dK stars that make up longer-period systems. For example, in $V$-band, an M0V star is 4.4 magnitudes fainter than a G0V star. Thus, shallow wide-field synoptic surveys, such as ASAS (Pojmanski 1997) that only reached $V=13$, have probed a very small volume of potential M-dwarf binaries compared to CSDR1 (e.g., see Rucinski 2006, figure 4).

In order to investigate the nature of the ultra-short period sources we reexamined the light curves of all the objects Drake et al. (2014) identified as eclipsing contact and ellipsoidal binary candidates below the nominal ultra-short period limit (0.22 day). We observed a clear division in the morphology of the source light curves. Approximately half exhibited the W-shaped light curves expected for W UMa contact binaries, while the other half exhibited much more sinusoidal light curves, as seen in over-contact systems where the stars share an outer envelope and both exceed their Roche limit.

Although over-contact, contact, semi-detached, and detached binaries can exhibit quite distinct light curve shapes, they appear similar at the limit between these types of binary systems. Or alternatively, when they are observed with low signal-to-noise. However, in this analysis we found that the light curves for short period binaries were generally quite well separated into just two groups. In Figure 2, we contrast the two main types of short period light curves.

This same shape division can also be seen in the light curves of the short period binary candidates presented by Nefs et al. (2012). However, the light curves of ellipsoidal variables closely resemble those of over-contact binaries. For ellipsoidal variables, the variation is due to the distorted shapes of a star or stars. This can occur even when the objects are far from contact. Thus the sinusoidal

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\(^9\) http://www.lpl.arizona.edu/css/

\(^{10}\) http://catalinadata.org
light curves of some of the Nefs et al. (2012) short period contact binary candidates are consistent with both over-contact binaries and the ellipsoidal variations due to compact companions such white dwarfs (WDs) or subdwarfs. Such short-period sinusoidal light curves have been found in many white dwarf main sequence (WDMS) systems (e.g. Rodriguez-Gil et al. 2009, Pyrzas et al. 2012, Parsons et al. 2013). In fact, systems with such light curves were specifically rejected from the short period main sequence contact binary sample of Norton et al. (2011), because of possible contamination of WDMS systems.

For ellipsoidal variables, the amplitude is generally limited to $\sim 0.3$ mag, since the variations are due to the distorted star filling its Roche lobe (Parsons et al. 2013). At very short periods, a distorted star will overflow its Roche lobe becoming a cataclysmic variable. The accretion induced variability in CV systems generally distinguishes them from stable non-accreting WDMS systems.

To investigate the nature of the objects with short period objects, we looked at the colours of sources in the two groups using WISE, SDSS and GALEX data. In Figure 3, we show the WISE data for the eclipsing binaries as well as $\delta$ Scuti stars (that have similar periods). The separation between the pulsating $\delta$ Scuti stars and the eclipsing and ellipsoidal-like ones is quite clear. However, some of the ellipsoidal candidates do have colours similar to $\delta$ Scutis. These objects may either be systems where the companion is a hot WD, or incorrectly classified $\delta$ Scutis. There is clearly significant overlap between ellipsoidal candidates and eclipsing systems. There are also ellipsoidal candidates that have $V - w1 > 3.5$. These objects are redder than most of the eclipsing objects and thus suggest late stellar types.

In Figure 4, we show the $u - g$ and $i - z$ vs $g - r$ plots for the contact eclipsing binaries from Drake et al. (2014) with SDSS DR9 photometry along with $\delta$ Scuti stars and spectroscopically identified WD+dM binaries from the Rebassa-Mangergas et al. (2012) cata-

log. We also plot the WD+d-M model isochrones given by Rebassa-Mangergas et al. (2012) and colours of other known WDMS systems detected in CSDR1 by Drake et al. (2014).

