Precise parameters for both white dwarfs in the eclipsing binary CSS 41177

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ABSTRACT

We present ULTRACAM photometry and X-Shooter spectroscopy of the eclipsing double white dwarf binary CSS 41177, the only such system that is also a double-lined spectroscopic binary. Combined modelling of the light curves and radial velocities yield masses and radii for both white dwarfs without the need to assume mass–radius relations. We find that the primary white dwarf has a mass of $M_1 = 0.38 \pm 0.02 \, M_\odot$ and a radius of $R_1 = 0.0222 \pm 0.0004 \, R_\odot$. The secondary white dwarf’s mass and radius are $M_2 = 0.32 \pm 0.01 \, M_\odot$ and $R_2 = 0.0207 \pm 0.0004 \, R_\odot$, and its temperature and surface gravity ($T_2 = 11678 \pm 313 \, K$, $\log(g_2) = 7.32 \pm 0.02$) put it close to the white dwarf instability strip. However, we find no evidence for pulsations to roughly 0.5 per cent relative amplitude. Both masses and radii are consistent with helium white dwarf models with thin hydrogen envelopes of $\leq 10^{-4} \, M_\odot$. The two stars will merge in 1.14 ± 0.07 Gyr due to angular momentum loss via gravitational wave emission.

Key words: methods: statistical – techniques: radial velocities – binaries: eclipsing – stars: individual: SDSS J100559.10+224932.3 – white dwarfs.

1 INTRODUCTION

More than 95 per cent of all stars end their lives as white dwarfs. These most common remnants of stellar evolution trace the initial stellar distribution and contain a history of the evolution of their progenitor stars, through the strong correlation between the progenitor star’s initial mass and the white dwarf’s final mass (Weidemann 2000). As even the oldest white dwarfs have not had enough time to cool below detectability, they provide useful and independent age estimates when found in, for example, the Galactic disc (Wood 1992), as well as providing distance estimates to globular clusters (Renzini et al. 1996). White dwarfs also feature as the most likely candidates for Type Ia supernova progenitors (Whelan & Iben 1973; Nomoto 1982; Iben & Tutukov 1984), in accreting binaries such as cataclysmic variables, and are potential progenitors of single hot sdB/sdO stars and extreme helium stars (Webbink 1984), AM CVn binaries (Breedt et al. 2012) and Type Ia supernovae (Bildsten et al. 2007).

Despite the abundance and importance of white dwarfs, it has proved difficult to measure fundamental parameters such as mass and radius directly, without the use of theoretical mass–radius relations. This leaves the empirical basis for this relation relatively uncertain (Schmidt 1996). For single white dwarfs, spectral fitting can be used to obtain the temperature and surface gravity, after which both mass and radius can be inferred, but only when combined with a mass–radius relation (see for example Provencal et al. 2002). White dwarfs in visual binaries, common proper motion pairs or in open clusters allow one to determine parameters without the use of this relation, therefore providing a direct test of it. These methods rely on accurate parallax measurements, spectral fitting and/or radial velocity measurements (Provencal et al. 2002; Casewell et al. 2009; Holberg, Oswalt & Barstow 2012). The number of stars to which these methods can be applied is limited, and with the exception of Sirius B (Barstow et al. 2005), they cluster around a mass of $M_{WD} \sim 0.6 \, M_\odot$, making it difficult to test the full range of the mass–radius relation.

Observing white dwarfs in eclipsing binaries enables high precision in determining masses and radii and these types of binaries also include white dwarfs across a wide range of masses (O’Brien, Bond
& Sion 2001; Parsons et al. 2012b; Pyrzas et al. 2012; this paper). For these systems, masses can be determined from orbital velocities and radii from light-curve analysis (Parsons et al. 2012a,c). Due to their eclipsing nature, the inclination of the system is strongly constrained, allowing for direct mass determinations as opposed to lower limits.

The number of known short-period, eclipsing, white dwarf binaries has grown substantially within the last decade, mainly due to large all-sky surveys such as the Sloan Digital Sky Survey (SDSS; York et al. 2000) and the Catalina Sky Survey (CSS; Drake et al. 2009). The latter and other survey work also led to the discovery of the first five eclipsing binaries in which both stars are white dwarfs: NLTT 11748 (Steinfadt et al. 2010), CSS 41177 (Parsons et al. 2011), GALEX J171708.5+675712 (Vennes et al. 2011), SDSS J065133.3+284423.37 (Brown et al. 2011) and SDSS J075141.18−014120.9 (Kilic et al. 2014).

These binaries provide us with an opportunity for precise and independent mass and radius measurements for two white dwarfs from one system. The double white dwarf binary that is the subject of this paper, CSS 41177 (SDSS J100559.10+224932.2), is the only one of the five that is also a double-lined spectroscopic binary, allowing direct measurement of the stars’ orbital velocities (Parsons et al. 2011) and therefore their masses without needing to assume a mass–radius relation.

CSS 41177 was initially discovered to be an eclipsing binary by Drake et al. (2010), who constrained it to be a white dwarf with a small M-dwarf companion, although they noted that a small faint object could produce a signal similar to what they observed. Parsons et al. (2011) obtained Liverpool Telescope + RISE fast photometry and Gemini + GMOS (Gemini Multi-Object Spectrograph) spectroscopy, which allowed them to determine that there were in fact two white dwarfs and to carry out an initial parameter study. In this paper, we present higher signal-to-noise data in order to determine the system parameters more precisely and independent of any mass–radius relationships.

