Post Common Envelope Binaries from SDSS. XV: Accurate stellar parameters for a cool $0.4\,M_\odot$ white dwarf and a $0.16\,M_\odot$ M-dwarf in a 3 h eclipsing binary

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ABSTRACT

We identify SDSS121010.1+334722.9 as an eclipsing post-common-envelope binary, with an orbital period of $P_{\text{orb}} = 2.988$ h, containing a very cool, low-mass, DAZ white dwarf and a low-mass main-sequence star of spectral type M5. A model atmosphere analysis of the metal absorption lines detected in the blue part of the optical spectrum, along with the GALEX near-ultraviolet flux, yields a white dwarf temperature of $T_{\text{eff},WD} = 6000 \pm 200$ K and a metallicity value of $\log[Z/H] = -2.0 \pm 0.3$. The Na i $\lambda\lambda$ 8183.27,8194.81 absorption doublet is used to measure the radial velocity of the secondary star, $K_{\text{sec}} = 251.7 \pm 2.0$ km s$^{-1}$ and Fe i absorption lines in the blue part of the spectrum provide the radial velocity of the white dwarf, $K_{\text{WD}} = 95.3 \pm 2.1$ km s$^{-1}$, yielding a mass ratio of $q = 0.379 \pm 0.009$. Light curve model fitting, using the Markov Chain Monte Carlo (MCMC) method, gives the inclination angle as $i = (79.05^{\circ} - 79.36^{\circ}) \pm 0.15^{\circ}$, and the stellar masses as $M_{\text{WD}} = 0.415 \pm 0.010 \, M_\odot$ and $M_{\text{sec}} = 0.158 \pm 0.006 \, M_\odot$. Systematic uncertainties in the absolute calibration of the photometric data influence the determination of the stellar radii. The radius of the white dwarf is found to be $R_{\text{WD}} = (0.0157 - 0.0161) \pm 0.0003 \, R_\odot$ and the volume-averaged radius of the tidally distorted secondary is $R_{\text{sec,vol,aver}} = (0.197 - 0.203) \pm 0.003 \, R_\odot$. The white dwarf in SDSS1210 is a very strong He-core candidate.

Key words: binaries: close - binaries: eclipsing - stars: fundamental parameters - stars: white dwarfs - stars: late-type - stars: individual: SDSS 121010.1+334722.9

1 INTRODUCTION

Our understanding of stellar structure and evolution leads to the fundamental prediction that the masses and radii of stars obey certain mass-radius (M-R) relations. The calibration and testing of the M-R relations requires accurate and model-independent measurements of stellar masses and radii, commonly achieved with eclipsing binaries (e.g. Andersen 1991; Southworth & Clausen 2007).

Among main-sequence (MS) stars, M-dwarfs of low mass (< 0.3$M_\odot$), are the most ubiquitous. However, few eclipsing low-mass MS+MS binaries are known (e.g. López-Morales 2007; Morales et al. 2004; Cakir & Ibanoglu 2010; Irwin et al. 2010; Dimitrov & Kjurkchieva 2010 and references therein) and have accurate measurements of their masses and radii, affecting the calibration of the low-mass end of the MS-M-R relation. To further complicate matters, existing measurements consistently result in radii up to 15% larger and effective temperatures 400 K or more below the values predicted by theory (e.g. Ribas 2006; López-Morales 2007). This is not only the case for low-mass MS+MS binaries (Bayless & Orosz 2006), but it is also present in field stars

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The situation is similar for white dwarfs, the most common type of stellar remnant. Very few white dwarfs have model-independent measurements of their masses and radii (see Parsons et al. 2010a), and eclipsing WD+MS binaries have only recently been discovered (Steinfadt et al. 2010; Parsons et al. 2011; Brown et al. 2011). Consequently, the finite temperature M-R relation of white dwarfs (e.g. Wood 1995; Panei et al. 2000) remains largely untested by observations (Provencal et al. 1998).

An alternative approach leading to accurate mass and radius measurements for WDs and MS stars is the study of eclipsing WD+MS binaries. Until recently, the population of eclipsing WD+MS binaries had stagnated with only seven systems known (see Pyrzas et al. 2009, for a list), a direct result of the small number of the entire WD+MS binaries sample (see Parsons et al. 2003).

However, in recent years, progress has been made thanks to the Sloan Digital Sky Survey (SDSS; York et al. 2000). A dedicated search for WD+MS binaries contained in the spectroscopic SDSS Data Release 6 (Adelman-McCarthy et al. 2008) and DR7 (Abazajian et al. 2009) yielded more than 1600 systems (e.g. Rebassa-Mansergas et al. 2010), of which \( \sim 1 \) \( \% \) are (short-period) post-common-envelope binaries (PCEBs) (Schreiber et al. 2008). The majority of these PCEBs contain low-mass, late-type M dwarfs (Rebassa-Mansergas et al. 2010), while a large percentage of the WD primaries are of low-mass as well (Rebassa-Mansergas et al. 2011).

A significant fraction of eclipsing systems should exist among this sample of PCEBs. Identifying and studying these eclipsing systems will substantially increase the observational constraints on the M-R relation of both WDs and MS stars. Therefore, we have begun the first dedicated search for eclipsing WD+MS binaries in the SDSS, and 5 new systems have already been published (Nebot Gómez-Morán et al. 2009; but see also Drake et al. 2010 for a complementary sample). SDSS121010.1+334722.9 (henceforth SDSS1210), the subject of this paper, is one of the new systems identified in this search. In what follows, we present our observations (Sec. 2), determine the orbital period and ephemeris (Sec. 3) and analyse the spectrum of the white dwarf (Sec. 4). Radial velocity measurements (Sec. 5) combined with light curve fitting (Sec. 6) lead to the determination of the masses and radii of the binary components (Sec. 7). We also explore the past and future evolution of the system (Sec. 8).