Figure 4 also shows that many of the short period ellipsoidal candidates, exhibit excess colour in $g-r$ compared to main sequence eclipsing binaries. This excess is completely consistent with the colours of spectroscopically identified WD+dM binaries from Rebassa-Mangergas et al. (2012). However, the colours of most objects lie at the red end of the known distribution, where WDs cooler than 10,000K are expected. Such systems are very difficult to identify spectroscopically since cool WDs can be much fainter than M-dwarfs. Thus they do not give rise to significant $u$-band flux. From $i - z$ we see that...
Ultra-short Period Binaries

Fig. 4.— Optical colour distribution for short period variables. Colours based on extinction correct SDSS photometry. The symbols are the same as Figure 3 with the addition of known CVs and white dwarfs shown as magenta crosses and spectroscopically selected WD+dM binaries from Rebassa-Mansergas et al. (2012) as small orange circles. The solid black line, short-dashed red line, long-dashed cyan line and blue dash-dotted line give model colours of WDMS binaries where the WDs have effective temperatures of 10,000K, 20,000K, 30,000K and 40,000K, respectively from Rebassa-Mansergas et al. (2012).

the ellipsoidal candidates are generally redder that the regular eclipsing sources, suggesting that the M-dwarfs in WDMS pairs are usually later types than those in MS binary pairs. The excess $g-r$ colour is indicative of a warm secondary, rather than a cool M-dwarf. In contrast, we see that most of the objects with regular eclipsing lightcurves do not exhibit any $g-r$ colour excess, suggesting that most are truly main sequence pairs. Although there may still be some confusion (as outlined below).

Aside from the true colour features, we note that the u-band magnitudes of the redder candidates are likely to be affected to some extent by the SDSS red leak\(^{11}\). There is also likely to be a measurable amount of scatter in colour due to the the SDSS data being taken at a single epoch.

In cases where one of the components is a hot WD, one expects the presence of significant UV flux. Therefore, we matched the periodic variables with GALEX sources (within 5\arcsec). We found matches for 20,000 of the 61,000 sources in Drake et al. (2014) periodic variable catalog.

In Figure 5, we compare the ellipsoidal candidates and eclipsing sources, with the known WD binaries as noted earlier. The eclipsing and ellipsoidal systems are not well separated in $NUV-V_{CSS}$ colour and overlap with other periodic variables (as do many of the spectroscopically WDMS systems). Some of the ellipsoidal candidates do stand out in $FUV-NUV$ colours. However, very few are detected at the depth of GALEX $FUV$ measurements. As expected, the short-period eclipsing systems are not detected in GALEX $FUV$ data.

The GALEX results strongly suggest that the companions must be much cooler than most of the known WDMS systems. Since WDs are among the most common stars, it is expected that numbers of cool WD+dM binaries should exceed the number of hot systems (Rebassa-Mansergas et al. 2013). Low accretion-rate CVs and pre-CV systems, such as SDSS 121010.1+334722.9 (Pyrzas et al. 2012), may also produce very little emission with cool WDs. The detection of FUV emission from the ellipsoidal candidates strongly suggests that some fraction of these systems contain hot WDs.

Another piece of evidence suggesting that ellipsoidal candidates are not contact binaries comes from the fact that some of the light curves exhibit clear eclipses. In Figure 6, we plot examples of short-period systems where a compact source eclipses a distorted companion. The shallow depth of the eclipses, along with the short ingress and egress times, suggests that the eclipsing source is much more compact than the distorted companion. The light curves also lack any obvious secondary eclipse. This further suggests that compact eclipsing source is much fainter than the star undergoing the eclipse. Thus in these cases at least, one of the components must be fainter and smaller than their companions.

The lower two light curves of Figure 6 demonstrate the difficulty there can be when discerning whether a system has the W-shaped eclipses of a contact binary, or the sinusoidal light curve of an ellipsoidally distorted M-dwarf with a faint, compact companion.

For most ellipsoidal candidates there was no sign of distinct eclipses. It is possible that some of the companions could be neutron stars. Indeed, $\gamma$-ray pulsar PSR J2339-0533 (Romani & Shaw 2011) was among the periodic sources detected in our analysis of periodic variables in CSDR1. This pulsar exhibits a high level of variability due to a highly distorted companion. It also has a period in the range of these sources (0.193 days). We matched the short-period sources with unidentified sources in the Fermi-LAT catalog (Nolan et al. 2012) but found no convincing matches. In this short-period range we expect that low mass companions to neutron stars should give rise to a higher level of variability than observed, suggesting that most of systems are likely to be due to WDs rather than other compact sources.

\(^{11}\) http://www.sdss3.org/dr9/imaging/caveats.php
Fig. 5.— UV and optical colours of the periodic variable stars. In the left panel we plot the GALEX GR5 near-UV colours of the periodic variables. The symbols match those given in Figure 4.