2 DATA

2.1 Photometry: ULTRACAM

The photometric data were taken with ULTRACAM (Dhillon et al. 2007), a visitor instrument that was mounted on the 4.2 m William Herschel Telescope (WHT) on the island of La Palma, Spain, and on the 3.5 m New Technology Telescope (NTT) at the La Silla Observatory, Chile. ULTRACAM is a high-speed camera that images ultraviolet, visual and red wavelengths simultaneously with three frame-transfer CCDs with ~25 ms dead time between exposures. Filters identical to the SDSS u′, g′ and r′ filters were used, and we windowed the CCD which allowed us to reach exposure times as short as 1.5 s in the slow readout speed. We observed 11 primary eclipses of CSS 41177 and 9 secondary eclipses in 2012 January with ULTRACAM mounted on the WHT, including one observation spanning a complete orbit (1.1 cycles). We also observed one primary eclipse in 2011 May with ULTRACAM on the NTT. We refer to a primary eclipse when the hotter, more massive white dwarf is being eclipsed.

The ULTRACAM pipeline (Dhillon et al. 2007) was used to debias and flat-field the data. The source flux was determined with relative aperture photometry, using a nearby star as a comparison. We used a variable aperture, where the radius of the aperture was scaled according to the full width at half-maximum of the stellar profile. The profiles were fitted with Moffat profiles (Moffat 1969).

Table 1. Log of the X-shooter observations. On all three nights the conditions were clear, with seeing between 0.5 and 1.0 arcsec.

| Date       | UT Start (UT) | UT End (UT) | No. of exposures |
|------------|---------------|-------------|------------------|
| 2012 March 25 | 00:13        | 04:31       | 44               |
| 2012 March 26 | 00:09        | 04:10       | 39               |
| 2012 March 27 | 23:51        | 04:36       | 46               |

The ULTRACAM data have absolute timestamps better than 0.001 s. We converted all times on to a TDB time-scale, thereby correcting for the Earth’s motion around the Solar system barycentre. A code based on SLALIB was used for these corrections, which has been found to be accurate at a level of 50 ms compared to TEMPO2 (a pulsar timing package, see Hobbs, Edwards & Manchester 2006). Compared to the statistical uncertainties of our observations, this is insignificant.

2.2 Spectroscopy: X-Shooter

We obtained spectra with the X-Shooter spectrograph (Vernet et al. 2011) on the Very Large Telescope UT2 (Kueyen) on the nights of the 2012 March 25, 26 and 27, obtaining a total of 117 spectra covering 1.5, 1.4 and 1.7 orbital cycles in the three nights. A log of the observations is given in Table 1.

The X-shooter spectrograph consists of three independent arms (UVB, VIS and NIR), giving a simultaneous wavelength coverage from 3000 to 24 800 Å. We obtained a series of spectra 310, 334 and 300 s in length for the UVB, VIS and NIR arms, respectively. Spectra were obtained consecutively with occasional short breaks of a few minutes in order to check the position of the target on the slit. We binned by a factor of 2 both spatially and in the dispersion direction in the UVB and VIS arms, and used slit widths of 0.8, 0.9 and 0.9 arcsec for the UVB, VIS and NIR arms, respectively. The NIR arm slit includes a K-band blocking filter which reduces the thermal background in the J and H bands.

We reduced these data using version 1.5.0 of the X-shooter pipeline and the Reflex workflow management tool. The standard recipes were used to optimally extract and wavelength calibrate each spectrum. We removed the instrumental response using observations of the spectrophotometric standard star LTT4364 (GJ-440). We obtained and reduced the data in ‘stare’ mode. For optimum sky subtraction in the infrared arm ‘nod’ mode would be preferable, but our priority was to maximize the temporal resolution for the spectral features of interest in the other two arms.

2.3 Photometry: RISE on the LT

In order to monitor any long-term orbital period variations, we also regularly observed primary eclipses of CSS 41177 with the fully robotic 2.0 m Liverpool Telescope (LT; Steele et al. 2004) and RISE camera. RISE contains a frame-transfer CCD, with a single ‘V+R’ filter. We observed a total of 10 primary eclipses from 2011 February until 2013 March.

The data were flat-fielded and debiased in the automatic pipeline, in which a scaled dark-frame was removed as well. Aperture photometry was performed using the ULTRACAM pipeline in the same manner as outlined in Section 2.1. We converted the resulting mid-eclipse times to the TDB time-scale. LT/RISE has absolute timestamps better than 0.1 s (Pollacco, private communication).
3 DATA ANALYSIS AND RESULTS

3.1 Radial velocity amplitudes

We analysed the reduced spectroscopic data using the MOLLY software, and used observations of the standard star to normalize the continuum and reduce telluric absorption features present in the CSS 41177 science spectra as far as possible.

To measure the radial velocity amplitudes $K_1$ and $K_2$, we fitted the H$\alpha$ line with multiple Gaussian profiles combined with a straight line fitted to the local continuum using Marquardt’s method of minimization. Each Gaussian profile was represented by two free parameters, the full width at half-maximum and the height. The radial velocity $v_r$ was calculated using

$$v_r = \gamma + K_{1,2} \sin(2\pi \phi),$$  \hspace{1cm} (1)

where $\gamma$ accounts for a systemic radial velocity, $K_1$ and $K_2$ are the radial velocity amplitudes of the two white dwarfs and $\phi$ is the orbital phase. Our best fit gave $K_1 = -176.1 \pm 1.1$ km s$^{-1}$ and $K_2 = 210.4 \pm 6.1$ km s$^{-1}$ for the primary and secondary white dwarfs, and $\gamma = 130.5 \pm 0.7$ km s$^{-1}$ for the offset. The phase-folded trail of the H$\alpha$ line is shown in the top panel in Fig. 1. From this best model, we set the Gaussian profiles corresponding to the secondary star’s line to zero, leaving a model of only the primary star’s line. We then subtracted the model from the original spectra to bring out the secondary’s contribution, shown in the middle panel of Fig. 1. The systemic radial velocity is clearly visible in both of these figures as the offset from zero. The bottom panel shows both the primary and secondary model H$\alpha$ line.

