

# The relativistic pulsar–white dwarf binary PSR J1738+0333 – I. Mass determination and evolutionary history

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## ABSTRACT

PSR J1738+0333 is one of the four millisecond pulsars known to be orbited by a white dwarf companion bright enough for optical spectroscopy. Of these, it has the shortest orbital period, making it especially interesting for a range of astrophysical and gravity related questions. We present a spectroscopic and photometric study of the white dwarf companion and infer its radial-velocity curve, effective temperature, surface gravity and luminosity. We find that the white dwarf has properties consistent with those of low-mass white dwarfs with thick hydrogen envelopes, and use the corresponding mass–radius relation to infer its mass;  $M_{\text{WD}} = 0.181^{+0.007}_{-0.005} M_{\odot}$ . Combined with the mass ratio  $q = 8.1 \pm 0.2$  inferred from the radial velocities and the precise pulsar timing ephemeris, the neutron star mass is constrained to  $M_{\text{PSR}} = 1.47^{+0.07}_{-0.06} M_{\odot}$ . Contrary to expectations, the latter is only slightly above the Chandrasekhar limit. We find that, even if the birth mass of the neutron star was only  $1.20 M_{\odot}$ , more than 60 per cent of the matter that left the surface of the white dwarf progenitor escaped the system. The accurate determination of the component masses transforms this system in a laboratory for fundamental physics by constraining the orbital decay predicted by general relativity. Currently, the agreement is within  $1\sigma$  of the observed decay. Further radio timing observations will allow precise tests of white dwarf models, assuming the validity of general relativity.

**Key words:** binaries: close – stars: neutron – pulsars: general – white dwarfs – stars: individual: PSR J1738+0333.

## 1 INTRODUCTION

Millisecond pulsars (MSPs) are extreme in many ways. Their interior consists of the densest form of observable matter known and they can spin at least as fast as 716 times per second (Hessels et al. 2006). Hence, they offer a rich laboratory for a wide range of physical inquiry: mass measurements provide direct comparison to quantum chromodynamics’ predictions for the state of ultra-dense matter (Lattimer & Prakash 2004; Demorest et al. 2010) and studies of their orbits in binaries have provided the first confirmation for gravitational wave emission and the most stringent strong-field tests of general relativity (Taylor & Weisberg 1982; Kramer et al. 2006; Weisberg, Nice & Taylor 2010).

Most of the fastest spinning Galactic-disc pulsars are paired with low-mass helium-core WDs (hereafter LMWDs; for recent reviews see Lorimer 2008; Tauris 2011), and their fast spins and weak magnetic fields are thought to be the product of mass transfer from the progenitor of the white dwarf (WD), a process also known as recycling. As the progenitor star evolves, it fills its Roche lobe and loses its envelope, either while on the main sequence (for sufficiently short initial periods), or when moving up the red-giant track (Webbink, Rappaport & Savonije 1983). The mass-transfer rate is a strongly increasing function of the initial orbital period and donor mass (Tauris & Savonije 1999), and is expected to be at a stable, sub-Eddington rate ( $\lesssim 10^{-8} M_{\odot} \text{ yr}^{-1}$ ) for light companions in relatively tight orbits. The final result of such long-term (nuclear time-scale) mass transfer is a highly circular (due to fast tidal dissipation in the secondary) close binary consisting of a fast spinning MSP and an LMWD.

These systems are important for several reasons. First, it is these binaries that allow one to probe certain aspects of the radiative

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properties of gravity that are poorly constrained by the relativistic effects seen in double neutron stars, like the Hulse–Taylor or the double pulsar. For example, in a wide range of theories, the rate of gravitational wave emission is driven by a leading dipolar term that depends crucially on the difference in gravitational binding energies between the binary members. Hence, if accurate component masses can be determined, one can directly confront the predictions of different gravity theories, in terms of dipolar radiation, with observations.

Secondly, measuring their masses provides access to the accretion process and evolution of these systems as well as the formation of MSPs, the only neutron stars with secure precise masses significantly above the Chandrasekhar limit (Demorest et al. 2010; Freire et al. 2011). In addition, observational constraints on the upper mass limit of stable neutron stars constrain the equation of state for supdense matter.

Unfortunately, precise MSP and companion masses can be determined from timing in exceptional cases only: either when the orbit is (unexpectedly) eccentric, allowing for a measurement of the rate of advance of periastron (Freire et al. 2011), or if the system has an orbit seen edge on (Kaspi, Taylor & Ryba 1994; Jacoby et al. 2005; Demorest et al. 2010) which allows for a measurement of pulse time-of-arrival (TOA) delays due to the curvature of space–time around the companion (Shapiro delay, Shapiro 1964).

Fortunately, another method exists that relies on combined optical and radio timing observations (van Kerkwijk, Bergeron & Kulkarni 1996; Callanan, Garnavich & Koester 1998). If the WD companion is bright enough for detailed spectroscopy, a comparison of its spectrum with model atmospheres yields its effective temperature and surface gravity. These can then be compared with a mass–radius relation for LMWDs to yield its mass. Combining the radial velocity for the WD with the pulsar timing measurements yields the mass ratio and therefore the mass of the pulsar.

In a companion paper (Van Kerkwijk et al., in preparation, hereafter vK+12), we test this method on PSR J1909–3744, for which the masses are precisely known from timing. We find it reliable and are confident to apply it also to other similar systems. Here, we report on an application to PSR J1738+0333, a pulsar–LMWD binary in an 8.5 h orbit. This system is particularly interesting because of its short period, which places it in a poorly studied regime for accretion physics of neutron stars, where nuclear-driven evolution competes with magnetic braking and gravitational radiation (cf. Phinney & Kulkarni 1994). Furthermore, the short orbital period implies relatively rapid orbital decay, making the system interesting for radiative tests of gravity, for which, as described above, knowledge of the component masses is necessary.

The paper is organized as follows. In Section 2 we report results from radio timing, necessary for calculations throughout the rest of the paper. These will be presented in detail separately (Freire et al., 2012, hereafter Paper II). In Section 3 we describe the spectroscopic and photometric observations and in Section 4 we present our results. We discuss our findings and comment on the evolution of the system and its importance for gravity tests in Section 5. Finally, in Section 6, we summarize our results.

## 2 PSR J1738+0333: RADIO OBSERVATIONS

PSR J1738+0333 was discovered in a 20-cm high Galactic latitude survey in 2001 (Jacoby 2005), carried out with the multi-beam receiver of the Parkes Telescope. The pulsar has a spin period of 5.85 ms and orbits an LMWD companion in a 8.5 h orbit. Since 2003 it has been regularly timed with the 305-m Arecibo Telescope,

leading to  $\sim 16\,000$  times of arrival with typically  $3\,\mu\text{s}$  uncertainties. The corresponding timing solution provides measurements of the system’s parallax and proper motion, and a significant detection of the intrinsic orbital period derivative (see Paper II for details). In Table 2 we list the measured spin, Keplerian and astrometric parameters of the system.

The spin period derivative is that of a typical low-surface magnetic field pulsar ( $B_0 = 3.7 \times 10^8\text{ G}$ ), and the characteristic age ( $\equiv P/2\dot{P}$ ) after subtracting the kinematic effects (Paper II) is 4.1 Gyr. The parallax measurement corresponds to a distance of  $d = 1.47 \pm 0.10\text{ kpc}$ . The system’s proper motion combined with the parallax implies transverse velocities of  $v_\alpha = d\mu_\alpha = 49\text{ km s}^{-1}$  and  $v_\delta = d\mu_\delta = 36\text{ km s}^{-1}$  in  $\alpha$  and  $\delta$ , respectively. In Section 4 we combine these values with the systemic radial velocity,  $\gamma$ , to derive the 3D spatial velocity and calculate the Galactic orbit of the binary. The estimate for the orbital eccentricity is one of the lowest observed in any binary system: when Shapiro delay is accounted for in the solution (Paper II), the apparent eccentricity diminishes to  $e = (3.5 \pm 1.1) \times 10^{-7}$ . We discuss the implication of this for evolutionary scenarios in Section 5.