2 TARGET INFORMATION, OBSERVATIONS AND REDUCTIONS

SDSS1210 was discovered by Rebassa-Mansergas et al. (2010) as a WDMS binary dominated by the flux of a low-mass companion with a spectral type M5V, suggesting that the white dwarf must be very cool. Inspecting the Na i \( \lambda \lambda 8183.27,8194.81 \) doublet in the six SDSS sub-spectra\(^\text{1}\), and the host stars of transiting extra-solar planets (Torres 2007).

\(^{1}\) The sub-exposures that are co-added to produce one SDSS spectrum of a given object

Table 1. SDSS coordinates and \( u, g, r, i, z \) magnitudes of the target SDSS1210 and the comparison stars used in the analysis. We also provide the GALEX near-UV magnitude of SDSS1210.

| Star | RA      | Dec     | \( u \) | \( g \) | \( r \) | \( i \) | \( z \) | NUV |
|------|---------|---------|--------|--------|--------|--------|--------|-----|
| T    | 182.54211 | 33.78969 | 18.10  | 16.94  | 16.16  | 14.92  | 14.02  | 20.821 |
| C1   | 182.55470 | 33.76832 | 17.72  | 15.98  | 15.33  | 15.11  | 15.02  |
| C2   | 182.54229 | 33.73406 | 19.95  | 17.33  | 16.01  | 15.33  | 14.94  |
| C3   | 182.62616 | 33.78141 | 16.85  | 15.80  | 15.46  | 15.34  | 15.34  |

\( \text{T} \) is the SDSS1210 target, while \( \text{C1}, \text{C2}, \text{C3} \) are (short-period) post-common-envelope binaries (PCEBs) (Schreiber & Gansicke 2003).

Table 2. Log of the photometric and spectroscopic observations. For the LT observations, we also provide the number of one-hour observing blocks per night.

| Date     | Telescope | Filter/Grating | Exp. [s] | Blocks | Frames | Eclipses |
|----------|-----------|----------------|---------|--------|--------|---------|
| 2009 Apr 01 | LT        | V+R            | 5       | 1      | 708    | 1       |
| 2009 Apr 02 | LT        | V+R            | 5       | 2      | 1416   | 0       |
| 2009 Apr 03 | LT        | V+R            | 5       | 2      | 1416   | 1       |
| 2009 Apr 04 | LT        | V+R            | 5       | 2      | 1416   | 1       |
| 2009 Apr 05 | LT        | V+R            | 5       | 3      | 2124   | 1       |
| 2009 Apr 06 | LT        | V+R            | 5       | 1      | 708    | 1       |
| 2009 Apr 05 | LT        | V+R            | 5       | 2      | 1416   | 1       |
| 2010 Apr 02 | LT        | V+R            | 5       | 1      | 708    | 1       |
| 2010 Apr 18 | LT        | R600B/R1200R   | 900     | -      | 1      | -       |
| 2009 May 02 | LT        | R600B/R1200R   | 900     | -      | 3      | -       |
| 2010 Apr 23 | LT        | R600B/R1200R   | 600     | -      | 1      | -       |
| 2010 May 18 | LT        | R600B/800R     | 900     | 12     | 1      |       |
| 2011 Feb 06 | LT        | V+R            | 5       | 1      | 720    | 1       |
| 2011 Mar 02 | LT        | V+R            | 5       | 1      | 720    | 1       |
| 2011 Apr 02 | LT        | V+R            | 5       | 1      | 720    | 1       |
| 2011 May 08 | LT        | V+R            | 5       | 1      | 720    | 1       |
| 2011 Jul 03 | LT        | V+R            | 5       | 1      | 720    | 1       |

\( \text{LT} \) is the Liverpool Telescope (LT) on La Palma, Canary Islands, equipped with a single wideband \( V+R \) filter (Steele et al. 2004) equipped with a single wideband \( V+R \) filter (Steele et al. 2004). The data were de-biased and flat-fielded in the... with exposure times of 15–30 min taken over the course of three nights, we found large radial velocity variations that strongly suggested an orbital period of a few hours. We obtained time-series photometry of SDSS1210 with a 16-inch telescope equipped with an ST8-XME CCD camera, with the aim to measure the orbital period from the expected ellipsoidal modulation, and immediately detected a shallow eclipse in the light curve. Enticed by this discovery, we scheduled SDSS1210 for additional high-time resolution photometry, using RISE on the Liverpool Telescope (LT), with which a total of 9 eclipses were observed.

Table 1 lists the SDSS coordinates and magnitudes of SDSS1210 and the three comparison stars used in the analysis presented in this paper, while Table 2 summarises our photometric and spectroscopic observations. We note that SDSS1210 has a GALEX (Morrisey et al. 2007) near-ultraviolet (NUV) detection, but no far-ultraviolet (FUV) detection.

2.1 Photometry: LT/RISE

Photometric observations were obtained with the robotic 2.0m Liverpool Telescope (LT) on La Palma, Canary Islands, using the high-speed frame-transfer CCD camera RISE (Steele et al. 2004) equipped with a single wideband \( V+R \) filter (Steele et al. 2008). Observations were carried out in one-hour blocks, using a 2x2 binning mode with exposure times of 5 seconds.

The data were de-biased and flat-fielded in the...
standard fashion within the LT reduction pipeline and aperture photometry was performed using SExtractor (Bertin & Arnouts 1996) in the manner described in Gänside et al. (2004).