Both radial velocity amplitudes are in agreement with the measurements in Parsons et al. (2011), but have uncertainties reduced by a factor of 3 and 2, respectively.

3.2 Light-curve analysis

In order to determine the eclipse times of all primary eclipses, we created a model that reproduced the shape of the eclipses and then varied the mid-eclipse time and an overall scaling factor to minimize the value of $\chi^2$.

We modelled the white dwarfs as spheres using a program that subdivides the visible face of each into 200 concentric annuli. Each annulus contributes an amount to the total stellar flux, which depends upon the limb darkening. The next section gives more details on how we included limb darkening. We accounted for Doppler beaming from the white dwarfs by following Bloemen et al. (2011), and modified the flux by a factor

$$I - B \frac{v_r}{c}.$$ \hspace{1cm} (2)

with $B$ the spectrum-dependent beaming factor and $v_r$ the radial velocity of the star. To calculate the beaming factors, we used white dwarf model spectra (Koester 2010) with log($g$) = 7.25 for both white dwarfs, and $T = 24,000$ K and $T = 12,000$ K for the primary and secondary, respectively. These values were chosen after an initial fit as described in this section. With these models, and following Bloemen et al. (2011), the bandpass-integrated beaming factors for the ($u'$, $g'$, $r'$) filters are (1.9, 2.2, 1.3) for the primary white dwarf and (3.4, 3.5, 1.8) for the secondary white dwarf. We did not include gravitational lensing in our models. Due to the similarity of the white dwarfs’ masses and radii, and their relatively small separation, the lensing amplification factor near both primary and secondary eclipses is $\sim 1.00003$, making this effect negligible (for the relevant equations, see Marsh 2001).

We then normalized each observed light curve individually to reduce any night-to-night variations and used the SDSS magnitudes for CSS 41177 (see Table 2) to determine the binary’s overall out-of-eclipse flux level. We allowed for an additional shift $\delta$, of the
secondary eclipse, on top of the 0.5 phase difference with respect to the primary eclipse, by adjusting the phase \( \phi \) according to

\[
\phi = \phi + \frac{\delta}{2P} (\cos(2\pi\phi) - 1),
\]

(3)

where \( P \) is the orbital period. This shift near the secondary eclipse allows for possible \( \text{Rømer} \) delays (Kaplan 2010) and/or a small eccentricity of the orbit.

Our program fits all individual eclipses simultaneously using a Markov chain Monte Carlo (MCMC) method to explore the 10-dimensional parameter space, favouring regions with small \( \chi^2 \) values of the model with respect to the data. The free parameters in the model were the two radii scaled by the binary separation, \( R_1/a \) and \( R_2/a \), the white dwarf temperatures, \( T_1 \) and \( T_2 \), the radial velocity amplitudes, \( K_1 \) and \( K_2 \), the inclination of the binary \( i \), the time delay \( \delta \), the orbital period \( P \) and the zero-point of the ephemeris, \( T_0 \), which was chosen to minimize the correlation with the orbital period.

Because we have accurate measurements for the radial velocity amplitudes from the analysis of the spectroscopic data, we used a prior to constrain them while modelling the photometric data. Given the 10 free parameters and combining them with

\[
K_1 + K_2 = \frac{2\pi a}{P} \sin(i),
\]

(4)

and Kepler’s equation given by

\[
G(M_1 + M_2) / a^3 = 4r^2 / P^2,
\]

(5)

the binary’s orbital separation \( a \) and the white dwarf masses \( M_1 \) and \( M_2 \) could also be calculated. Note that \( q = K_1/K_2 = M_2/M_1 \) and that the surface gravities follow from \( g_{1,2} = G M_{1,2} / R_{1,2}^2 \).

As a reference, our best model is shown in Fig. 2, on top of the phase-folded and binned data. This model has the lowest chi-squared value, corresponding to a reduced chi-squared of \( \chi^2_r = 1.03 \) (43 351 data points, 10 free parameters).

Our final ephemeris is given by

BMJD(TDB) = \( 55936.3446719(6) + 0.1160154352(15)E \),

(6)

with \( E \) the cycle number, and the individual primary mid-eclipse times are listed in Table 3. The parameters are summarized in Table 4 (columns 2 and 3), which lists both the mean and rms for each parameter.

2 Named after the Danish astronomer O. \( \text{Rømer} \), who was the first to realize that the speed of light is finite by observing deviations from strict periodicity for eclipses of Io, a satellite of Jupiter (Sterken 2005).

Table 2. Properties of CSS 41177. The I2000 coordinates and the magnitudes are taken from SDSS III DR9, where the magnitudes are the photometric PSF magnitudes.

| Property | Value |
|----------|-------|
| RA       | 10:05:59.1 |
| Dec.     | +22:49:32.26 |
| \( m_u \) | 17.32 ± 0.02 |
| \( m_g \) | 17.29 ± 0.02 |
| \( m_r \) | 17.62 ± 0.02 |

Figure 2. ULTRACAM \( u' \) (top), \( g' \) (middle) and \( r' \) (bottom) data, folded with the binary’s orbital period, normalized and binned using a binwidth of 0.0002. The \( u' \) and \( r' \) data are offset by +0.3 and –0.3, respectively, and the \( g' \) data are not offset. The black lines show the best model. Left-hand side: a total of 12 observed eclipses of the primary, hotter white dwarf. Right-hand side: nine eclipses of the secondary, cooler white dwarf.

3.3 Limb darkening

To account for limb darkening of the white dwarfs, we used the limb-darkening law as first described by Claret (2000), in which the specific intensity across the stellar disc can be calculated using

\[
\frac{I(\mu)}{I(1)} = 1 - c_1(1 - \mu^{1/2}) - c_2(1 - \mu)
- c_3(1 - \mu^{3/2}) - c_4(1 - \mu^2),
\]

(7)

where \( c_1 \)–\( c_4 \) are the limb-darkening coefficients, and \( \mu \) is the cosine of the angle between the line of sight and the surface normal of the white dwarf, so that \( I(1) \) is the specific intensity at the centre of the white dwarf’s disc.