## 3 OPTICAL OBSERVATIONS

### 3.1 Spectroscopy

Our main data set consists of 18 long-slit phase-resolved spectra of PSR J1738+0333, obtained with the Gemini South telescope at Cerro Pachón on 10 different nights between 2006 April and June (see Table 1). For our observations we used the Gemini Multi-Object Spectrograph (GMOS-S). The GMOS detector consists of three  $2048 \times 4608$  EEV CCDs, each of which was read-out at  $2 \times 2$  binning by a different amplifier, giving a scale of 0.14 arcsec per binned pixel in the spatial direction, and, with the 1200 lines per mm B1200 grism, 0.4 Å per binned pixel in the dispersion direction. We chose a relatively wide, 1.5 arcsec slit, to minimize atmospheric dispersion losses (see below). This meant that the resolution was set by the seeing, at  $\sim 3\text{ Å}$ , or  $\sim 200\text{ km s}^{-1}$  at 4300 Å. In order to cover the higher Balmer lines, we centred the grating at 4300 Å, for a wavelength coverage from 3500 to 5100 Å.

All exposures had integration times of 3720 s and were followed by an internal flat-field exposure and a copper–argon (CuAr) exposure for wavelength calibration. The slit was oriented to include a bright comparison star located 25.2 arcsec at position angle 127°57' (south through east) of the WD (see Fig. 1). We use this star as a local velocity and flux standard (since GMOS-S does not have an atmospheric dispersion corrector, slit losses vary with offset from the parallactic angle).

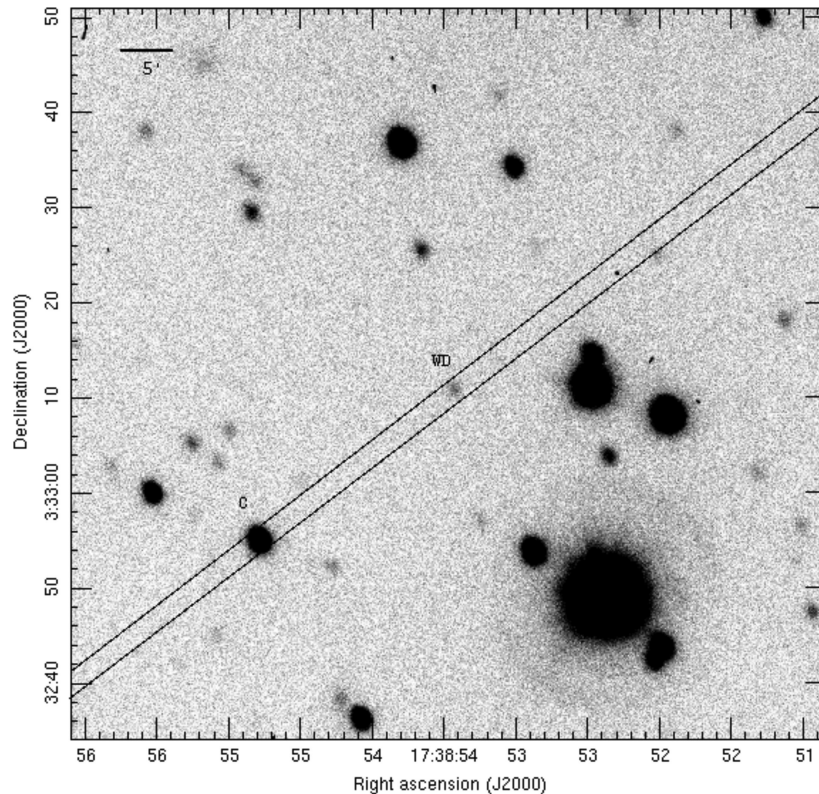
The conditions during the observations were mostly good to photometric, but some exposures were taken through thin cirrus. The seeing ranged from 0.6 to 1.2 arcsec. For flux calibration, we acquired additional frames of the comparison star and the spectrophotometric standard EG 274 through a 5.0 arcsec slit on the night of 2006 April 27 (which was photometric and had 0.8 arcsec seeing). Furthermore, for absolute velocity calibration, we observed the radial-velocity standard WD 1743–132 on 2006 June 19.

The data were reduced using standard and custom routines inside the Munich Image and Data Analysis System (MIDAS). First, the bias level of each exposure was removed using average values from the overscan region. Subsequently, we corrected the raw counts on the red and middle chips for the small, few per cent variations in gain (see vK+12 for details on the method), that affected several sets of exposures (but fortunately not those of the night the flux

**Table 1.** Log of observations and radial-velocity measurements.

| Date           | MJD <sub>mid,bar</sub><br>(1) | $\phi$<br>(2) | $v_R$<br>(km s <sup>-1</sup> )<br>(3) | $v_{WD}$<br>(km s <sup>-1</sup> )<br>(4) | $\Delta v$<br>(km s <sup>-1</sup> )<br>(5) | $\Delta B'$<br>(6) |
|----------------|-------------------------------|---------------|---------------------------------------|--|--|--------------------|
| Gemini, GMOS-S |                               |               |                                       |  |  |                    |
| 2006 Apr 27    | 53852.310219                  | 0.0250        | +56.3 ± 0.8                           | -209 ± 27                                | -265 ± 27                                  | 2.91 ± 0.06        |
|                | 53852.366314                  | 0.1831        | +49.1 ± 0.8                           | -143 ± 26                                | -192 ± 26                                  | 2.88 ± 0.06        |
| 2006 Apr 28    | 53853.295453                  | 0.8019        | +53.7 ± 0.5                           | -100 ± 14                                | -154 ± 14                                  | 2.88 ± 0.04        |
|                | 53853.350638                  | 0.9575        | +68.8 ± 0.6                           | -185 ± 15                                | -254 ± 15                                  | 2.88 ± 0.04        |
| 2006 May 07    | 53862.333037                  | 0.2749        | +40.1 ± 0.5                           | -35 ± 13                                 | -75 ± 13                                   | 2.83 ± 0.03        |
|                | 53862.391933                  | 0.4409        | +84.9 ± 0.6                           | +162 ± 21                                | +77 ± 21                                   | 2.87 ± 0.04        |
| 2006 May 26    | 53881.198674                  | 0.4489        | +60.8 ± 1.1                           | +121 ± 37                                | +60 ± 37                                   | 3.03 ± 0.11        |
|                | 53881.252933                  | 0.6018        | +67.0 ± 0.9                           | +33 ± 32                                 | -34 ± 32                                   | 2.97 ± 0.09        |
| 2006 May 27    | 53882.352291                  | 0.7005        | +43.1 ± 0.5                           | -6 ± 15                                  | -49 ± 15                                   | 2.85 ± 0.04        |
| 2006 May 28    | 53883.296760                  | 0.3625        | +54.9 ± 0.6                           | +28 ± 16                                 | -27 ± 16                                   | 2.86 ± 0.03        |
|                | 53883.350144                  | 0.5130        | +53.9 ± 0.6                           | +134 ± 17                                | -189 ± 17                                  | 2.85 ± 0.03        |
| 2006 Jun 19    | 53905.174549                  | 0.0264        | +41.5 ± 0.5                           | -226 ± 12                                | +80 ± 12                                   | 2.85 ± 0.04        |
| 2006 Jun 23    | 53909.170100                  | 0.2881        | +39.9 ± 0.7                           | -5 ± 14                                  | -45 ± 14                                   | 2.88 ± 0.03        |
|                | 53909.210618                  | 0.4023        | +95.6 ± 1.1                           | -103 ± 36                                | -45 ± 36                                   | 2.84 ± 0.04        |
| 2006 Jun 26    | 53912.156147                  | 0.7045        | +60.4 ± 0.5                           | -7 ± 14                                  | -67 ± 14                                   | 2.85 ± 0.04        |
|                | 53912.209838                  | 0.8558        | +60.7 ± 0.6                           | -136 ± 15                                | -197 ± 15                                  | 2.88 ± 0.04        |
| 2006 Jun 27    | 53913.120000                  | 0.4212        | +42.5 ± 0.5                           | +79 ± 12                                 | +37 ± 12                                   | 2.84 ± 0.04        |
|                | 53913.176660                  | 0.5809        | +43.6 ± 0.5                           | +106 ± 13                                | +62 ± 13                                   | 2.82 ± 0.04        |
| Keck, LRIS     |                               |               |                                       |  |  |                    |
| 2008 Aug 04    | 54682.377697                  | 0.6224        | 50 ± 1, +61 ± 5                       | -2 ± 9                                   | -52 ± 9                                    | 3.01 ± 0.05        |