Fig. 6.— Candidate ellipsoidal variables with discrete eclipsing features (top three curves) compared to a morphologically similar, likely contact binary. The variables labeled 1 through 4 are CSS\_J090826.3+123648 (red, $P = 0.139$ days), CSS\_J093508.0+270049 (blue, $P = 0.201$ days), CSS\_J165352.4+391410 (green, $P = 0.220$ days), and CSS\_J234131.5+375439 (magenta, $P = 0.171$ days), respectively.

3.1. Spectroscopic Follow-up

In order to confirm the nature of the ultra-short period binary candidates we carried out low-resolution spectroscopy with the Optical System for Imaging and Low Resolution Integrated Spectroscopy (OSIRIS) tunable imager and spectrograph (Cepa et al. 2003; Cepa 2010) at the 10.4m Gran Telescopio CANARIAS (GTC), located at the Observatorio Roque de los Muchachos in La Palma, Canary Islands, Spain. The heart of OSIRIS is a mosaic of two $4k \times 2k$ e2v CCD44–82 detectors that gives an unvignetted field of view of $7.8 \times 7.8$ arcmin$^2$ with a plate scale of 0.127 arcsec pix$^{-1}$. However, to increase the signal-to-noise ratio of our observations, we chose the standard operation mode of the instrument, which is a $2 \times 2$-binning mode with a readout speed of 100kHz. All spectra were obtained with the OSIRIS R1000B grism. We used the 1.23 arcsec-width slit, oriented at the parallactic angle to minimize losses due to atmospheric dispersion. The resulting resolution, measured on arc lines, was $R \sim 700$ in the approximate 3500–8000 Å spectral range. An additional seven spectra were obtained with the Palomar 5m telescope (P200) using the Double Beam Spectrograph (DBSP) using a 1 arcsec-width slit and spectral range 3700–10000 Å.

All the spectra were reduced using standard reduction procedures within IRAF. The GTC observing program concentrated on taking spectra of the short-period objects with contact binary light curves, while the Palomar program concentrated on sources with the shortest periods (which are mostly ellipsoidal candidates). In addition to these programs, we matched all the ultra-short period binaries with objects having spectra within the Sloan Digital Sky Survey Data Release 10 (SDSS DR10; Ahn et al. 2014). We found three SDSS matches to our eclipsing candidates, and one to an ellipsoidal candidate.

In Table 1, we present the details of the SDSS, Palomar and GTC spectra and in Figures 7, 8 and 9, we present the GTC, Palomar and SDSS spectra, respectively. Spectral types were derived by comparison to SDSS classifications. In particular, the M-dwarfs were classified using the high signal-to-noise combined templates of Bochnaski et al. (2007). Overall, the GTC spectra consist of five K-dwarfs and three early M-dwarfs, while the shorter period systems observed with Palomar all contain M-dwarfs. One system with an SDSS spectrum, and one object observed by GTC, were re-observed with Palomar as a consistency check. The spectral types were in excellent agreement.

Inspection of the spectra revealed the presence of clear Balmer emission in almost all of the spectra. Such emission is seen in a large fraction of M-dwarfs and increases significantly for late types (Bochnaski et al. 2005). However, only $\sim 10\%$ of M1 and M2 stars are known to exhibit such activity. Furthermore, balmer emission is also seen in the K-dwarfs observed by GTC. Only a couple of percent of the stars are expected to exhibit emission
### TABLE 1
Spectra of Ultra-short Period Binaries