The limb-darkening coefficients were recently calculated for a wide range of white dwarf temperatures and surface gravities, for both the \( \text{Johnson–Kron–Cousins} \) \( UBVRI \) system and the \( ugrizy \) filters to be used by the LSST (Gianninas et al. 2013). The filter profiles of the ULTRACAM \( u' \), \( g' \) and \( r' \) filters are similar to those of the LSST, and therefore, we used the coefficients calculated for
Table 3. Mid-eclipse times for the primary eclipses of CSS 41177. All ULTRACAM times shown are the weighted averages of the $u'$, $g'$ and $r'$ mid-eclipse times.

| Cycle number | Mid-eclipse time BMJD(TDB) | Sampling time (s) | Telescope/instrument | Observing conditions |
|--------------|----------------------------|-------------------|----------------------|----------------------|
| -3017        | 555 99.087 790(13)         | 13                | LT/RISE              | Clear, seeing 1.8 arcsec |
| -2846        | 556 18.926 645(15)         | 12                | LT/RISE              | Clear, seeing 2.5 arcsec |
| -2544        | 556 53.963 110(18)         | 12                | LT/RISE              | Clear, seeing 3 arcsec |
| -2130        | 557 01.993 5029(77)        | 2–8.2             | NTT/ULTRACAM         | Thin clouds, seeing 1–2 arcsec |
| -309         | 559 13.257 605(22)         | 10                | LT/RISE              | Clear, seeing 1.5 arcsec |
| -44          | 559 44.001 6959(49)        | 3–6               | WHT/ULTRACAM         | Thin clouds, seeing 1–3 arcsec |
| -43          | 559 44.117 7028(65)        | 3–6               | WHT/ULTRACAM         | Thin clouds, seeing 1.5–3.5 arcsec |
| -42          | 559 44.233 727(10)         | 3–6               | WHT/ULTRACAM         | Clouds, seeing 3–10 arcsec |
| -34          | 559 45.161 8417(55)        | 1.5–3             | WHT/ULTRACAM         | Clear, seeing 2 arcsec |
| -33          | 559 45.277 8858(53)        | 1.5–3             | WHT/ULTRACAM         | Some small clouds, seeing 2–7 arcsec |
| -16          | 559 47.250 1251(62)        | 1.5–3             | WHT/ULTRACAM         | Thin clouds, seeing 2–4 arcsec |
| -8           | 559 48.178 2455(38)        | 2–4               | WHT/ULTRACAM         | Clear, seeing 1–2 arcsec |
| -7           | 559 48.294 2481(58)        | 2–4               | WHT/ULTRACAM         | Cloud during egress, seeing 1–5 arcsec |
| -1           | 559 48.990 3480(47)        | 2–4               | WHT/ULTRACAM         | Clear, seeing 1.2 arcsec |
| 0            | 559 49.106 3669(37)        | 2–4               | WHT/ULTRACAM         | Clear, seeing 1 arcsec |
| 1            | 559 49.222 3834(39)        | 2–4               | WHT/ULTRACAM         | Clear, seeing 1 arcsec |
| 3077         | 563 06.085 857(15)         | 10                | LT/RISE              | Clear, seeing 2 arcsec |
| 3259         | 563 27.200 698(16)         | 10                | LT/RISE              | Clear, seeing 2 arcsec |
| 3568         | 563 63.049 447(13)         | 10                | LT/RISE              | Thin clouds during ingress, seeing 2 arcsec |

Table 4. Parameters of the binary and both white dwarfs, where the numbers in parentheses indicate the uncertainty in the last digit(s). The second and third column list the results from the analysis of the spectroscopic and photometric data (see Section 3). The last two columns shows the results from two more MCMC analyses, where the limb-darkening coefficients (ldc) have been multiplied by 1.05 (fourth column) and where $T_1$ has been fixed (fifth column).

| Parameter | Spectroscopy | MCMC analysis | MCMC with ldc*1.05 | MCMC with fixed $T_1$
|-----------|--------------|---------------|--------------------|------------------|
| $T_0$ (BMJD(TDB)) | – | 559 36.344 6719(6) | 559 36.344 6719(6) | 559 36.344 6720(6) |
| $P_{orb}$ (d) | – | 0.116 015 4352(15) | 0.116 015 4352(15) | 0.116 015 4351(15) |
| $a$ (R$_\odot$) | – | 0.886(14) | 0.886(14) | 0.888(14) |
| $i$ (deg) | – | 88.97(2) | 88.96(2) | 88.95(2) |
| $\delta$ (s) | – | -0.79(24) | -0.80(25) | -0.78(25) |
| $M_1$ (M$_\odot$) | – | 0.378(23) | 0.378(23) | 0.381(23) |
| $M_2$ (M$_\odot$) | – | 0.316(11) | 0.316(11) | 0.317(11) |
| $R_1$ (R$_\odot$) | – | 0.022 24(41) | 0.022 27(41) | 0.022 20(41) |
| $R_2$ (R$_\odot$) | – | 0.020 66(42) | 0.020 66(42) | 0.020 87(42) |
| $T_1$ (K) | – | 24 362(652) | 24 362(652) | 21 100 |
| $T_2$ (K) | – | 11 664(311) | 11 664(311) | 10 436(21) |
| log($g_1$) | – | 7.321(15) | 7.319(15) | 7.325(15) |
| log($g_2$) | – | 7.307(11) | 7.307(11) | 7.300(11) |
| $K_1$ (km s$^{-1}$) | – | 176.1(1.1) | – | – |
| $K_2$ (km s$^{-1}$) | – | 210.4(6.1) | – | – |
| $\gamma$ (km s$^{-1}$) | – | 130.5(0.7) | – | – |
| Minimum $\chi^2$ | – | 44 457 | 44 457 | 44 482 |

these LSST filters. We also computed the central specific intensities for these three filters.