*Notes.* (1) The barycentric mid-exposure time. (2) The orbital phase using the ephemeris in Table 2. (3) The comparison's velocity with respect to the Solar system barycentre and (4) the raw barycentric velocities of PSR J1738+0333. (5) The differential velocity used to determine the orbit in Section 4. (6) The differential spectrophotometric magnitudes in  $B'$  (equal to  $B$ , but limited to the wavelength range covered by our spectra; see Section 3). Here, the errors are the quadratic sum of the photometric uncertainties of the WD and the comparison. For LRIS, two velocities are listed for the comparison star, for the blue and red arm, respectively. For the WD, the velocity is for the blue arm (see text).



**Figure 1.** Finding chart for PSR J1738+0333 (using the SOAR V image). Indicated are the WD counterpart, the slit orientation used and the comparison star that was included in the slit.



calibrator was taken). Finally, the frames were corrected for small-scale sensitivity variations using normalized lamp exposures, where the normalization was done both along each wavelength position and along each spatial position. These normalization steps were required since the lamp spectra showed rather sharp bumps in the dispersion direction whose position and shape were different from bumps seen in target spectra, and also varied between sets of spectra (possibly because the holographic grating was not illuminated exactly identically between the different exposures), while in the spatial direction they showed striations due to irregularities in the slit.

For sky subtraction, we selected a 100 arcsec region centred on the WD, but excluding 5 arcsec spots around it and the comparison star. Each column in the spatial direction was fitted with a second-degree polynomial and the interpolated sky contributions at the positions of the WD and the comparison were removed.

Optimally weighted spectra and their uncertainties were extracted using a method similar to that of Horne (1986). The extraction was done separately in each chip and the spectra were merged after flux calibration.

The dispersion solution was established using the CuAr spectra taken after each exposure. First, the 1D lamp spectrum was extracted by averaging the signal over the spatial direction in areas of the chip that coincided with each star. Then the lines' positions were measured and identified and the dispersion relation was approximated with a third-degree polynomial that gave rms residuals of less than 0.04 Å for typically 18 lines.

The wide-slit spectra of EG 274 and the comparison star were extracted with the same procedure and used to calibrate the narrow-slit exposures. Initially, all wide- and narrow-slit data were corrected for atmospheric extinction using the average extinction table for La Silla (which should be a good approximation to that of Cerro Pachón). Then, we calculated the wavelength-dependent flux losses due to the finite size of the slit by comparing the wide-slit spectrum of the comparison with each of the narrow-slit spectra. The relation was analytically approximated with a quadratic function of wavelength that was then applied to the narrow-slit observations. Finally, the GMOS instrumental response was calculated by dividing the spectrum of EG 274 with a synthetic template and smoothly interpolating the ratio. The template was created by normalizing an appropriate DA model atmosphere to the catalogued flux ( $V = 11.03$ ; Zwitter, Castelli & Munari 2004, see Section 4.5 for more details on the model atmospheres used in this work). Prior to comparison, we smoothed the template with a Gaussian kernel to match the resolution of the observed spectrum and excluded the cores of the Balmer lines.

Given the possible issues with the detector gain and the flat-fielding, both of which could affect the flux calibration, we obtained an additional smaller set of spectra of the WD companion, the comparison star and the spectro-photometric standard Feige 110 using the two-armed Low Resolution Imaging Spectrometer (LRIS; Oke et al. 1995) of the Keck telescope on the night of 2008 August 3 (Table 1). During the night the sky was photometric and the seeing was  $\sim 0.8$  arcsec.

For the observations we used the atmospheric dispersion corrector and both narrow, 0.7 arcsec, and wide, 8.7 arcsec, slits. The light was split with a dichroic at 6800 Å and directed on the two arms of LRIS (hereafter blue and red arm). On the blue arm we used a 600 lines mm<sup>-1</sup> grism, blazed at 4000 Å, that covers 3100–5600 Å with a resolution of  $\Delta\lambda = 3.2$  Å or  $\Delta v = 220$  km s<sup>-1</sup>. On the red arm we used the 1200 lines mm<sup>-1</sup> grating, blazed at 8000 Å, that covers 7600–8900 Å at  $\Delta\lambda = 2.1$  Å or  $\Delta v = 75$  km s<sup>-1</sup>. The blue-side

detector is a mosaic of two Marconi CCDs with 4096 × 4096 pixels 15 μm on the side, which we read out binned by two in the dispersion direction. The red-side detector is a Tektronic CCD with 2048 × 2048 pixels 24 μm on the side, which we read-out unbinned.

The spectra were extracted and calibrated as above. Here, on the blue arm we replaced the poorly exposed part of the flat-fields shortwards of 4000 Å with unity and normalized the rest using a third-degree polynomial. On the red side we normalized the flat-field using a bi-linear fit. Wavelength calibration was done using arc spectra and sky lines. On the blue arm we used the well-exposed arc frames taken at the beginning of the night to establish an overall solution that had rms residuals of 0.16 Å for 22 lines fitted with a third-degree polynomial and then calculated offsets using the less well exposed arc frames taken throughout the night. For the red arm we used the well-exposed arc frames taken interspersed with the science exposures. Here, we corrected for offsets by shifting the bright OH and O<sub>2</sub> lines at 8344.602, 8430.174 and 8827.096 Å to laboratory values. Flux calibration was again done as above; we found that the solution was consistent with that obtained from Gemini (see also below).

### 3.2 Photometry

On the night of 2008 February 28, images of the field containing PSR J1738+0333 were acquired for us with the 4.1-m Southern Astrophysical Research Telescope (SOAR) at Cerro Pachón, Chile, using the Goodman High Throughput Spectrograph (Clemens, Crain & Anderson 2004), with its Fairchild 4096 × 4096 CCD and *B* and *V* filters (with throughputs on the Kron–Cousins photometric system). The instrument has a plate scale of 0.15 arcsec pixel<sup>-1</sup> and a usable field of view of 5.0 arcmin. During the run, the sky was photometric and the seeing as determined from the images was  $\sim 1.8$  arcsec. Two 300 s images each in *V* and *B* were obtained. Of these, however, the first had reduced count rates for all stars and a distorted point-spread function, possibly because the telescope and instrument had not yet settled when the exposure was started; we have not used that image. For calibration, sets of 30 s *B* and *V* images of the photometric standard field PG 1633+099 were acquired both before and after the science frames.