A sample light curve is shown in Figure 1. The out-of-eclipse variation is elliptoidal modulation, arising from the tidally deformed secondary.

2.2 Spectroscopy: WHT/ISIS

Time-resolved spectroscopy was carried out at the 4.2 m William Herschel Telescope (WHT) on La Palma, Canary Islands, equipped with the double-armed Intermediate dispersion Spectrograph and Imaging System (ISIS). The spectrograph was used with a 1" slit, and an 600 lines/mm grating (R600B/R600R) on each of the blue and red arms, although a few spectra were obtained with a 1200 lines/mm grating (R1200R). Both the EEV12 CCD on the blue arm and the REDPLUS CCD on the red arm were binned by three in the spatial direction and two in the spectral direction. This setup resulted in an average dispersion of 0.88 Å per binned pixel over the wavelength range 3643 – 5137 Å (blue arm) and 0.99 Å per binned pixel over the wavelength range 7691 – 9184 Å (red arm, R600R). From measurements of the full width at half maximum of arclines and strong skylines, we determine the resolution to be 1.4 Å.

The spectra were reduced using the STARLINK packages KAPPA and FIGARO and then optimally extracted (Horne 1989) using the PAMELA code (Marsh 1989). The wavelength scale was derived from Copper-Neon and Copper-Argon arc lamp exposures taken every hour during the observations, which we interpolated to the middle of each of the science exposures. For the blue arm the calibration was obtained from a 5th order polynomial, to 17 arclines. The RMS determined from a 5th order polynomial fit to 25 lines, with a root mean square (RMS) of 0.029 Å. Wherever the SDSS spectrum of SDSS1210 remained inconclusive with respect to the nature of the white dwarf (Rebassa-Mansergas et al. 2010), our blue-arm WHT spectroscopy immediately revealed a host of narrow metal lines.

### Table 3. Times of mid-eclipse (and their errors), O-C values (and their errors) and cycle number for the ephemeris of SDSS1210. Mid-eclipse times and errors are in MJD(BTDB), O-C values and errors are in seconds.

| Mid-Eclipse [d] | Error [d] | O-C [s] | Error [s] | Cycle |
|----------------|-----------|--------|-----------|-------|
| 54923.0336744  | 0.0000060 | -1     | 1         | 0     |
| 54925.0255324  | 0.0000082 | 1      | 1         | 16    |
| 54926.1459281  | 0.0000069 | -0     | 1         | 25    |
| 54927.1418460  | 0.0000087 | -0     | 1         | 33    |
| 55599.1376175  | 0.0000061 | 3      | 1         | 5431  |
| 55623.0396100  | 0.0000056 | -1     | 1         | 5623  |
| 55654.0375754  | 0.0000081 | -0     | 1         | 5872  |
| 55690.0151216  | 0.0000063 | 1      | 1         | 6161  |
| 55745.9109933  | 0.0000069 | -2     | 1         | 6610  |

3 ORBITAL PERIOD AND EPHEMERIS

We determined the orbital period and ephemeris of SDSS1210 through mid-eclipse timings. This was achieved as follows:

Mid-eclipse times were measured by mirroring the observed eclipse profile around an estimate of the eclipse centre and shifting the mirrored profile against the original until the best overlap was found. This method is particularly well-suited for the box-shaped eclipse profiles in (deeply) eclipsing PCEBs.

An initial estimate of the cycle count was then obtained by fitting eclipse phases $(\phi_0^{\text{observed}} - \phi_0^T)^{-1}$ over a wide range of trial periods. Once an unambiguous cycle count was established, a linear fit, of the form $T = T_0 + P_{\text{orb}} \times E$, was performed to the times of mid-eclipse versus cycle count, yielding a preliminary orbital ephemeris.

Subsequently, we phase-folded our data set using this preliminary ephemeris and proceeded with the light curve model fitting (see Sec. 2). Having an accurate model at hand, we re-fitted each light curve individually. This provides a robust estimate of the error on the mid-eclipse time, as our code includes the time of mid-eclipse $T_0$ as a free parameter.

Repeating the cycle count determination and the linear ephemeris fitting, as described above, we obtain the following ephemeris for SDSS1210,

\begin{align*}
\text{MJD (BTDB)} &= 54923.033686(6) + 0.1244897641(1) \ \text{E} \ (1)
\end{align*}

calculated on a Modified Julian Date-timescale and corrected to the solar system barycentre, with the numbers in parentheses indicating the error on the last digit. Thus, SDSS1210 has an orbital period of $P_{\text{orb}} = 2.987 754 336(24)$ h. The mid-eclipse times, the observed minus calculated values (O-C) and their respective errors are given in Table 3. Given the short baseline, there is as yet no evidence for period changes which are frequently seen in eclipsing PCEBs.

### 4 SPECTROSCOPIC ANALYSIS

Whereas the SDSS spectrum of SDSS1210 remained inconclusive with respect to the nature of the white dwarf (Rebassa-Mansergas et al. 2010), our blue-arm WHT spectroscopy immediately revealed a host of narrow metal lines
that exhibit radial velocity variations anti-phased with respect to those of the M-dwarf. The WHT spectra obtained in May 2010, averaged in the white dwarf restframe and continuum-normalised, are shown in Fig 2 and illustrate the wealth of absorption lines from Mg, Al, Si, Ca, Mn, and Fe. Similar metal lines have been detected in the optical spectra of a few other cool PCEBs, e.g. RR Cae (Zuckerman et al. 2003) or LTT 560 (Tappert et al. 2007), and indicate accretion of mass via a wind from the M-dwarf.