For a given temperature and surface gravity, we used a bilinear interpolation between the closest values to calculate all four coefficients and the central specific intensity. These then allowed us to determine the total specific intensity of the white dwarfs, depending on where they are in their orbit and on the fraction of each annulus visible. The total specific intensity\(^3\) is related to the binary’s flux\(^4\) by a constant, $\alpha$, which we calculated during the MCMC by minimizing the difference between the flux defined by the SDSS magnitudes for CSS 41177 and the product of the total specific intensity with $\alpha$. The constant is related to the solid angle the binary subtends as

$$\alpha = a^2/D^2,$$

where $a$ is the binary’s orbital separation and $D$ is the distance to the binary, allowing us to effectively measure the distance from our light curves. For our three filters, the resulting distances are $D_u = 481 \pm 37$ pc, $D_r = 473 \pm 35$ pc and $D_g = 464 \pm 34$ pc. These give an inverse variance weighted value of $D = 473 \pm 35$ pc, with the quoted error similar to those for the individual distances. We believe these errors to be dominated by the uncertainties in the SDSS

\(^3\) In units of erg s$^{-1}$ cm$^{-2}$ Hz$^{-1}$ sr.
\(^4\) In units of erg s$^{-1}$ cm$^{-2}$ Hz$^{-1}$ sr.

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magnitudes, which is why a weighted error would overestimate the precision with which we can determine the distance. These values are significantly higher than the distance quoted in Parsons et al. (2011), a natural result due to the fact that we also obtained higher temperatures for both white dwarfs.

The calculations in Gianninas et al. (2013) are based on 1D white dwarf models. Tremblay et al. (2013) have recently shown that the standard 1D mixing-length theory overpredicts surface gravities and, to a lesser extent, temperatures, especially near the values we found for the cooler white dwarf. To assess the effect of using 1D models, we compared a 1D and an averaged 3D intensity profile, using a temperature and surface gravity representative of the cooler white dwarf. Full 3D and averaged 3D spectral synthesis produce very similar results at all wavelengths (Tremblay et al. 2011), and so the averaged 3D approximation, where the average is performed over constant Rosseland optical depth, is likely to be appropriate for the present study. We found the difference between the two profiles is a factor of 1.05 in the limb-darkening coefficients. Running a separate MCMC analysis in which we multiplied each limb-darkening coefficient by 1.05, showed that the effect on our values for the parameters is much less than the statistical uncertainty in the parameters (Table 4, column 4).

4 DISCUSSION

4.1 Details of the binary orbit

For an eclipsing binary on a circular orbit, it is often assumed that the primary and secondary eclipses occur exactly half an orbital cycle after one another. However, this is not the case if the two binary components are of unequal mass. The changing distance to the stars at times of eclipses and the finite speed of light cause a shift in the phase of the secondary eclipse. While modelling our light curve, we allowed for such a time shift, and found an indication of a small displacement of $\delta = -0.79 \pm 0.24$. For CSS 41177, we theoretically expect the Römer delay to be $\delta_R = P(K_2 - K_1)/\pi c = 0.36 \pm 0.08$ s (Kaplan 2010), so that the secondary eclipse occurs slightly after phase 0.5. The fact that we measure a delay of the opposite sign to that expected, and that our measurement is $4.6\sigma$ away from the theoretical prediction indicates that there may be another process at work.

The measured time delay could be the result of a small eccentricity of the binary’s orbit, in which case we can use the measured time delay to constrain the eccentricity. With $\delta = 2P e \cos(\omega)/\pi$ (Kaplan 2010; Winn 2010), where $\omega$ is the argument of pericentre, we obtain an eccentricity of $e \cos(\omega) = -(1.24 \pm 0.38) \times 10^{-4}$, which is a lower limit on the eccentricity. Although not extremely significant, it is certainly possible that the binary did not emerge from the last common envelope phase on a completely circular orbit, or that small perturbations have been induced into the binary’s orbit by a third body.

We tried to confirm the measurement of a small eccentricity by fitting the primary white dwarf’s radial velocity curve. The result is consistent with an eccentricity of zero, with a $3\sigma$ upper limit at 0.034. However, this limit is weak compared to the value of $e \cos(\omega)$, which is more than 100 times smaller.

The only other precise eccentricity measurement in an eclipsing double white dwarf binary (NLTT 11748) is consistent with a circular orbit, and the measured Römer delay for this system agrees with the expected value (Kaplan et al. 2014).

If the CSS 41177 binary orbit is indeed eccentric, apsidal precession will occur. Tidal deformation and rotational distortions of both stars and relativistic processes all contribute to the apsidal precession (Sterne 1939; Valsecchi et al. 2012). The relativistic apsidal precession amounts to 5.6 deg yr$^{-1}$, compared to which the precession rates due to tides and rotation are negligible.

Due to gravitational wave emission the white dwarfs will eventually merge. We calculate the merger time to be $\tau_m = 1.14 \pm 0.07$ Gyr (Marsh, Dhillon & Duck 1995, section 4.3).

4.2 Masses, radii and hydrogen envelopes

Typical white dwarf surface gravities are high enough to force elements heavier than hydrogen and helium to settle out of the photosphere on time-scales much shorter than evolutionary time-scales (Paquette et al. 1986; Koester 2009). As a result, all heavy elements sink below the white dwarf’s photosphere, leaving the light elements to form the outer layers. The two low-mass helium white dwarfs in CSS 41177 have hydrogen envelopes, and are therefore classified as DA white dwarfs.