Following standard prescriptions, individual frames were bias-corrected and flat-fielded using twilight flats. Hot pixels and cosmic rays were replaced by a median over their neighbours. The instrumental fluxes were measured inside 3.6 arcsec radii and then corrected to a radius of 7 arcsec using measurements of bright isolated stars. For the calibration, we used five standard stars with a range of *B* – *V* colours in the PG 1633+099 field (Stetson 1990). Measured magnitudes were compared to their catalogued counterparts to derive zero-points and colour terms. Both calibration sets yielded similar results. Small differences in airmass were corrected using standard values for La Silla. The rms residuals of the zero-points in both bands were  $\sim 0.01$  mag. We find that the optical counterpart of the WD has  $V = 21.30(5)$  and  $B = [21.70(7), 21.73(7)]$ , where the two measurements in *B* are for the two exposures, and where for the errors, we combined in quadrature the measurement and zero-point uncertainties. For the comparison star, we measure  $V = 18.00(1)$  and  $B = [18.73(2), 18.75(3)]$ . Since the *B* magnitudes are consistent, we use the averages below.

We verified our calibration in several ways. First, we integrated our flux-calibrated spectra over the *B*-band filter curve of Bessell (1990). For the comparison star, using the wide-slit spectra, we find  $B' = 18.81$  for the Gemini spectrum and  $B = 18.71$  for the Keck spectrum. For the WD, we find  $B' = 21.69$  for the averaged

Gemini WD spectra, and  $B = 21.70$  for the single narrow-slit Keck spectra. Here, we label the Gemini magnitudes as  $B'$ , since the GMOS spectra do not fully cover the Bessell- $B$  bandpass, which will introduce colour terms.

Secondly, we tried to calibrate the  $g'$ -band GMOS acquisition images by calibrating relative to our velocity standard, WD 1743–132, which has  $V = 14.290$ ,  $B - V = 0.300$  (Mermilliod et al. 1990), and thus, using the relations of Fukugita et al. (1996),  $g' = V + 0.56(B - V) - 0.12 = 14.34$ . We find  $g' = 18.23$  for the comparison star and, using the average magnitude difference  $\Delta g' = 3.091(17)$  between the WD and the comparison, we infer  $g' = 21.32$  for the WD (here, the uncertainty will be dominated by systematics, but should be  $\lesssim 0.05$  mag). These numbers are consistent with the  $g' = 18.39(7)$  and  $21.42(7)$  expected from our SOAR photometry.

Looking at individual acquisition frames, the scatter of the magnitude difference was  $\sim 0.05$  mag, somewhat larger than expected based on measurement noise, though with no obvious correlation with orbital phase. We find somewhat smaller scatter from convolving individual flux calibrated WD and comparison spectra with the Bessell  $B$  band, and using those to determine differences (see Table 1). Ignoring the two points from our worst night (2006 May 26), the rms scatter is 0.032 mag. Since no obvious phase dependence is found, this places a limit on the irradiation of the WD atmosphere from the pulsar. However, the limit is too weak to be useful: assuming a spin-down luminosity of  $L_{\text{PSR}} = dE/dt = -4\pi^2 I \dot{P} / P^3 \sim 4.8 \times 10^{33} \text{ erg s}^{-1}$  and defining an irradiation temperature  $T_{\text{irr}} = (L_{\text{PSR}} / 4\pi a^2 \sigma)^{1/4} \simeq 3800 \text{ K}$  (where from Table 2, we inferred  $a \simeq 1.8 \times 10^{11} \text{ cm}$ ), the expected orbital modulation is only  $\Delta L/L \simeq [\pi R_{\text{WD}}^2 (L_{\text{PSR}} / 4\pi a^2) / L_{\text{WD}}] \sin i \simeq [T_{\text{irr}}^4 / 4T_{\text{WD}}^4] \sin i \lesssim 4 \times 10^{-3}$ .

## 4 RESULTS

### 4.1 Radial velocities

Radial velocities of the WD, the comparison and the velocity standard were extracted by fitting their spectra with templates using the method discussed in Bassa et al. (2006). For the comparison, we first classified it using the online atlas by R. O. Gray.<sup>1</sup> We find that its spectrum resembles that of a G0V star, with an uncertainty of about 1 subtype. Comparing with various spectra from the UVESPOP<sup>2</sup> library of high-resolution spectra (Bagnulo et al. 2003), we find the best fit for the G1V star HD 20807 (where, to match the resolution of the observations, we convolve the UVESPOP spectra with a Gaussian with full width at half maximum equal to that of the seeing, truncated at the slit width). We fitted this template to each spectrum for a range of velocities, from  $-600$  to  $600 \text{ km s}^{-1}$  with a step size of  $5 \text{ km s}^{-1}$ . We corrected for the  $11.5 \text{ km s}^{-1}$  barycentric velocity of HD 20807 after the fact.

Similarly, the WD spectra were compared to an appropriate DA model atmosphere. The latter was determined iteratively, where we first fitted a high signal-to-noise ratio (S/N) single spectrum with a grid of model atmospheres created by one of us (DK; see the next section), then used the best-fitting solution to shift the spectra and average them at zero velocity, and finally fitted the average again to determine the best template. For WD 1743–132 we fitted the single spectrum with the grid and determined all parameters simultaneously.

**Table 2.** Properties of the PSR J1738+0333 system. Numbers in parentheses (where given) are the formal errors of the best-fitting model. For details on the timing analysis, including uncertainties not relevant here, see Paper II.

| Timing parameter   | Value  |
|--|--|
| Reference epoch (MJD)  | 54 600   |
| Time of ascending node (MJD)   | 5 3400.297 958 820(6)                                |
| Right ascension, $\alpha$ (J2000)  | 17 <sup>h</sup> 38 <sup>m</sup> 53 <sup>s</sup> .965 |
| Declination, $\delta$ (J2000)  | 03 deg 33' 10".866                                   |
| $\mu_\alpha$ (mas yr <sup>-1</sup> )                                     | +7.058(5)  |
| $\mu_\delta$ (mas yr <sup>-1</sup> )                                     | +5.176(10)   |
| Parallax, $\pi$ (mas)  | 0.67(4)  |
| $P$ (ms)   | 5.85   |
| $\dot{P}$ (s s <sup>-1</sup> )   | $2.412 \times 10^{-20}$                              |
| Dispersion measure, DM (cm <sup>-3</sup> pc)                             | 33.77  |
| Orbital period, $P_b$ (d)  | 0.35479  |
| Projected semi-major axis, $x$ (lt-s)                                    | 0.3434   |
| Eccentricity, $e$  | $3.5(1.1) \times 10^{-7}$                            |
| Mass function, $f(M_\odot)$  | 0.000 345 5012(12)                                   |
| Optical parameter  | Value  |
| Temperature (K)  | 9130(150)  |
| Surface gravity (log $g$ , spectroscopy)                                 | 6.55(10)   |
| Surface gravity (log $g$ , $\dot{P}_b + q + \pi$ +photometry)            | 6.45(7)  |
| Photometry, $V$ band   | 21.30(5)   |
| Photometry, $B$ band   | 21.71(4)   |
| Semi-amplitude of radial velocity, $K_{\text{WD}}$ (km s <sup>-1</sup> ) | 171(5)   |
| Systemic radial velocity, $\gamma$ (km s <sup>-1</sup> )                 | -42(16)  |
| Transverse velocity, $v_T$ (km s <sup>-1</sup> )                         | 59(6)  |
| 3D velocity amplitude (km s <sup>-1</sup> )                              | 72(17)   |
| Mass ratio, $q$  | 8.1(2)   |
| WD mass, $M_{\text{WD}}$ ( $M_\odot$ , spectroscopy)                     | $0.181^{+0.007}_{-0.005}$                            |
| WD mass, $M_{\text{WD}}$ ( $M_\odot$ , $q + \dot{P}_b$ )                 | $0.182 \pm 0.016$                                    |
| WD radius (spectroscopy) ( $R_\odot$ )                                   | $0.037^{+0.004}_{-0.003}$                            |
| WD radius (photometry) ( $R_\odot$ )                                     | 0.042(4)   |
| Cooling age, $\tau_c$ (Gyr)  | 0.5–5  |
| Pulsar mass, $M_{\text{PSR}}$ ( $M_\odot$ )                              | $1.47^{+0.07}_{-0.06}$                               |
| inclination, $i$ ( $^\circ$ )  | 32.6(1.0)  |