<table>
<thead>
<tr>
<th>CRTS ID</th>
<th>RA</th>
<th>Dec (J2000)</th>
<th>$V_{CSS}$</th>
<th>Period</th>
<th>Telescope</th>
<th>Category</th>
<th>$u-g$</th>
<th>$g-r$</th>
<th>Spectral Type</th>
</tr>
</thead>
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<td>CSS J090826.3+123648</td>
<td>09:08:26.26</td>
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<td>15.27</td>
<td>0.139198</td>
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<td>ELL</td>
<td>0.87</td>
<td>0.78</td>
<td>M7V</td>
</tr>
<tr>
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<td>+29:46:02.8</td>
<td>17.06</td>
<td>0.146249</td>
<td>P200/SDSS</td>
<td>ELL</td>
<td>1.73</td>
<td>1.27</td>
<td>M3.5V</td>
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<td>08:11:58.58</td>
<td>+31:19:59.5</td>
<td>16.13</td>
<td>0.156187</td>
<td>P200</td>
<td>ELL</td>
<td>2.39</td>
<td>1.51</td>
<td>M2V</td>
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<tr>
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<td>0.164086</td>
<td>P200</td>
<td>ELL</td>
<td>1.78</td>
<td>1.29</td>
<td>M5V</td>
</tr>
<tr>
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<td>12:23:37.06</td>
<td>+37:21:30.2</td>
<td>16.56</td>
<td>0.168744</td>
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<td>EW</td>
<td>2.70</td>
<td>1.44</td>
<td>M4.5V</td>
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<td>0.164086</td>
<td>P200</td>
<td>ELL</td>
<td>1.78</td>
<td>1.29</td>
<td>M5V</td>
</tr>
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<td>P200</td>
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<td>0.95</td>
<td>0.98</td>
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<td>EW</td>
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<td>0.62</td>
<td>M5V</td>
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<td>+11:42:54.7</td>
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<td>0.186678</td>
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<td>ELL</td>
<td>2.76</td>
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<td>17.07</td>
<td>0.184749</td>
<td>P200</td>
<td>EW</td>
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<td>0.190148</td>
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<td>15.04</td>
<td>0.196014</td>
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<td>EW</td>
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<td>1.38</td>
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<td>EW</td>
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<td>1.04</td>
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<td>+02:16:35.0</td>
<td>18.03</td>
<td>0.19777</td>
<td>GTC</td>
<td>EW</td>
<td>1.91</td>
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<td>K6V</td>
</tr>
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<td>+20:41:22.2</td>
<td>16.29</td>
<td>0.198047</td>
<td>GTC</td>
<td>EW</td>
<td>2.76</td>
<td>1.33</td>
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<td>0.198785</td>
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<td>EW</td>
<td>2.24</td>
<td>1.38</td>
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<td>+35:44:39.3</td>
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<td>0.199725</td>
<td>GTC</td>
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<td>2.11</td>
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<td>GTC</td>
<td>EW</td>
<td>2.25</td>
<td>1.08</td>
<td>K5V</td>
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</table>

Col. (1) Catalina ID. Cols. (2) & (3) Right Ascension and Declination Col. (4) Period in days. Col. (5) Source of the spectrum where P200 is the Palomar 5m, and GTC is Gran Telescopio Canarias 10.4m. Col. (6) Type of periodic variable (ELL = ellipsoidal candidate, EW = contact or W UMa type, EA = detached or Algol type). Cols. (7) & (8) Extinction corrected colours from SDSS DR10 photometry. Col. (9) Spectral type.

- **a** Matches high proper motions system LP 486-53, with $\Delta \alpha = -122, \Delta \delta = -172$ mas/yr (Lepine & Shara 2005).
- **b** System where radial velocity variations were measured.
- **c** Matches SDSS J111647.81+294602.7. Previously identified as candidate binary based on SDSS spectra by Clark, Blake & Knapp (2012).

Fig. 7.— GTC optical spectra of ultra-short period eclipsing binary candidates. In the left panel (from top to bottom), we plot the spectra for contact binaries with K-types: CSS J151531.4-153418 (blue); CSS J044647.5+021635 (black); CSS J234002.2+204122 (red); CSS J013224.5+011522 (green) and CSS J161945.9+241312 (cyan). In the right panel (from top to bottom), we plot the spectra for sources with M spectral types: CSS J115533.4+354439 (blue); CSS J213019.2-065136 (green) and CSS J171508.5+350658 (red). Zhao et al. (2013). The enhanced number here is a sign of magnetic activity induced in these compact binaries. Similar highly enhanced active fractions were found WD+dM systems by Morgan et al. (2012). Additionally, Ca H+K lines are present in emission in most of the spectra. This is also a sign of strong magnetic interaction between the components.

Comparison of the spectra for the ellipsoidal candidates with the regular eclipsing binaries, does not show any obvious difference. Among the sources from Table 1, only CSS J090826.3+123648, and CSS J112237.0+395219 show some evidence for an additional component at the bluest wavelengths. As noted in Table 1, these two stars also have the bluest colours ($u-g < 1$ and $g-r < 1$) of the candidates with SDSS photometry. The lack of clear evidence for a white dwarf candidates with the regular eclipsing binaries, does not show any obvious difference. Among the sources from Table 1, only CSS J090826.3+123648, and CSS J112237.0+395219 show some evidence for an additional component at the bluest wavelengths. As noted in Table 1, these two stars also have the bluest colours ($u-g < 1$ and $g-r < 1$) of the candidates with SDSS photometry. The lack of clear evidence for a white dwarf
companion in the ellipsoidal systems is not unexpected since van den Besselaar et al. (2007), Rodriguez-Gil et al. (2009), Rebassa-Mansergas et al. (2010), Pyrzas et al. (2012), Parsons et al. (2013) and Rebassa-Mansergas et al. (2013) all present examples of WDMS spectra where evidence for the WD is not clearly discerned. The lack of a blue component in these spectra suggests that the sources causing the distortion are generally cooler than the hot WDs that have previously been found using SDSS spectra (Rebassa-Mansergas et al. 2012). The absence of a blue component is also expected based on the SDSS and GALEX colours presented earlier.