We have analysed the blue WHT spectra using hydrogen-dominated but metal-polluted (DAZ) spectra calculated with the stellar atmosphere code described by Koester (2010). We fixed the surface gravity to log g = 7.70, as determined from the fits to the LT light curve (Sect. 5). The model grid covered effective temperatures 5400 K $\leq T_{\text{eff, WD}} \leq 7400$ K in steps of 200 K and metal and He abundances of log[Z/H] = $-3.0$, $-2.3$, $-2.0$, $-1.3$, $-1.0$, with all relevant elements up to zinc included, and fixed their relative abundances ratios to the respective solar values. We then fitted the model spectra to the average WHT spectrum in the range 3645–3930 Å, where the contribution of the M-dwarf is entirely negligible. A good fit is found for $T_{\text{eff, WD}} \approx 6000$ K and metal abundances at $\approx 0.01$ their solar values, however, the effective temperature and the metal abundances are strongly correlated (Fig. 3).

This degeneracy is lifted by including the GALEX detection of SDSS1210, as the predicted near-UV flux is a strong function of the effective temperature. The uncertainty in the absolute flux calibrations of our WHT spectra and the GALEX observations introduces a small systematic uncertainty on the final result, and we settle for $T_{\text{eff, WD}} = 6000 \pm 200$ K and log[Z/H] = $-2.0 \pm 0.3$. Independently, the weakness of the Balmer lines in the WHT spectrum also requires that $T_{\text{eff, WD}} \lesssim 6400$ K. The spectral modelling of SDSS1210 is illustrated on Fig. 4.

Adopting the white dwarf radius from the light curve fit (Sect. 3 and 7), $R_{\text{WD}} = 0.0159 R_\odot$, the flux-scaling factor of the best-fit spectral model implies a distance of $d \approx 50 \pm 5$ pc, which is in good agreement with $d \sim 66 \pm 34$ pc estimated by Rebassa-Mansergas et al. (2010) from fitting the M-dwarf.

The detection of metals in the photosphere of the white dwarf allows an estimate of the accretion rate (e.g. Dupuis et al. 1993, Koester & Wilken 2006), as long as the system is in accretion-diffusion equilibrium. In cool, hydrogen-rich atmospheres, such as the one in SDSS1210, the diffusion time scales of the different metals detected in the WHT spectrum vary by a factor of $\sim 2$ for a given temperature, and are, for $T_{\text{eff, WD}} = 6000$ K, in the range 30000–60000 years. It is plausible to assume that the average accretion rate over the diffusion time scales involved is constant, as the binary configuration (separation of the two stars, Roche-lobe filling factor of the companion) changes on much longer time scales. Summing up the mass fluxes at the bottom of the convective envelope, and taking into account the uncertainties in $T_{\text{eff, WD}}$ and the metal abundances, gives $\dot{M} \approx (5 \pm 2) \times 10^{-15} M_\odot$ yr$^{-1}$. There are now three PCEBs with similar stellar components that have measured accretion rates, RR Cae ($\dot{M} \approx 4 \times 10^{-16} M_\odot$ yr$^{-1}$; Debes 2006), LTT 560 ($\dot{M} \approx 5 \times 10^{-15} M_\odot$ yr$^{-1}$; Tappert et al. 2011), and SDSS1210 ($\dot{M} \approx 5 \times 10^{-15} M_\odot$ yr$^{-1}$).

Whereas SDSS1210 and LTT 560 have similar orbital periods, the period of RR Cae is roughly twice as long, suggesting that the efficiency of wind-accretion decreases as the binary separation and Roche-lobe size of the companion increase, as is expected. A more systematic analysis of the wind-loss rates of M-dwarfs and the efficiency of wind accretion in close binaries would be desirable, but will require a much larger sample of systems.

4 For completeness, we note that because we have adopted solar abundance ratios for the metals, these small differences in diffusion time scales imply slightly non-solar ratios in the accreting material. In principle, the individual metal-to-metal ratios can be determined from the observed spectrum of the white dwarf, and hence allow to infer the abundances of the companion star, however, this requires data with substantially higher spectral resolution to resolve the line blends.
5 THE SPECTROSCOPIC ORBIT

Radial velocities of the binary components have been measured from the Fe\,I $\lambda\lambda$ 4045.813, 4063.594, 4071.737, 4132.058, 4143.869 absorption lines for the white dwarf and the Na\,I $\lambda\lambda$ 8183.27, 8194.81 absorption doublet for the secondary star.

The Fe\,I lines were simultaneously fitted with a second-order polynomial plus five Gaussians of common width and a separation fixed to the corresponding laboratory values. A sine fit to the radial velocities, phase-folded using the orbital ephemeris (Equation 1) yields $K_{\text{WD}} = 95.3 \pm 2.1$ km s$^{-1}$ and $\gamma_{\text{WD}} = 24.2 \pm 1.4$ km s$^{-1}$.

The Na\,I doublet was fitted with a second-order polynomial plus two Gaussians of common width and a separation fixed to the corresponding laboratory value. A sine fit to the radial velocities, phase-folded using the orbital ephemeris yields $K_{\text{sec}} = 251.7 \pm 2.0$ km s$^{-1}$ and $\gamma_{\text{sec}} = 12.2 \pm 0.9$ km s$^{-1}$.

Figure 5 shows the measured radial velocities phase-folded on the orbital period and the corresponding sine-fits. Knowledge of both radial velocities allows us to obtain the mass ratio $q$ of the binary, namely $q = K_{\text{WD}}/K_{\text{sec}} = 0.379 \pm 0.009$. We tentatively interpret the difference between $\gamma_{\text{WD}}$ and $\gamma_{\text{sec}}$ as the gravitational redshift of the white dwarf $z_{\text{WD,spec}}$, which yields $z_{\text{WD,spec}} = 11.9 \pm 1.7$ km s$^{-1}$ (see also Sec. 7).