For all above fits, we multiplied the templates with a third-degree polynomial to account for the normalization and possible variations with wavelength (see Section 4.5 for details). Our best fits gave typical reduced  $\chi^2$  values of  $\chi_{\text{red, min}}^2 \sim 1.2, 2.2$  and  $1.6$  for the WD, the comparison star and the velocity standard, respectively. Best-fitting velocities were determined by fitting a parabola to the  $\chi^2$  values to within  $60 \text{ km s}^{-1}$  of minimum, with uncertainties taken to be the difference in velocity over which  $\chi^2$  increased by  $\chi_{\text{red, min}}^2$  (thus effectively increasing our uncertainties to account for the fact that  $\chi_{\text{red, min}}^2$  did not equal unity).

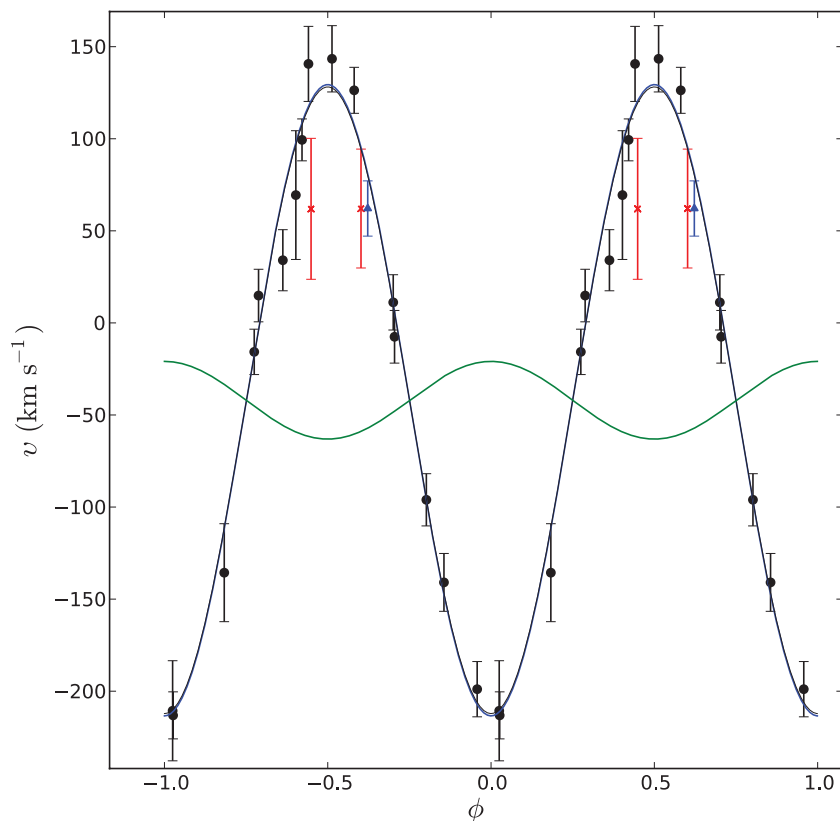
For the Keck spectra, we proceeded similarly. Here on the red side, we could not use the UVES spectrum due to a gap over the Ca II triplet, and hence we used instead a  $T_{\text{eff}} = 6000 \text{ K}$ ,  $\log g = 4.5$  dex model by Zwitter et al. (2004). As we trust the absolute wavelength calibration of this observation most (being calibrated relative to telluric emission lines), we use this estimate of the velocity below to transform all velocities to the barycentric reference frame.

### 4.2 Radial-velocity orbit and mass ratio

In Table 1, we list the measured radial velocities for all targets, with barycentric corrections applied. For determining the orbit, we

<sup>1</sup> <http://nedwww.ipac.caltech.edu/level5/Gray/Graycontent>

<sup>2</sup> <http://www.sc.eso.org/santiago/uvespop/DATA>



**Figure 2.** Radial-velocity measurements of the companion to PSR J1738+0333 as a function of the orbital phase. Filled black circles depict the points used to fit the orbit and the blue line the best-fitting solution. Red crosses indicate two outliers that we excluded and the black line the best-fitting solution with these points included. The latter agrees well and is almost indistinguishable. The blue triangle shows the Keck point. The green line depicts the velocity of the pulsar as inferred from radio timing. All velocities are relative to the comparison star, but corrected for its estimated  $61 \text{ km s}^{-1}$  barycentric radial velocity. All error bars represent  $1\sigma$  uncertainties. The orbit is depicted two times for clarity.

folded the barycentric velocities using the ephemeris in Table 2 and fitted for a circular orbit keeping the orbital period and time of ascending node passage fixed to the timing values. The fit gave a radial-velocity semi-amplitude of  $K_{\text{obs}} = 165 \pm 7 \text{ km s}^{-1}$  and a systemic radial velocity of  $\gamma = -50 \pm 4 \text{ km s}^{-1}$  with  $\chi^2_{\text{red}} = 1.55$  for 16 degrees of freedom.

The radial velocity of the comparison star in the Gemini data set varied as much as  $55 \text{ km s}^{-1}$  which is considerably higher than the uncertainties of individual points. We found no evidence for binarity and thus we attribute the large scatter to systematics, likely induced by slit positioning errors and differential atmospheric diffraction. For that reason, we chose to use velocities relative to the comparison star,  $\Delta v$ . This choice relies on the assumption that both the WD and the comparison star are affected by the same systematics. This should be correct to the first order, but given the relatively large separation of the two stars on the slit, their different distances from the centre of rotation of the instrument, and their different colours, small second-order differences may remain. Even if any are present, however, they should not be correlated with orbital phase (since our measurements are taken on many different nights), and thus be taken into account automatically by our rescaling of the measurement errors such that reduced  $\chi^2$  equals unity.

After subtracting the velocity of the comparison star, we obtain  $K_{\text{obs}} = 166 \pm 6 \text{ km s}^{-1}$ ,  $\Delta\gamma = -101 \pm 4 \text{ km s}^{-1}$  with  $\chi^2_{\text{red}} = 1.07$ . This orbit is shown in Fig. 2. This fit has two outliers, which both are from spectra taken in the night with the worst condition (they are also outliers in the relative flux between the WD and the comparison

star; see Table 1). Excluding these, we find  $K_{\text{obs}} = 167 \pm 5 \text{ km s}^{-1}$  and  $\Delta\gamma = -103 \pm 3 \text{ km s}^{-1}$  with  $\chi^2_{\text{red}} = 0.93$  for 14 degrees of freedom. We will use these latter values as our best estimates, but note that all fits gave consistent results, so our inferences do not depend on this choice.