3.1.1. Radial Velocities

Since the spectra of the short-period systems poorly constrain cases where the primary is too faint to be seen, we undertook a program to better classify the binary systems using radial velocity variations. For short-period systems, an unseen yet relatively massive companion (such as a WD), is expected to produce large radial velocity variations in low mass companion stars (such as M-dwarfs). The presence of small velocity variations can also be used to exclude possible sources of contamination, such as pulsating stars. For example, δ Scuti variables have velocity variations of only a few km/s (Penfold 1971, Zima et al. 2007, Antoci et al. 2013), while WD+dM binaries have typical radial velocity amplitudes of around 150km/s (Nebot Gómez-Morán et al. 2011).

Multiple epochs of optical spectra were obtained for five of the systems noted in Table 1. As the spectra only exhibit clear emission from one component, it is only possible to measure the velocity variations of a single source in each system. Future high resolution observations of these objects may enable the detection features from both sources.

For each source, we measured velocity variations by the average Doppler velocities of the Balmer and Ca II H+K lines. In each case the average was weighted by the relative strength of the lines. The velocity errors are for these low resolution spectra are of order $\sim 15$ km/s. As the light curves themselves are measured over a period of years the phases of our observations are expected to accurate to $\sim 0.01$ cycles.

To determine the parameters for these binary systems we simultaneously fit the observed radial velocities and lightcurves using the Nightfall\textsuperscript{12} software. In Table 2, we present the fit parameters for the five systems and in Figures 10, 11 & 12, we present the light curves and radial velocity variations. For each system we used the measured spectral type to estimate the approximate effective temperature based on Baraffe & Chabrier (1996). The

\textsuperscript{12} For details on Nightfall, see http://www.hs.uni-hamburg.de/DE/Ins/Per/Wichmann/Nightfall.html
TABLE 2
ULTRA-SHORT PERIOD BINARY FITS

<table>
<thead>
<tr>
<th>CRSID</th>
<th>(V1_{\text{max}}) (km/s)</th>
<th>(V2_{\text{max}}) (km/s)</th>
<th>(M1) (M(_\odot))</th>
<th>(M2) (M(_\odot))</th>
<th>Trend1 (K)</th>
<th>Trend2 (K)</th>
<th>I (deg)</th>
<th>R1 (R(_\odot))</th>
<th>R2 (R(_\odot))</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSS_J001242.4+130809</td>
<td>77</td>
<td>110</td>
<td>0.24</td>
<td>0.17</td>
<td>3200</td>
<td>2900</td>
<td>40.5</td>
<td>0.410</td>
<td>0.36a</td>
</tr>
<tr>
<td>CSS_J090119.2+114254</td>
<td>54</td>
<td>256</td>
<td>0.58</td>
<td>0.12</td>
<td>7800</td>
<td>3100</td>
<td>69.9</td>
<td>0.018</td>
<td>0.58</td>
</tr>
<tr>
<td>CSS_J090826.3+123648</td>
<td>86</td>
<td>294</td>
<td>0.62</td>
<td>0.18</td>
<td>6500</td>
<td>2500</td>
<td>85.9</td>
<td>0.008</td>
<td>0.26</td>
</tr>
<tr>
<td>CSS_J111647.8+294602</td>
<td>109</td>
<td>242</td>
<td>0.52</td>
<td>0.23</td>
<td>6500</td>
<td>3150</td>
<td>73.5</td>
<td>0.016</td>
<td>0.32</td>
</tr>
<tr>
<td>CSS_J081158.6+311059</td>
<td>101</td>
<td>206</td>
<td>0.47</td>
<td>0.23</td>
<td>6300</td>
<td>3400</td>
<td>61.3</td>
<td>0.018</td>
<td>0.33</td>
</tr>
</tbody>
</table>

As noted in the text, these fits are based on velocities and fluxes from a single component in each system. They are thus only approximate. The fit temperatures for the secondary components are very uncertain and have been rounded to the nearest 100K. Col. (1) Catalina ID. Cols. (2) & (3) Maximum radial velocities. Cols. (4) & (5) Masses of components. Cols. (6) Fit effective temperatures of component. Cols. (7) Input effective temperature based on observed spectral type. Col. (8) Orbital inclination. Cols. (9) & (10) Average radii.