6 LIGHT CURVE MODELLING

To obtain the stellar parameters of the binary components, light curve models were fitted to the data using LCURVE (see Copperwheat et al. 2010 for a description, as well as
During the minimisation, we kept $T_{\text{eff, WD}}$ fixed at $T_{\text{eff, WD}} = 6000 \text{ K}$. The gravity darkening of the secondary was also kept fixed at 0.08 (the usual value for a convective atmosphere). Limb darkening coefficients were also held fixed. For the white dwarf we calculated quadratic limb darkening coefficients from a white dwarf model with $T_{\text{eff, WD}} = 6000 \text{ K}$ and $\log g = 7.70$, folded through the RISE filter profile. The corresponding values were found to be $a = 0.174$ and $b = 0.421$ for $I(\mu)/I(1) = 1 - a(1 - \mu) - b(1 - \mu)^2$, with $\mu$ being the cosine of the angle between the line of sight and the surface normal. For the secondary star we used the Tables of Claret & Bloemen (2011). We interpolated between the values of $V$ and $R$ for a $T = 3000 \text{ K}$ and $\log g = 5 \text{ star}$, to obtain quadratic limb darkening coefficients $a' = 0.62$ and $b' = 0.273$. All other parameters were allowed to vary.

### 6.3 Minimisation

Initial minimisation is achieved using the downhill-SIMPLEX and LEVENBERG-MARQUARDT methods (Press 2002), while the Markov Chain Monte Carlo (MCMC) method (Press et al. 2002) was used to determine the distributions of our model parameters (e.g. Ford 2006, and references therein).

The MCMC method involves making random jumps in the model parameters, with new models being accepted or rejected according to their probability computed as a Bayesian posterior probability (the probability of the model parameters, $\theta$, given the data, D, $P(\theta|D)$). $P(\theta|D)$ is driven by a combination of $\chi^2$ and a prior probability, $P(\theta)$, that is based on previous knowledge of the model parameters.

In our case, the prior probabilities for most parameters are assumed to be uniform. The photometric data provide constraints for the radii and inclination angle, however, the photometry alone cannot constrain the masses, as the light curve itself is only weakly dependent on $q$. To alleviate this, we can use our knowledge of $K_{\text{WD}}$ and $K_{\text{sec}}$. At each jump, the model values $K_{\text{WD}}^m$ and $K_{\text{sec}}^m$ are calculated through $q$, $i$ and $V_S$. $P(\theta)$ is then evaluated on the basis of the observed $K_{\text{WD}}$ and $K_{\text{sec}}$, assuming a Gaussian prior probability $P(\mu, \sigma^2)$, with $\mu$ and $\sigma$ corresponding to the measured values and errors of $K_{\text{WD}}$ and $K_{\text{sec}}$.

A crucial practical consideration of MCMC is the number of steps required to fairly sample the parameter space, which is largely determined by how closely the distribution of parameter jumps matches the true distribution. We therefore built up an estimate of the correct distribution starting from uncorrelated jumps in the parameters, after which we computed the covariance matrix from the resultant chain of parameter values. The covariance matrix was then used to define a multivariate normal distribution that was used to make the jumps for the next chain. At each stage the actual size of the jumps was scaled by a single factor set to deliver a model acceptance rate of $\approx 25\%$ (Roberts et al. 1997). After 3 such cycles, the covariance matrix showed only small changes, and at this point we carried out the long “production runs” during which the covariance and scale factor which define the parameter jumps were held fixed.

### 6.4 Stellar parameters

Using the following set of equations, the stellar and binary parameters are obtained directly from the posterior distribution of the model parameters, as outputed from the MCMC minimisation.

The binary separation is obtained from the model parameter $V_S$ through

$$a = \frac{P_{\text{orb}}}{2\pi} \frac{V_S}{2\pi G (1 + q)} V_S^3 \tag{2}$$

The white dwarf and secondary masses are obtained from the model parameters $q$ and $V_S$ as

$$M_{\text{WD}} = \frac{P_{\text{orb}}}{2\pi G} \frac{1}{1 + q} V_S^3 \tag{3}$$

and

$$M_{\text{sec}} = \frac{P_{\text{orb}}}{2\pi G} \frac{q}{1 + q} V_S^3 \tag{4}$$
The stellar radii are directly obtained from the model parameters $r_{\text{WD}}$ and $r_{\text{sec}}$ and Eq. (2) and the surface gravity of the white dwarf is of course given by
\[
\log g = \log \left( \frac{G M_{\text{WD}}}{R_{\text{WD}}^2} \right) \quad (5)
\]

### 6.5 Intrinsic data uncertainties

The acquisition of high-precision absolute photometry on the LT in service mode is somewhat difficult to achieve. Each observing block individually covered only a third of the orbital phase and the blocks were obtained over many nights, under varying conditions (seeing, sky brightness, extinction, airmass). The data are sensitive to changes in conditions, as they have been obtained through the very broad and non-standard V+R filter of RISE. In the absence of a flux standard, the photometry cannot be calibrated in absolute terms. When phase-folding the LT data, significant scatter is found at orbital phases where individual observing blocks with discrepant calibrations contribute. This affects both the shape of the eclipse, mainly the steepness of the WD ingress/egress and, to a lesser extent, the eclipse duration, and the out-of-eclipse variation, i.e. the profile of the ellipsoidal modulation. As a result, there is an unavoidable systematic uncertainty in the photometric accuracy of our data, which will influence the determination of the stellar parameters.