Because the exposure time is a significant fraction of the orbit ( $t_{\text{exp}} \simeq 0.12 P_b$ ), the observed semi-amplitude is affected by velocity smearing. This reduces the measured amplitude by a factor  $\sin(\pi t_{\text{exp}}/P_b)/(\pi t_{\text{exp}}/P_b) = 0.976$ . Thus, the true radial-velocity amplitude is  $K_{\text{WD}} = 171 \pm 5 \text{ km s}^{-1}$ .

Likewise, the semi-amplitude of the pulsar's projected radial velocity is  $K_{\text{PSR}} = 2\pi cx/P_b = 21.103059(2) \text{ km s}^{-1}$ , where  $x$  is the projected semi-major axis of the pulsar orbit. Based on the two values calculated above we derive a mass ratio of  $q = K_{\text{WD}}/K_{\text{PSR}} = 8.1 \pm 0.2$ .

### 4.3 Systemic velocity

The systemic velocity  $\Delta\gamma$  derived above is relative to the comparison star. Thus, for an absolute value one needs to obtain an estimate of the true velocity of the latter. From the Gemini spectra we derived an average value of  $64 \pm 5 \text{ km s}^{-1}$ . As discussed above, the individual velocities have a large scatter and one may thus worry about systematics. It seems that these are of the order of  $15\text{--}20 \text{ km s}^{-1}$ . First, for the velocity standard WD 1743–132 we find a velocity of  $-58.6 \pm 1 \text{ km s}^{-1}$ , which is offset by  $14.2 \text{ km s}^{-1}$  from the catalogue value of  $-72.8 \text{ km s}^{-1}$  (Reid 1996). Secondly, for the

comparison star, our Keck spectrum yields  $61 \pm 5 \text{ km s}^{-1}$ . As mentioned above, we believe the wavelength calibration is most reliable for the Keck spectrum, so we adapt this velocity. For PSR J1738+0333, correcting for the gravitational redshift of the WD of  $3 \text{ km s}^{-1}$  (using the mass and radius derived in Section 4.6), we infer a systemic velocity of  $\gamma = -42 \pm 16 \text{ km s}^{-1}$ .

#### 4.4 Interstellar reddening

We calculated the run of reddening along the line of sight using the Galactic extinction model of Drimmel, Cabrera-Lavers & López-Corredoira (2003). We find that the interstellar extinction increases smoothly to reach a maximum value of  $A_V = 0.56$  at 1.3 kpc and remains constant thereafter. This is similar to the maximum value along this line of sight of  $A_V = 0.65$  inferred from the maps of Schlegel, Finkbeiner & Davis (1998). Therefore, for both PSR J1738+0333 and the comparison value we adopt  $A_V = 0.56 \pm 0.09$ , with the uncertainty taken to be the difference between the two models.

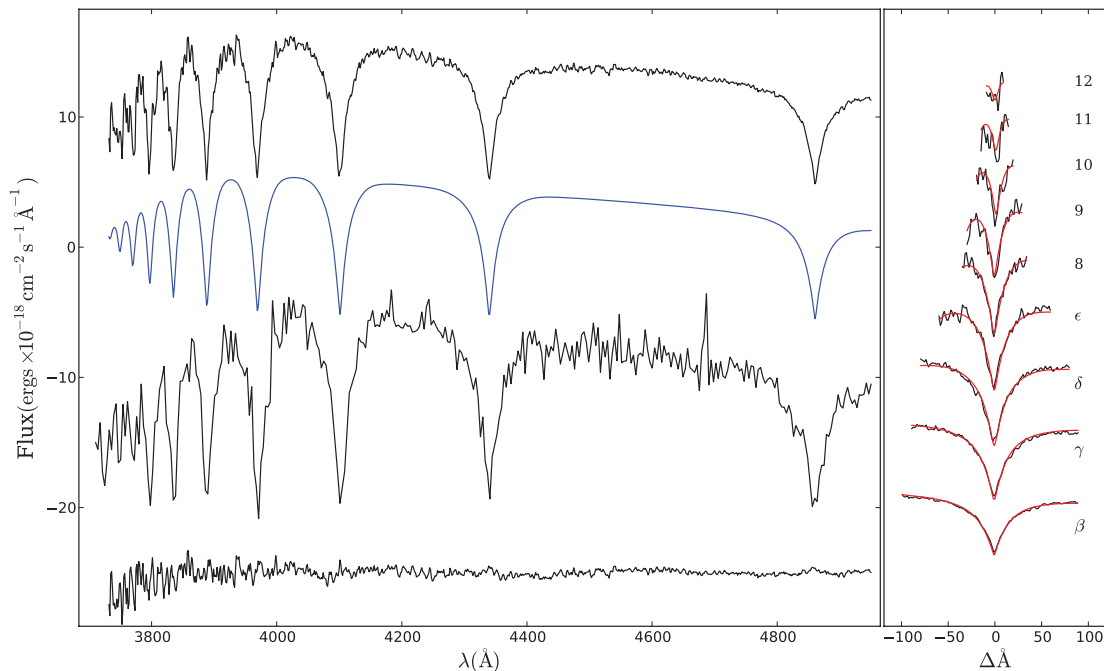
We can now use these results to estimate the distance of the comparison star: adopting  $M_V = 4.3$  and  $(B - V)_0 = 0.57$  for a G0V star (Cox 2000) and  $A_B = 1.321A_V$  (Schlegel et al. 1998) we obtain a distance of  $\sim 4.3 \text{ kpc}$  for both bands. As a sanity check for the systemic velocity derived above, we can calculate the expected velocity of the comparison for the photometric parallax: assuming the Galactic potential of Kenyon et al. (2008), a distance to the Galactic centre of 8.0 kpc and a peculiar velocity of the Sun relative to the local standard of rest of  $(U, V, W) = (10.00, 5.25, 7.17) \text{ km s}^{-1}$  (Cox 2000), we find that the local standard of rest at the position of the comparison star moves with a speed of  $\sim 60 \text{ km s}^{-1}$ . Given the uncertainties of the model and our measurements and the possibility of peculiar motion, the latter agrees well with our estimated value.

#### 4.5 Temperature and surface gravity of the WD

The zero-velocity average spectrum (Fig. 3) shows deep Balmer lines up to H12, typical for a WD with a hydrogen atmosphere and low surface gravity.