\(^{a}\)Main sequence binary model solution for the system.
\(^{b}\)WDMS binary model solution for the system.

As noted in the text, these fits are based on velocities and fluxes from a single component in each system. They are thus only approximate. The fit temperatures for the secondary components are very uncertain and have been rounded to the nearest 100K. Col. (1) Catalina ID. Cols. (2) & (3) Maximum radial velocities. Cols. (4) & (5) Masses of components. Cols. (6) Fit effective temperatures of component. Cols. (7) Input effective temperature based on observed spectral type. Col. (8) Orbital inclination. Cols. (9) & (10) Average radii.

The goodness-of-fit value for the dM+dM model was \(\chi^2 = 1.1\), while for the WD+dM model it was \(\chi^2 = 1.8\). The dM+dM model is thus favored by this. Additionally, the presence of emission from the M-dwarf seems more likely as it occurs for the other four systems. If the observed emission does originate from the WD, this would suggest that material from the M-dwarf is being accreted onto the WD. For two similar WD+dM systems van den Besselaar et al. (2007) and Bruch (1999) found that the emission was due to the activity of the M-dwarf, rather than the WD. Alternately, there are a few known examples of very low-mass WDs in binaries (Brown et al. 2012). Future high signal-to-noise observations, with increased phase coverage and multi-band photometry, should be able to break the degeneracy between the two models.

4. DISCUSSION AND CONCLUSIONS

In Drake et al. (2014) we classified 231 of the sources as short period eclipsing contact binaries and 136 as candidate ellipsoidal variables. Thus, among the \(\sim 31,000\) contact and ellipsoidal binary candidates there are \(\sim 370\) systems with periods below the 0.22 day cutoff. Accounting for recent discoveries this work still increases the number of ultra-short period eclipsing binaries and short period ellipsoidal systems by an order of magnitude. However, our analysis demonstrates the difficulty in separating ultra-short period binaries containing pairs of late main sequence stars, from those with cool WDs in WDMS systems. For example, in cases where the observed flux from a WDMS system is dominated the main sequence star, the presence of a WD may not be seen in optical spectra or multi-colour photometry (such as pro-
Fig. 11.— The lightcurves and radial velocities variations of ultra-short period binaries. The left panel presents the results for CSS\,J090826.3+123648, while the right panel shows the values for CSS\,J090119.2+114254. The red dashed lines gives the model fit to photometric and velocity variation. The fits are uncertain since only a single set of spectral features is observed.

Fig. 12.— The lightcurves and radial velocities variations of ultra-short period binaries. The left panel presents the results for CSS\,J111647.8+294602, while the right panel shows the values for CSS\,J081158.58+311959. The red dashed lines gives the model fit to photometric and velocity variation. The fits are uncertain since only a single set of spectral features is observed.

provided by SDSS and GALEX). This suggests that such systems are best found using light curves and confirmed using radial velocity variations. However, in cases where the amplitude of variation is $> 0.3$ mag, systems are likely to contain main sequence binaries, since the variation amplitude of a WDMS is limited by the degree of distortion that the MS star can undergo before transferring material onto the WD (Parsons et al. 2013).