Fig. 3 shows the results from our MCMC analysis for the masses and radii of both white dwarfs, as 68 and 95 percentile joint confidence regions. Also shown in Fig. 3 are mass–radius relations for hydrogen envelope masses of $10^{-4}$ (solid lines) and $10^{-5}$ (dashed lines) of the stellar mass, $M_*$, for both white dwarf temperatures (Benvenuto & Althaus 1998). Our results are in good agreement with both relations, but may favour a low-mass hydrogen envelope for the higher mass and hotter white dwarf. Observational studies of pulsating white dwarfs suggest that the hydrogen content can be several orders of magnitude smaller than the standard prediction of stellar evolution of $10^{-4} M_*$, see Bradley (2001, table 1). However, note that those listed white dwarfs are all of significantly higher mass than the CSS 41177 white dwarfs.

The current state of affairs is displayed in Fig. 4, which shows all highly accurate white dwarf masses and radii, determined independently of mass–radius relations. The two CSS 41177 white dwarfs (numbered 1 and 2) fall in an area of the mass–radius diagram that has hardly been explored so far, and supply new tests for the theoretical mass–radius relations at low white dwarf masses. In general, the measurements agree reasonably well with the models. Note that the solid and dashed grey mass–radius relations are for temperatures of $T_{\text{eff}} = 24500$ and 11500 K (upper and lower curves), and that
the two notable outliers are both white dwarfs that are significantly hotter (CSS 03170: Parsons et al. 2012b and NN ser: Parsons et al. 2010).

Using the same models by Benvenuto & Althaus (1998), we determined the cooling age for the hotter white dwarf to be ~50 Myr. The cooler white dwarf is substantially older at ~330 Myr.

In general, there is good agreement that double white dwarf binaries like CSS 41177 go through two phases of mass transfer during their evolution, the second of which is thought to result in a common envelope phase. The nature of the first is less certain, but was most likely a common envelope or stable Algol-like mass transfer (Iben, Tutukov & Yungelson 1997). Different binary population synthesis codes agree that both of these evolutionary paths could produce the final CSS 41177 parameters (Toonen et al. 2013, figs A.22 and A.24). Under conservative mass transfer, Algol evolution may lead to too small a final orbital separation. Therefore, stable non-conservative mass transfer (Woods et al. 2012), or a common envelope following the $\gamma$-prescription (Nelemans et al. 2000) could be a more accurate description of the first phase of mass transfer.

### 4.3 White dwarf pulsations

In the method explained in Section 3, we effectively measured the white dwarf temperatures from the depths of the eclipses in the different bands and the temperature-dependent specific intensities from Gianninas et al. (2013). With this approach the temperatures determined are independent of both the SDSS spectrum and model spectra, which formed the basis of the temperatures derived by Parsons et al. (2011). In contrast to their results, we obtain somewhat higher values for both white dwarf temperatures. This is, at least in part, due to the fact that they did not include the effect of reddening.

The SDSS spectrum and a group of representative models from our MCMC analysis are plotted in Fig. 5, with reddening accounted for. The model spectra show that we overestimate the GALEX far-UV flux, indicating that our white dwarf temperatures may be too high. To assess how this influences our conclusions on the masses and radii, we ran an additional MCMC analysis in which we fixed the temperature of the hotter white dwarf to $T_1 = 21100$ K, the value found in Parsons et al. (2011). The results are shown in the last column of Table 4. As expected, the temperature of the cooler white dwarf is also reduced, but the effect on other parameters is well within the uncertainties.

The results from our light-curve analysis place the cooler, secondary white dwarf very close to the blue edge of the DA white dwarf instability strip, and the results from our analysis with the fixed low $T_1$ places it near the red edge of the strip, so we looked for signs of pulsations in the light curve. We inspected the 2012 January data, excluding the single primary eclipse observation from 2011 May to avoid artificial low-frequency signals. Looking at the out-of-eclipse data, we did not find any pulsations with an amplitude exceeding 3.0, 1.0 and 1.1 mmag in the $u'$, $g'$ and $r'$ band. However, the secondary white dwarf’s contribution to the flux is strongly diluted by the presence of the primary white dwarf and the flux ratios differ in the three bands. For the $u'$, $g'$ and $r'$ band, the primary to secondary flux ratios are 7.7, 4.3 and 3.5, respectively. Correcting for the flux dilution this translates to a non-detection of pulsations with an amplitude exceeding 26.1, 5.3 and 5.0 mmag in the $u'$, $g'$ and $r'$ band.

The contribution of the secondary to the total amount of flux is highest in the $r'$ band, but white dwarf pulsation amplitudes for non-radial modes increase towards bluer wavelengths. For the $l = 1$
Comparison of observed and model spectra of CSS 41177. The broad light grey line shows 100 different overlapping models, randomly chosen from our MCMC analysis. Each consists of a combination of two white dwarf model spectra corresponding to the MCMC parameters. The total model is scaled to the dereddened \( g' \)-band SDSS magnitude (\( m_g = 17.14 \)) and an interstellar extinction of \( E(B-V) = 0.0339 \) (Schlegel, Finkbeiner & Davis 1998) is taken into account using the expressions presented in Seaton (1979) and Howarth (1983). The dark grey line shows the observed SDSS spectrum, and the black dots indicate the \textit{GALEX} far-UV, \textit{GALEX} near-UV and SDSS \( u' \), \( g' \), \( r' \), \( i' \) and \( z' \) fluxes (from left to right; error bars too small to be seen).

Figure 6. ZZ Ceti diagram, showing the position of the cooler secondary white dwarf in CSS 41177, both from our standard analysis and from our analysis with a fixed low value for \( T_1 \) put the secondary at the red edge. Because Parsons et al. (2011) did not account for reddening, the temperatures they derived are an underestimate and the secondary will be somewhat hotter than shown with the star in Fig. 6, placing it even inside the current empirical instability strip.