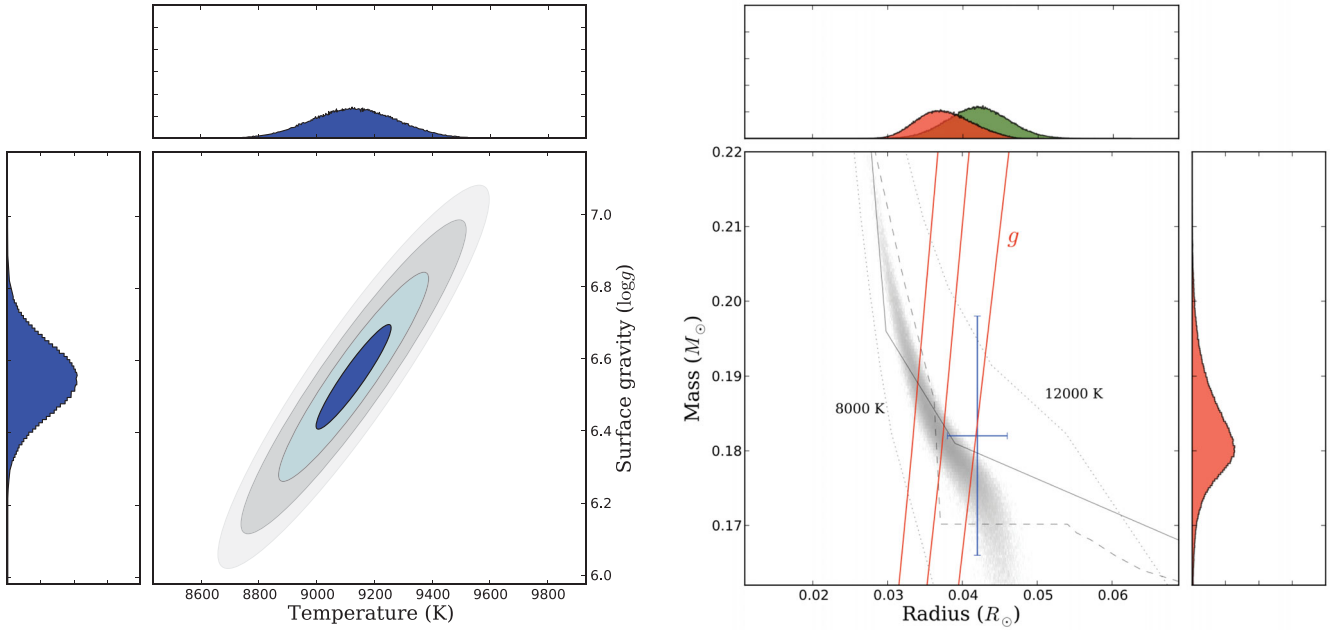
Quantitative estimates for the atmospheric parameters were obtained by modelling the spectrum with a grid of DA model atmospheres extending from 7000 to 25 000 K and  $\log g = 6.00$  to  $\log g = 8.00$  dex with step sizes of 100 K and 0.1 dex, respectively. The models used in this work are a recent update of the grid presented in Koester (2008) which incorporates the improved treatment of pressure broadening of the absorption lines by Tremblay & Bergeron (2009).

At each point of the grid that we scanned, we fitted for the normalization with a polynomial function of the wavelength. This was found necessary in order to account for the (up to)  $\sim 10$  per cent, slowly varying continuum deviations, caused by imperfect flux calibration. Assuming our flux calibration is perfect (namely, using a normalization factor that does not vary with wavelength) resulted in a poor fit with large-scale structure in the residuals and lines systematically deeper than the best-fitting model (best-fitting values:  $T_{\text{eff}} = 9010 \pm 50 \text{ K}$ ,  $\log g = 6.81 \pm 0.12$  dex with  $\chi^2_{\text{red}} \sim 9$ ). Similarly underestimated lines were obtained using a fitting routine normally used by one of us (DK) that assumes a fixed slope for the continuum over the length of each line. The former comparison revealed that there was also a smaller spectral range between 4400 and 4780 Å with features similar to the ones seen in the flat-fields (see Section 3), likely associated with the holographic grating [we were alerted to this effect because it was much more obvious for the companion of PSR J1909–3744 (vK+12).]. Fortunately, no Balmer lines are present in this region, and hence we simply modelled the spectrum excluding this range (specifically, we fitted the ranges



**Figure 3.** Left-hand panel: from top to bottom: the zero-velocity flux-calibrated average spectrum of PSR J1738+0333 obtained with Gemini, the corresponding best-fitting atmospheric model, the (single) spectrum obtained with Keck, and the residuals from the fit (see Section 4). The model and the Keck spectrum are shifted down by 10 and 20 units, respectively. Right-hand panel: details of the Balmer series in the average spectrum (H $\beta$  to H12, from bottom to top), with the best-fitting model overdrawn (red lines). Lines are shifted by 8 units with respect to each other.





**Figure 4.** Left-hand panel: constraints on the temperature and gravity of the WD companion to PSR J1738+0333 inferred from our model-atmosphere fit, with contours at  $\Delta\chi^2 = \chi_{\text{red,min}}^2, 4\chi_{\text{red,min}}^2, 9\chi_{\text{red,min}}^2$  and  $16\chi_{\text{red,min}}^2$ . The horizontal and vertical sub-panels show the histograms of the distributions for  $T_{\text{eff}}$  and  $\log g$  from our Monte Carlo simulation (Section 4.4). Right-hand panel: constraints on the mass and radius of the WD. The shaded area depicts the distribution of realizations from our Monte Carlo simulation (Section 4.6). Overdrawn are: the central value and  $1\sigma$  confidence limits of the observed surface gravity (red lines); the model tracks of Panei, Althaus & Benvenuto (2000) for constant temperature (8000 and 12000 K; dotted lines); the mass–radius relations of Serenelli et al. (2001) (solid) and Panei et al. (2007) (dashed) for our best-fitting temperature of 9130 K; error bars showing the independent constraints from photometry and radio timing. The horizontal and vertical panels show the inferred distributions for the WD radius and mass, respectively, as well as the independent photometric estimate for the former (in green; see Section 4.5).

3700–4400 and 4780–4960 Å). Like for our radial-velocity fits, we accounted for the spectral resolution by convolving the models with a truncated Gaussian.

Using the choices described above we obtain  $T_{\text{eff}} = 9129 \pm 20$  K (implying a spectral type DA5.5) and  $\log g = 6.55 \pm 0.07$  dex with  $\chi_{\text{red,min}}^2 \simeq 1.5$  (for  $\sim 800$  points and six parameters). Here, the best-fitting values and statistical uncertainties were determined by fitting the  $\chi^2$  surface with a paraboloid as in Bassa et al. (2006). We verified these estimates using a Monte Carlo simulation with  $10^6$  iterations (see Fig. 4). The results are almost identical, with the simulation giving slightly larger uncertainties. However, as we will see below, the systematic uncertainties are larger.

The best-fitting model is shown in Fig. 3. Most lines are matched almost perfectly, but H11 and H12 are slightly underestimated. We do not know the reason for this. As the continuum matches very well, it cannot be due to errors in the flux calibration (which would be multiplicative), while most other observational issues (scattered light, etc.) would lead to lines that have reduced rather than increased depth.

Given the above discrepancies, as well as previous experience with fitting model atmospheres, it is likely our uncertainties are dominated by systematics rather than measurement errors. We investigated this in three ways. First, we tried small changes in the assumed spectral resolution (by 5 per cent) and varied the different polynomial degrees for the continuum (second to fourth order). The former had only very small effect ( $\sim 20$  K changes in  $T$  and  $\sim 0.03$  dex changes in  $\log g$ ), while changing the degree of the polynomial caused larger differences: 0.1 dex ( $1.5\sigma$ ) for the surface gravity and up to 150 K ( $7\sigma$ ) for the temperature. Our central val-

ues are based on a third-degree polynomial, since it gave the best fit for the higher lines.

As a second check, we obtained an independent measure of the atmospheric parameters using the Keck spectrum. Again using a third-degree polynomial for the continuum, and fitting the same wavelength regions, we find  $T_{\text{eff}} = 9281 \pm 110$  K and  $\log g = 6.57 \pm 0.13$  dex. Here, switching between polynomials for the continuum normalization had a slightly smaller impact on the estimated values ( $\sim 100$  K in  $T$  and  $\sim 0.1$  in  $\log g$ ). While the surface gravity agrees almost perfectly with the Gemini value, the effective temperature is somewhat higher, suggesting, again, that temperature is more sensitive to our modelling assumptions.