The PTF survey discovered three WD+dM systems with cool WDs in a search for planets transiting M-dwarfs (Law et al. 2012). This survey covered $< 500$ sq deg for systems reaching $m_R \sim 18$. The three systems found have periods between 0.35 to 0.45 days. Based on this result the authors suggest that binaries with cool WDs are preferentially found at large orbital radii, in contrast to the systems with hotter WDs presented by Rebassa-Mansergas et al. (2012). However, since the search undertaken by Law et al. (2012) was designed to find planets transiting M-dwarfs they used the standard box-fitting BLS technique of Kovacs et al. (2002) to find variables. The BLS technique is specifically designed to discover small dips in otherwise featureless lightcurves, rather than other general types of periodic behaviour. In particular, since short-period WD+dM systems exhibit large sinusoidal flux variations due to the distorted M-dwarf their lightcurves do not resemble transiting planets (Drake et al. 2003). Additionally, Parsons et al. (2013) have shown, only a small fraction of the hundreds of known WD+dM binaries exhibit the discrete eclipses that Law et al. (2012) was sensitive to. Considering this fact and the relatively small area covered by the Law et al. (2012) analysis compared to our survey, it
is not surprising they did not find cool WD+dM systems with short periods. Indeed, in contrast to the Law et al. (2012) results, Pyrzas et al. (2012) discovered a cool (6000K) WD+dM system with a period of just 0.12 days. Nevertheless, as our analysis is limited to systems with periods < 0.22 days, we cannot constrain the possibility that there is indeed a much larger fraction of cool WD binaries at long periods.

The separation of WD+dM binaries from dM+dM systems is more difficult when the M-dwarfs are in the spectral range from M0V to M2.5V. Such M-dwarfs have masses in the range 0.6-0.3M⊙ (Baraffe & Chabrier 1996), and absolute magnitudes $8 < M_V < 11$ (Kroupa & Tout 1997). Since their masses overlap with the white dwarf mass distribution (Kleinman et al. 2013), they give rise to the same radial velocity amplitudes as WDMS systems. Additionally, in WDMS binary systems, one does not expect to observe split narrow emission lines that may be present in a main sequence binary pairs. Although, pairs of lines may not be present in many such systems. Furthermore, as WDs have absolute magnitudes in the range 12 < $M_V$ < 16 (Bergeron et al. 1995, Andreuzzi et al. 2002), cool white dwarfs can be many magnitudes fainter than their M-dwarfs companions and thus be undetectable. In order to distinguish these systems one has to investigate slight variations between over-contact and WDMS binary solutions. However, if discrete eclipses are present this demonstrates that these systems are detached rather than in contact.

In this analysis we have found many of the short period sources with the ellipsoidal variable-type light curves. As noted above, while contact and detached binaries have different light curve shape, WD+dM binaries and over-contact binaries with amplitudes $< 0.3$ mag often have very similar shapes. Some of the systems exhibit excess $g - r$ flux compared to main sequence binaries. A few systems do exhibit $F_UV - NUV$ colours (similar to those of previously known CVs and WD+dM binaries). However, these binary systems generally do not exhibit different $NUV - V_{CSS}$ colours compared to main sequence eclipsing binaries or other periodic variables. Such systems therefore cannot be found through colour selections with SDSS or GALEX, nor with individual SDSS spectra as analysed by Rebassa-Mansergas et al. (2012).

The radial velocities for four of the five systems observed are sufficient to establish that the primaries are much more massive than the M-dwarfs seen in the spectra. Instead, they are consistent with cool WDs. For the remaining system, two situations are possible: a WD+dM binary, or an M-dwarf pair. An M dwarf pair is favored due to the improved model fit, relatively small radial velocities, and presence of narrow emission lines from the primary.

In comparison to our results, Nefs et al. (2012) present a number of short-period systems that exhibit small amplitudes and sinusoidal light curves. Of the four Nefs et al. (2012) sub-0.2 day systems, the lightcurve morphology of 07g-3-05744 best matches that of the ellipsoidal type variables we select. Additionally, the extinction corrected SDSS DR9 colours for this source ($u - g = 0.89$, $g - r = 0.67$, $r - i = 1.2$, $i - z = 0.74$) strongly suggest that the object has a colour excess. This system appears to be more likely an WD+dM binary than a main sequence pair. No spectroscopic observations were presented for this systems by Nefs et al. (2012). Two of the remaining three short period objects from Nefs et al. (2012) have SDSS u-band uncertainties greater than a magnitude, while the third is not detected and none of these objects have measured radial velocities. This makes it difficult to completely discount the possibility that the systems contain cool white dwarfs. However, this possibility seems very unlikely for two of the systems, since they exhibit regular detached binary lightcurves. In particular, 19h3-14992 clearly exhibits two eclipses of similar span and differing depth. Nefs et al. (2012) confirms that this detached system contains an M-dwarf based on a WHT ISIS spectrum. Although, the spectrum itself does not cover the $\lambda < 5000\AA$ region where a white dwarf might be seen, and there is no evidence for a companion in the spectrum presented.