Note that the data we have are not ideally suited to search for pulsations, due to the brief sections of out-of-eclipse data. With continuous observations spanning several orbital periods one could push the limit further down, or possibly detect small amplitude pulsations.

4.4 Orbital period variations

Fig. 7 shows the mid-eclipse times of the primary eclipses in an observed minus calculated (\( O-C \)) diagram, where the calculation is based on the linear ephemeris in equation (6). All our ULTRACAM and LT/RISE data are included. For the ULTRACAM data, we show the weighted mean of the \( u' \), \( g' \) and \( r' \) data. All eclipse times are listed in Table 3.

This binary is an ideal target for eclipse timing, a method which can be used to detect the presence of circumbinary planetary-like companions (see for example Beuermann et al. 2010; Potter et al. 2011; Beuermann, Dreizler, & Hessman 2013; Marsh et al. 2013). This is because the orbital decay through gravitational wave radiation is only \( \sim 0.5 \) s over a baseline of 10 yr. Also orbital period variations due to magnetic cycles in the stars (the so-called Applegate’s mechanism, see Applegate 1992) are unlikely, as this mechanism is expected to be extremely weak or non-existent in white dwarfs. Even if the orbit is indeed eccentric, as discussed in Section 4.1, the apsidal precession of the orbit is too slow to cause a noticeable deviation in the eclipse times over a realistic observational baseline.
the eclipse times.

2012 M 10 − 3

on 29 July 2018

for a list of our eclipse times.

M 10 − 3

CSS 41177 white dwarfs are thinner than the commonly assumed hydrogen envelopes. There are signs that the hydrogen layers on both models for the corresponding temperatures and with standard hydrogen layers.

Our results agree with white dwarf models. Additionally, the secondary, cooler white dwarf explores a new region of the ZZ Ceti diagram. Although its temperature and surface gravity put it close to the boundary of the ZZ Ceti instability strip, we found no significant pulsations in the light curve to a limit of roughly 0.5 per cent relative amplitude.

We also found an indication that the secondary eclipse does not occur exactly half an orbital period after the primary eclipse. Although the Rømer delay predicts such an offset, it also predicts that the secondary eclipse will occur later, whereas we measured it to occur early. Therefore, the orbit of the two white dwarfs may be slightly eccentric. To measure this effect more precisely more secondary eclipse observations are needed.

5 CONCLUSIONS

We have presented our high signal to noise observations of CSS 41177 and the analysis of both the spectroscopic and photometric data. The high spectral and temporal resolution and the ULTRACAM observations in three wavelength bands allowed us to accurately model the binary and both white dwarfs, without the need to use mass–radius relations.

The results place these two white dwarfs in a region of the mass–radius diagram that is as yet unexplored; they are the lowest mass white dwarfs with parameters determined without the need to assume a mass–radius relation. Our results agree with white dwarf models for the corresponding temperatures and with standard hydrogen layers. There are signs that the hydrogen layers on both CSS 41177 white dwarfs are thinner than the commonly assumed $M_{\ast} = 10^{-4} M_{\odot}$.

Additionally, the secondary, cooler white dwarf explores a new region of the ZZ Ceti diagram. Although its temperature and surface gravity put it close to the boundary of the ZZ Ceti instability strip, we found no significant pulsations in the light curve to a limit of roughly 0.5 per cent relative amplitude.

We also found an indication that the secondary eclipse does not occur exactly half an orbital period after the primary eclipse. Although the Rømer delay predicts such an offset, it also predicts that the secondary eclipse will occur later, whereas we measured it to occur early. Therefore, the orbit of the two white dwarfs may be slightly eccentric. To measure this effect more precisely more secondary eclipse observations are needed.

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REFERENCES

Applegate J. H., 1992, ApJ, 385, 621
Backhaus U. et al., 2012, A&A, 538, A84
Barstow M. A., Bond H. E., Holberg J. B., Burleigh M. R., Hubeny I., Koester D., 2005, MNRAS, 362, 1134
Benvenuto O. G., Althaus L. G., 1998, MNRAS, 293, 177
Beuermann K. et al., 2010, A&A, 521, L60
Beuermann K., Dreizler S., Hessman F. V., 2013, A&A, 555, A133
Bildsten L., Shen K. J., Weinberg N. N., Nelemans G., 2007, ApJ, 662, L95
Bloomen et al., 2011, MNRAS, 410, 1787
Bradley P. A., 2001, ApJ, 552, 1011
Breedt E., Gänssicke B. T., Marsh T. R., Steeghs D., Drake A. J., Copperware C. M., 2012, MNRAS, 425, 2548
Brown W. R., Kilic M., Hermes J. J., Allende Prieto C., Kenyon S. J., Winget D. E., 2011, ApJ, 737, L23
Casewell S. L., Dobbie P. D., Napiwotzki R., Burleigh M. R., Barstow M. A., Jameson R. F., 2009, MNRAS, 395, 1795
Claret A., 2000, A&A, 363, 1081
Dhillon V. S. et al., 2007, MNRAS, 378, 825
Drapek A. J. et al., 2009, ApJ, 696, 870
Drapek A. J. et al., 2010, preprint (arXiv:1009.3048)
Gianninas A., Bergeron P., Ruiz M. T., 2011, ApJ, 743, 138
Gianninas A., Strickland B. D., Kilic M., Bergeron P., 2013, ApJ, 766, 3
Hermes J. J., Montgomery M. H., Winget D. E., Burleigh M. R., Kilic M., Kenyon S. J., 2012, ApJ, 750, L28
Hermes J. J. et al., 2013a, ApJ, 765, 102
Hermes J. J. et al., 2013b, MNRAS, 436, 3573
Hermes J. J., Kepler S. O., Castanheira B. G., Gianninas A., Winget D. E., Montgomery M. H., Brown W. R., Harrold S. T., 2013c, ApJ, 771, L2
Hobbs G. B., Edwards R. T., Manchester R. N., 2006, MNRAS, 369, 655
Holberg J. B., Barstow M. A., Sion E. M., 1998, ApJS, 119, 207
Holberg J. B., Oswalt T. D., Barstow M. A., 2012, AJ, 143, 88
Howarth I. D., 1983, MNRAS, 203, 301
Iben I., Jr, Tutukov A. V., 1984, ApJS, 54, 335
Iben I., Jr, Tutukov A. V., Yungelson L. R., 1997, ApJ, 475, 291
Kaplan D. L., 2010, ApJ, 714, L108
Kilic M. et al., 2014, ApJ, 780, 167
Kilic M. et al., 2014, MNRAS, in press, doi:10.1093/mnrasl/slt151
Koester D., 2009, A&A, 498, 517
Koester D., 2010, Mem. Soc. Astron. It., 81, 921
Marsh T. R., 2001, MNRAS, 324, 547
Marsh T. R., Dhillon V. S., Duck S. R., 1995, MNRAS, 275, 828
Marsh T. R. et al., 2014, MNRAS, 437, 475
Maxted P. F. L., Marsh T. R., Morales-Rueda L., Barstow M. A., Dobbie P. D., Schreiber M. R., Dhillon V. S., Brinkworth C. S., 2004, MNRAS, 355, 1143
Maxted P. F. L., O’Donoghue D., Morales-Rueda L., Napiwotzki R., Smalley B., 2007, MNRAS, 376, 919
Moffat A. F. J., 1969, A&A, 3, 455
Nelemans G., Verbunt F., Yungelson L. R., Portegies Zwart S. F., 2000, A&A, 360, 1011
Nomoto K., 1982, ApJ, 253, 798
O’Brien M. S., Bond H. E., Sion E. M., 2001, ApJ, 563, 971