To gauge the effect of the systematic uncertainties we worked in the following fashion: each observing block has been reduced thrice, each time using one of the three comparison stars reported in Table 1: C1 has a $g-r$ colour index comparable to SDSS1210, C2 is fairly red, while C3 is fairly blue. The data of each reduction were then phase-folded together and two light curves were produced: one containing all the photometric points and one where (2-3) observing blocks with an obviously large intrinsic scattering were omitted. Thus, we ended up with six phase-folded light curves. A dedicated MCMC optimisation was calculated for each light curve. We will use the following notation when referring to these chains: C1A denotes a light curve produced with comparison star C1 and all data points, C2E denotes a light curve produced with comparison star C2 excluding observing blocks, and so on.

### 7 RESULTS

The results of the six MCMC processes are summarised in Table 1. The quoted values and errors are purely of statistical nature and represent the mean and RMS of the posterior distribution of each parameter. The radius of the secondary, as determined by $r_{\text{sec}}$ and $a$, is measured along the line connecting the centres of the two stars and, due to the tidal distortion, its value is larger than the average radius. Therefore, on Table 1, we also report the more representative value of the volume-averaged radius.

To illustrate the achieved quality of the fits, we plot models C1A and C1E in Figure 6. While the overall quality of the fit is very satisfactory, the model seems to slightly overpredict the flux at the “wings” of the ellipsoidal modulation profile (phases $\sim 0.05 - 0.15$ and $\sim 0.85 - 0.95$).

**Figure 7.** Mass-radius plot for white dwarfs. Black points are data from Provencal et al. (1998), Provencal et al. (2002) and Casewell et al. (2009). The dotted line is the zero-temperature mass-radius relation of Eggleton as quoted in Verbunt & Rappaport (1988). The dashed line, marked as (He,6) is a M-R relation for a $T_{\text{eff}}$,WD = 6000 K, He-core WD, with a hydrogen layer of $M(\text{H})/M_{\text{WD}} = 3 \times 10^{-4}$, interpolated from the models of Althaus & Benvenuti (1992). NN Ser (Parsons et al. 2010a) is marked, along with the track for $T_{\text{eff}}$,WD = 6000 K, C/O-core WD, $M(\text{H})/M_{\text{WD}} = 10^{-4}$ (long dash-dot line), indicating the accuracy obtained in eclipsing PCEBs. The results of the six chains for SDSS1210 are plotted in red (online version only). Inset panel: zoom-in on the values of SDSS1210. The points are C1A: open circle; C1E: filled circle; C2A: open square; C2E: filled square; C3A: open triangle; C3E: filled triangle.

This discrepancy could be data related, due to the intrinsic scattering of points; system related, e.g. due to the presence of starspots affecting the modulation; model related, as the treatment of stellar temperatures is based on blackbody spectra, for one specific wavelength; or due to a combination of these factors.

With regard to the binary and stellar parameters, the MCMC results indicate the following: as expected for a detached system, the light curves depend very weakly on $q$ and its value is well constrained by the radial velocities. All six chains give inclination angle values just above 79°, consistent with each other within the errors. There is a slight shift upwards when excluding blocks from the phase-folded light curve.

The tight spectroscopic constraints, mean that the component masses are largely independent of the model/data set used. Thus, the white dwarf in SDSS1210 has a mass of $M_{\text{WD}} = 0.415 \pm 0.010 M_{\odot}$ and the secondary star a mass of $M_{\text{sec}} = 0.158 \pm 0.006 M_{\odot}$.

The quantity most seriously affected by systematics is the white dwarf radius. This is especially evident when considering models C3A and C3E. However, such a discrepancy is expected, since C3 is considerably bluer than SDSS1210 and is more susceptible to airmass/colour effects, leading to large intrinsic scattering. The values for $R_{\text{WD}}$ as obtained from C1A, C1E, C2A and C2E are consistent within their errors, indicating a systematic uncertainty comparable to the statistical one. This is illustrated in Figure 7.

The secondary star radius is affected in a similar, albeit less pronounced, way. All six models lead to values broadly...
consistent within their statistical errors and a systematic uncertainty of the same order as the statistical one. Figure 6 shows the six different values of the volume-averaged secondary star radius overplotted on a M-R relation for MS stars. Taken at face value, the results of the MCMC optimisation indicate that the secondary is ~ 10 percent larger than theoretically predicted. As can be seen in Figure 6, this discrepancy drops to ~ 5 percent, if magnetic activity of the secondary is taken into account. With regard to the secondary temperature, we note again that due to the black-

Table 4. Stellar and binary parameters obtained from MCMC optimisation. The quoted values and errors are the mean and RMS of the posterior distribution of each parameter. The chains represent light curves created using comparison stars C1, C2 or C3 and either including all (A) observing blocks or excluding (E) those with obviously large scattering. See text for details.