Comparing the number of short-period binaries discovered by Nefs et al. (2012) one finds a much greater fraction than found in our analysis. For example, Nefs et al. (2012) found 14 source with periods < 0.22 days from a sample of 262,000 sources, while we find 367 among 198 million sources. This difference can be partially explained by the much greater red sensitivity of the Nefs et al. (2012) J-band data. In contrast, Norton et al. (2011) found only 15 similar short-period binaries sources among 30 million lightcurves using very well sampled, but shallower, SuperWASP data. Another reason for the relatively large number of Nefs et al. (2012) sources is that the survey fields were taken much closer to the galactic plane. The CSS project avoided the plane because of crowding, yet as shown by Drake et al. (2014) the contact binaries are strongly concentrated near the Galactic plane (as expected).

Using GTC, SDSS and Palomar spectroscopy we have confirmed the presence of M-dwarf systems among ultra-short period eclipsing contact binaries. The only other spectroscopically confirmed ultra-short period M-dwarf contact binary was discovered by Davenport et al. (2013). This system, originally identified by Becker et al. (2011), has a period of $\sim 0.2$ days and clearly exhibits a sinusoidal light curve with an amplitude of 0.2 mags. As with our ellipsoidal variable selection, this object exhibits a slight deviation from a single sinusoid. The object’s lightcurve shape is most consistent with our confirmed WD+dM systems. Furthermore, as with the WD+dM binaries, the Davenport et al. (2013) spectra lack evidence for a blue component yet exhibits an single Hα emission line. Davenport et al. (2013) find that the masses of the components to be $M_1 = 0.54M_\odot$ and $M_2 = 0.25M_\odot$. As noted above, such masses are consistent with a either an early M-dwarf or WD primary. The strongest evidence against this system being an WD+dM system, is the presence of faint pairs of Ca-I absorption lines at 6102Å and 6122Å. However, as Pyrzas et al. (2012) have shown, WD+dM binaries also include metal lines in their spectra. In such cases the source of the lines has been attributed to WD accretion of M-dwarf wind. Since Davenport et al. (2013) did not attempt to fit a WD+dM model, the exact nature of this systems still appears uncertain.

Our analysis firmly shows the existence of a population of contact binaries with periods < 0.2 days. This result suggests that current binary evolution models discounting the existence of these systems provide an incomplete
picture of the binary population. Nevertheless, since M-dwarfs are very common and short-period systems very rare, it is entirely possible that such systems only occur under special conditions. One possibility suggested by Nefs et al. (2012) is that such systems occur due to interactions in stellar triple systems. Such interactions may not be uncommon since, as noted by Rucinski, Pribulla & van Kerkwijk (2007), hierarchical triples are very common among short period binaries.

The recent theoretical results of Jiang et al. (2012) suggest that contact binaries are not found with masses less than 0.61 M⊙ and periods < 0.2 days due to their very short evolutionary times (<1 Gyr) that are caused by unstable mass transfer. It is not possible to resolve the timescale of the unstable transfer presented by Jiang et al. (2012), though the presented results suggest this is \( \approx 0.01 \)Gyr. It is possible that the small number of short-period contact binaries we detect might be those undergoing such transfer. However, there is no observational evidence for this within the lightcurves.

In stark contrast to Jiang et al. (2012), the Stepien (2006) binary models explain the lack of such systems as being due to such systems not reaching contact within a Hubble time. Jiang et al. (2012) explains the difference between their model and those of Stepien (2006), as being due to a different assumption for the angular momentum loss rate. Given the apparently highly discrepant theories, the cause for the contact binary period limit remains very poorly understood. Nevertheless, our discovery of contact systems below the 0.2 day limit should serve as an additional constraint for future binary models.

In the near future the Gaia mission (Perryman et al. 2001) and the VVV survey (Minniti et al. 2010) will begin to harvest Galactic disk fields and are expected to find millions of periodic variables (Eyer et al. 2012; Catelan et al. 2013). Although Gaia is only expected to reach stars to the same depth as CSDR1, with far fewer epochs, it is expected to have ultra-precise photometry. This will greatly increase the accuracy with which over-contact and WD+dM systems can be separated. Likewise, the LSST survey will reach far greater depths than any existing wide-field survey (Ivezic et al. 2008). The LSST will thus be able to probe M-dwarf binaries within a far greater volume than other surveys, and thereby enable a better constrain the true frequency and period distribution of such systems.

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