Figure 7. Observed minus calculated (O–C) diagram for the primary eclipses of CSS 41177, including our ULTRACAM and LT/RISE data and five eclipse observations from Backhaus et al. (2012, shown in grey). We used the ephemeris from equation (6). The ULTRACAM eclipses were observed in three filters simultaneously, and the times shown here are the weighted averages of these. See Table 3 for a list of our eclipse times.
Paquette C., Pelletier C., Fontaine G., Michaud G., 1986, ApJS, 61, 197
Parsons S. G. et al., 2010, MNRAS, 407, 2362
Parsons S. G., Marsh T. R., Gänsicke B. T., Drake A. J., Koester D., 2011, ApJ, 735, L30
Parsons S. G. et al., 2012a, MNRAS, 420, 3281
Parsons S. G. et al., 2012b, MNRAS, 419, 304
Parsons S. G. et al., 2012c, MNRAS, 426, 1950
Potter S. B. et al., 2011, MNRAS, 416, 2202
Provencal J. L., Shipman H. L., Hog E., Thejll P., 1998, ApJ, 494, 759
Provencal J. L., Shipman H. L., Koester D., Wesemael F., Bergeron P., 2002, ApJ, 568, 324
Pyrzas S. et al., 2012, MNRAS, 419, 817
Renzini A. et al., 1996, ApJ, 465, L23
Robinson E. L. et al., 1995, ApJ, 438, 908
Schlegel D. J., Finkbeiner D. P., Davis M., 1998, ApJ, 500, 525
Schmidt H., 1996, A&A, 311, 852
Seaton M. J., 1979, MNRAS, 187, 73v
Shipman H. L., Provencal J. L., Hog E., Thejll P., 1997, ApJ, 488, L43
Steele I. A. et al., 2004, in Oschmann J. M., Jr, ed., Proc. SPIE Vol. 5489, Ground-Based Telescopes SPIE, Bellingham, p. 679
Steinfadt J. D. R., Kaplan D. L., Shporer A., Bildsten L., Howell S. B., 2010, ApJ, 716, L146
Steinfadt J. D. R., Bildsten L., Kaplan D. L., Fulton B. J., Howell S. B., Marsh T. R., Ofek E. O., Shporer A., 2012, PASP, 124, 1
Sterken C., 2005, in Sterken C., ed., ASP Conf. Ser. Vol. 335, The Light-Time Effect in Astrophysics: Causes and Cures of the O-C Diagram. Astron. Soc. Pac., San Francisco, p. 181
Sterne T. E., 1939, MNRAS, 99, 451
Toonen S., Claeyts J. S. W., Mennekens N., Ruiter A. J., 2013, preprint (arXiv:1311.6503)
Tremblay P.-E., Ludwig H.-G., Steffen M., Bergeron P., Freytag B., 2011, A&A, 531, L19
Tremblay P.-E., Ludwig H.-G., Steffen M., Freytag B., 2013, A&A, 552, A13
Valsecchi F., Farr W. M., Willems B., Deloye C. J., Kalogera V., 2012, ApJ, 745, 137
Vennes S. et al., 2011, ApJ, 737, L16
Verbunt F., Rappaport S., 1988, ApJ, 332, 193
Vernet J. et al., 2011, A&A, 536, A105
Webbink R. F., 1984, ApJ, 277, 355
Weidemann V., 2000, A&A, 363, 647
Whelan J., Iben I., Jr, 1973, ApJ, 186, 1007
Winn J. N., 2010, preprint (arXiv:1001.2100)
Wood M. A., 1992, ApJ, 386, 539
Wood M. A., 1995, in Koester D., Werner K., eds, Lecture Notes in Physics, Vol. 443, White Dwarfs. Springer Verlag, Berlin, p. 41
Woods T. E., Ivanova N., van der Sluys M. V., Chaichenets S., 2012, ApJ, 744, 12
York D. G. et al., 2000, AJ, 120, 1579

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