| Parameter                  | C1A       | C1E       | C2A       | C2E       | C3A       | C3E       |
|----------------------------|-----------|-----------|-----------|-----------|-----------|-----------|
| q                          | 0.380 ± 0.010 | 0.380 ± 0.010 | 0.381 ± 0.010 | 0.380 ± 0.010 | 0.378 ± 0.010 | 0.379 ± 0.010 |
| i [°]                      | 79.05 ± 0.15  | 79.28 ± 0.15  | 79.03 ± 0.15  | 79.13 ± 0.15  | 79.36 ± 0.18  | 79.29 ± 0.16  |
| $M_{\text{WD}}$ [M$_{\odot}$] | 0.415 ± 0.010 | 0.414 ± 0.010 | 0.415 ± 0.010 | 0.415 ± 0.010 | 0.414 ± 0.010 | 0.414 ± 0.010 |
| $R_{\text{WD}}$ [R$_{\odot}$] | 0.0157 ± 0.0003 | 0.0159 ± 0.0003 | 0.0161 ± 0.0003 | 0.0159 ± 0.0003 | 0.0138 ± 0.0003 | 0.0150 ± 0.0003 |
| WD log $g$                  | 7.664 ± 0.015  | 7.652 ± 0.016  | 7.641 ± 0.015  | 7.649 ± 0.017  | 7.773 ± 0.023  | 7.700 ± 0.019  |
| $M_{\text{sec}}$ [M$_{\odot}$] | 0.158 ± 0.006  | 0.157 ± 0.006  | 0.158 ± 0.006  | 0.158 ± 0.006  | 0.156 ± 0.007  | 0.157 ± 0.006  |
| $R_{\text{sec}}$ [R$_{\odot}$] | 0.217 ± 0.003  | 0.212 ± 0.003  | 0.217 ± 0.003  | 0.215 ± 0.003  | 0.210 ± 0.004  | 0.211 ± 0.003  |
| $R_{\text{sec,vol,aver}}$ [R$_{\odot}$] | 0.202 ± 0.003  | 0.199 ± 0.003  | 0.203 ± 0.003  | 0.201 ± 0.003  | 0.197 ± 0.003  | 0.198 ± 0.003  |
| $T_{\text{sec}}$ [K]       | ∼ 2530    | ∼ 2550    | ∼ 2530    | ∼ 2550    | ∼ 2500    | ∼ 2550    |
| Binary separation [R$_{\odot}$] | 0.871 ± 0.008  | 0.870 ± 0.008  | 0.871 ± 0.008  | 0.871 ± 0.008  | 0.869 ± 0.008  | 0.870 ± 0.008  |

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The results of the six chains for the volume-averaged radius of the secondary in SDSS1210 are plotted in red (online version only). Inset panel: zoom-in on the values of SDSS1210. The points are C1A: open circle; C1E: filled circle; C2A: open square; C2E: filled square; C3A: open triangle; C3E: filled triangle.

body approximation, the value of $T_{\text{sec}}$ does not necessarily represent the true temperature of the star, it is effectively just a flux scaling factor.

The gravitational redshift predicted by the light curve models (Table 4), correcting for the redshift of the secondary star, the difference in transverse Doppler shifts and the potential at the secondary star owing to the white dwarf, are $z_{\text{WD}} = 15.9 \pm 0.4 \text{ km s}^{-1}$ from C1E and $z_{\text{WD}} = 15.8 \pm 0.4 \text{ km s}^{-1}$ from C2E, where the errors are purely statistical and have been derived in the same manner as the other quantities reported in Table 4. The systematic uncertainties in our photometric data might still be influencing the result, as the inclination angle and the stellar radii enter the calculation of $z_{\text{WD}}$. Comparing $z_{\text{WD}}$ with the spectroscopically determined value of $z_{\text{WD,spec}} = \gamma_{\text{WD}} - \gamma_{\text{sec}} = 11.9 \pm 1.7 \text{ km s}^{-1}$ we find that they are consistent within $\sim 2\sigma$. The systemic velocities $\gamma_{\text{WD}}$ and $\gamma_{\text{sec}}$ are determined from spectroscopic observations obtained using a dual-arm spectrograph, with the white dwarf velocity measured in the blue arm and that of the secondary measured in the red arm (Sec 2). The observations in both arms are independently wavelength-calibrated and the RMS of $\sim 0.03 \text{ A}$ (Sec 2) corresponds to an accuracy of the zero-point of $\sim 1 - 2 \text{ km s}^{-1}$. The potential of an offset in the calibrations of the two arms enters the determination of $z_{\text{WD,spec}}$ as an additional systematic uncertainty.

8 PAST AND FUTURE EVOLUTION OF SDSS1210

Considering its short orbital period, SDSS1210 must have formed through common-envelope evolution (Paczynski 1976; Webbink 2008). As shown by Schreiber & Gänsicke (2003), if the binary and stellar parameters are known, it is possible to reconstruct the past and predict the future evolution of PCEBs for a given angular momentum loss prescription. Here, we assume classical disrupted magnetic braking (Verbunt & Zwaan 1981). In this context, given the low mass of the secondary, the only angular momentum loss mechanism for SDSS1210 is gravitational radiation. Based on the temperature and the mass of the white dwarf we interpolate the cooling tracks of Althaus & Benvenuto (1997) and obtain a cooling age of $t_{\text{cool}} = 3.5 \text{ Gyr}$. This corresponds to the time that passed since the binary left the common envelope. We calculate the period it had when it left the common envelope to be $P_{\text{CE}} = 4.24 \text{ h}$. Following the same method as in Zorotovic et al. (2010) and based on their results we reconstructed the initial parameters of the system using a common-envelope efficiency of $\alpha_{\text{CE}} = 0.25$ and the same fraction of recombination energy (see Zorotovic et al. 2010, for more details). We found an initial mass of $M_{\text{prog}} = 1.33 M_\odot$ for the progenitor of the white dwarf, which filled its Roche lobe when its radius was $R_{\text{prog}} = 91.3 R_\odot$. At that point, the orbital separation was $a = 162.7 R_\odot$, and the age of the system was $t_{\text{sys}} = 4.4 \text{ Gyr}$, since the time it was formed. Using the radius of the secondary we calculate that the system will reach a semidetached configuration and become a cataclysmic variable (CV) at an orbital period of $P_{\text{sd}} \sim 2 \text{ h}$ in $t_{\text{ad}} = 1.5 \text{ Gyr}$.

Given that the current $P_{\text{orb}}$ places SDSS1210 right at the upper edge of the CV orbital period gap and that the calculated $P_{\text{sd}}$ when SDSS1210 will start mass-transfer, is right at the lower edge of the period gap, we are tempted to speculate whether SDSS1210 is in fact a detached CV entering (or just having entered) the period gap. Davis et al. (2008) have shown that a large number of detached WD+MS binaries with orbital periods between 2-3 hours are in fact CVs that have switched off mass-transfer and are crossing the period gap. This could in principle explain the apparently over-sized secondary in SDSS1210, as expected from the disrupted magnetic braking theory (e.g. Rappaport et al. 1983). However, the temperature of the white dwarf in SDSS1210 seems to be uncomfortably low for a WD that has recently stopped accreting (Townsend & Gmsccke 2004).

9 DISCUSSION AND CONCLUSIONS

In this paper, we have identified SDSS1210 as an eclipsing PCEB containing a very cool, low-mass, DAZ white dwarf and a low-mass main-sequence companion.

Using combined constraints from spectroscopic and photometric observations we have managed to measure the fundamental stellar parameters of the binary components. Systematic uncertainties in the absolute calibration of our photometric data, influence the determination of the stellar radii. The stellar masses, however, remain unaffected and were measured to a 1% accuracy. The formal statistical uncertainties in all binary parameters indicate the level of

$\sigma_{\text{sec,vol.aver.}} = 0.2 R_\odot$ for the volume-averaged radius of the secondary

$\sigma_{\text{spec}} = 0.03 \text{ A}$ (Sec 2) corresponds to an accuracy of the zero-point of $\sim 1 - 2 \text{ km s}^{-1}$. The potential of an offset in the calibrations of the two arms enters the determination of $z_{\text{WD,spec}}$ as an additional systematic uncertainty.
Table 5. Adopted stellar and binary parameters for SDSS1210.

| Parameter          | Value                           |
|--------------------|---------------------------------|
| $P_{\text{orb}}$ [d] | 0.124489764(1)                  |
| $g$                | 0.379 ± 0.009                   |
| $a$ [R$_{\odot}$]  | 0.870 ± 0.008                   |
| Inclination [°]    | $(79.05 - 79.36) ± 0.15$       |
| $M_{\text{WD}}$ [M$_{\odot}$] | 0.415 ± 0.010           |
| $R_{\text{WD}}$ [R$_{\odot}$] | (0.0157 - 0.0161) ± 0.0003   |
| log $g$            | 7.65 ± 0.02                     |
| $T_{\text{eff, WD}}$ [K] | 6000 ± 200                      |
| $K_{\text{WD}}$ [km s$^{-1}$] | 95.3 ± 2.1                    |
| $M_{\text{acc}}$ [M$_{\odot}$] | 0.158 ± 0.006                  |
| $R_{\text{sec}}$ [R$_{\odot}$] | (0.210 - 0.217) ± 0.003       |
| $R_{\text{sec,vol,aver}}$ [R$_{\odot}$] | (0.197 - 0.203) ± 0.003      |
| $K_{\text{sec}}$ [km s$^{-1}$] | 251.7 ± 2.0                    |

precision that can be achieved in this system. All parameters are summarised in Table 5.

With a mass of $M_{\text{WD}} = 0.415 ± 0.010$ M$_{\odot}$ and a temperature of $T_{\text{eff, WD}} \sim 6000$ K, the DAZ white dwarf in SDSS1210 pushes the boundaries in a hitherto unexplored region of the WD parameter space. The M-R results from the four Chains C1 and C2 are consistent with a He-core WD, assuming a hydrogen layer of $M(\text{H})/M_{\text{WD}} = 3 \times 10^{-4}$. However, due to lack of observational constraints for the H-layer thickness and the uncertainty in the radii, we will defer identifying the WD as a definite He-core and simply emphasise the strong candidacy.

The secondary star, with a mass of $M_{\text{sec}} = 0.158 ± 0.006$ M$_{\odot}$, illustrates once more the excellent opportunity that PCEBs give us for testing and calibrating the M-R relations of low-mass stars. Taking the radius measurements at face value, the secondary star seems to be $\sim 10$ percent larger than the theoretical values, although this drops to $\sim 5$ percent, if magnetic activity is taken into consideration. In this context, the magnetic activity present in the secondary can lead to the formation of stellar (dark) spots on the surface. The effect of these spots is to block the outgoing heat flux, reducing $T_{\text{eff}}$ and, as a result, the secondary expands to maintain thermal equilibrium (Chabrier et al. 2007; Morales et al. 2010). Kraus et al. (2011) found that low-mass stars in short period binaries appear to be overinflated (although their analysis was restricted to $M_{\text{sec}} > 0.3$ M$_{\odot}$), which seems to be the case for SDSS1210. We should note however, that the mass and radius of the secondary star in the eclipsing PCEB NN Ser (with $M_{\text{sec}} = 0.111 ± 0.004$ M$_{\odot}$ and comparable orbital period to SDSS1210) is consistent with theoretical M-R predictions, even though it is heavily irradiated by the hot WD primary (Parsons et al. 2010b).

We have speculated whether SDSS1210 is in fact a detached CV entering the period gap, which could explain the large radius of the secondary. This hypothesis could be tested by measuring the rotational velocity of the white dwarf. This can be achieved through high-resolution spectroscopy of the FeI absorption lines in the WD photosphere (see e.g. Tappert et al. 2011).

In any case, it is highly desirable to improve the measurement of the stellar radii in SDSS1210 to the comparable precision to the masses presented here. This will require high-precision photometry in standard filters, such as e.g. delivered by ULTRACAM (Dhillon et al. 2007).

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