Finally, we fitted the individual spectra with the model atmospheres and obtained a mean temperature of  $\langle T \rangle = 9153 \pm 38$  K with an rms scatter of 155 K.

From the above, it is clear the formal uncertainty on especially the temperature is too small, and we adopt as realistic estimates  $T_{\text{eff}} = 9130 \pm 150$  K and  $\log g = 6.55 \pm 0.10$  dex. Fortunately, the effect of the larger temperature uncertainty on the derived masses is small (see Section 4.6), because the mass–radius relation is much more sensitive to surface gravity than to temperature. For our mass calculation below, we thus choose to inflate the original  $\chi^2$  map to include the systematics mentioned above but preserve information about the covariance between parameters.

Finally, we searched the average spectrum for signatures of rotational broadening. For that we proceeded in two ways: first, we broadened a 9000 K,  $\log g = 6.5$  model atmosphere using the analytical profile of Gray (2005) with a limb darkening coefficient of 0.3 and scanned a grid of rotational velocities  $0 \leq v_r \sin i \leq$



1500 km s<sup>-1</sup> in steps of 50 km s<sup>-1</sup>. Secondly, we let all parameters free. In both cases we accounted for the spectral resolution of the instrument as above. We find the rotational broadening consistent with zero with the 1 $\sigma$  upper limit being 440 and 510 km s<sup>-1</sup>, respectively.

#### 4.6 White dwarf radius from photometry

We can use the best-fitting atmosphere model, the observed fluxes and the distance to obtain an estimate of the WD radius. In terms of magnitudes,

$$m_\lambda - 5 \log(d/10 \text{ pc}) - A_\lambda = 43.234 - 5 \log(R/R_\odot) - 2.5 \log F_\lambda + c_\lambda, \quad (1)$$

where  $m_\lambda$  is the apparent magnitude in band  $\lambda$ , the numerical term is  $-5 \log(R_\odot/10 \text{ pc})$ ,  $F_\lambda$  is the emitted flux per unit surface area integrated over the relevant filter and  $c_\lambda$  is the zero-point. Convoluting the best-fitting model with the  $B$  and  $V$  bandpasses of Bessell (1990) yields  $F_B = 6.289 \times 10^7 \text{ erg cm}^{-2} \text{ s}^{-1} \text{ \AA}^{-1}$  and  $F_V = 4.353 \times 10^7 \text{ erg cm}^{-2} \text{ s}^{-1} \text{ \AA}^{-1}$ . Here the uncertainty due to the fit is  $\sim 5$  per cent (mostly due to the  $\sim 1.5$  per cent uncertainty in temperature). Using the zero-points of Bessell (1990),  $c_B = -20.498$  and  $c_V = -21.100$ , and the reddening inferred in Section 4.4 we obtain radii  $R = 0.042 \pm 0.004 R_\odot$  and  $R = 0.042 \pm 0.004 R_\odot$  for  $B$  and  $V$ , respectively (with the uncertainty dominated by the uncertainty in the parallax).

#### 4.7 Masses of the white dwarf and the pulsar

The mass of the WD can be estimated using a mass–radius relation appropriate for low-mass helium-core WDs. We use the finite-temperature relation for low-mass WDs from Panei et al. (2000), which gave good agreement for the companion of PSR J1909–3744 (vK+12).

For the calculation we proceeded as follows: we sampled the inflated  $\chi^2$  surface derived in Section 4.3 in a Monte Carlo simulation using  $10^6$  points uniformly distributed in the  $T_{\text{eff}} - \log g$  plane. For each point within the expectations, we linearly interpolated the 8000 and 12000 K models of Panei et al. (2000) for WDs with extended hydrogen envelopes to the given temperature and calculated the mass and radius at the cross-section of the observed value (which scales as  $g = GM/R^2$ ) and the model. Subsequently, we calculated the mass of the pulsar, assuming a normal distribution for the mass ratio with  $q = 8.1 \pm 0.2$  (see Section 4.2). Furthermore, we calculated the inclination using the mass function  $f_M$  of the binary [ $\sin^3 i = f_M(M_{\text{WD}} + M_{\text{PSR}})^2/M_{\text{WD}}^3$ ].

We show the mass distribution in Fig. 4. Since the mass–radius relation is steeper towards higher masses, the companion’s mass distribution is asymmetric, with larger wings towards higher masses. The same holds for the distribution for the radius, with larger wings towards smaller radii. The error on the pulsar mass is dominated by the uncertainties in the companion’s mass estimate. To summarize, the values that we will be using for the rest of this paper are:  $M_{\text{WD}} = 0.181^{+0.007, +0.017}_{-0.005, -0.013} M_\odot$ ,  $M_{\text{PSR}} = 1.47^{+0.07, +0.14}_{-0.06, -0.08} M_\odot$ ,  $R_{\text{WD}} = 0.037^{+0.004, +0.007}_{-0.003, -0.006} R_\odot$  and  $i = 32.6^{+1.0, +2.1}_{-1.0, -2.1}$ . Here, the errors separated by commas are the corresponding 68 per cent and 95 per cent intervals spanned by the Monte Carlo realizations.

Finally, we also derived mass estimates using two different sets of tracks, that gave reliable results for PSR J1909–3744 (vK+12): The tracks of Serenelli et al. (2001) yielded  $M_{\text{WD}} = 0.183^{+0.007, +0.011}_{-0.004, -0.005} M_\odot$  and  $R_{\text{WD}} = 0.037^{+0.005, +0.007}_{-0.004, -0.007} R_\odot$ , almost identical to the above. The tracks of Panei et al. (2007) yielded

slightly different values:  $M_{\text{WD}} = 0.175^{+0.017, +0.029}_{-0.005, -0.006} M_\odot$  and  $R_{\text{WD}} = 0.038^{+0.005, +0.010}_{-0.003, -0.004} R_\odot$ . However, we note that these models predict a cooling age much smaller than the characteristic age of the pulsar (see the next section).

#### 4.8 Cooling age

We compared the absolute photometric magnitudes in  $B$  and  $V$  with the theoretical cooling tracks of Serenelli et al. (2001) for solar metallicity progenitors to infer the cooling age of the WD. We did this by minimizing a  $\chi^2$  merit function based on the sum of differences between observed and model fluxes in both bands. The track of Serenelli et al. (2001) closest in mass to the companion of PSR J1738+0333 is that of a  $0.169 M_\odot$ , for which we find  $\tau_c \sim 4.2$  Gyr. For that age and mass, the predicted temperature and surface gravity are  $T_{\text{eff}} \sim 8500$  K and  $\log g \sim 6.35$  dex. For our best-fitting spectroscopic estimates the same track yields  $\tau_c \sim 2.6$  Gyr. Since the observed mass is slightly heavier, its cooling age must be somewhat lower. Using the  $0.193 M_\odot$  track, we get  $\tau_c \sim 600$  Myr. The large difference is due to the dichotomy around  $0.2 M_\odot$  expected between WDs with thick and thin hydrogen atmospheres. Using the tracks of Panei et al. (2007), for the mass of  $0.175 M_\odot$  inferred using those, we again find short ages,  $\tau_c \sim 500$  Myr from the photometry and  $\tau_c \sim 450$  Myr for the spectroscopic parameters.

Finally, the suggested relatively large age of the system (4 Gyr plus 2–10 Gyr for the progenitor to have evolved) motivated us to compare our observations with models for lower metallicity progenitors. Using the  $0.183 M_\odot$ ,  $Z = 0.001$  track of Serenelli et al. (2002) we obtain  $\tau_c \sim 5$  Gyr.

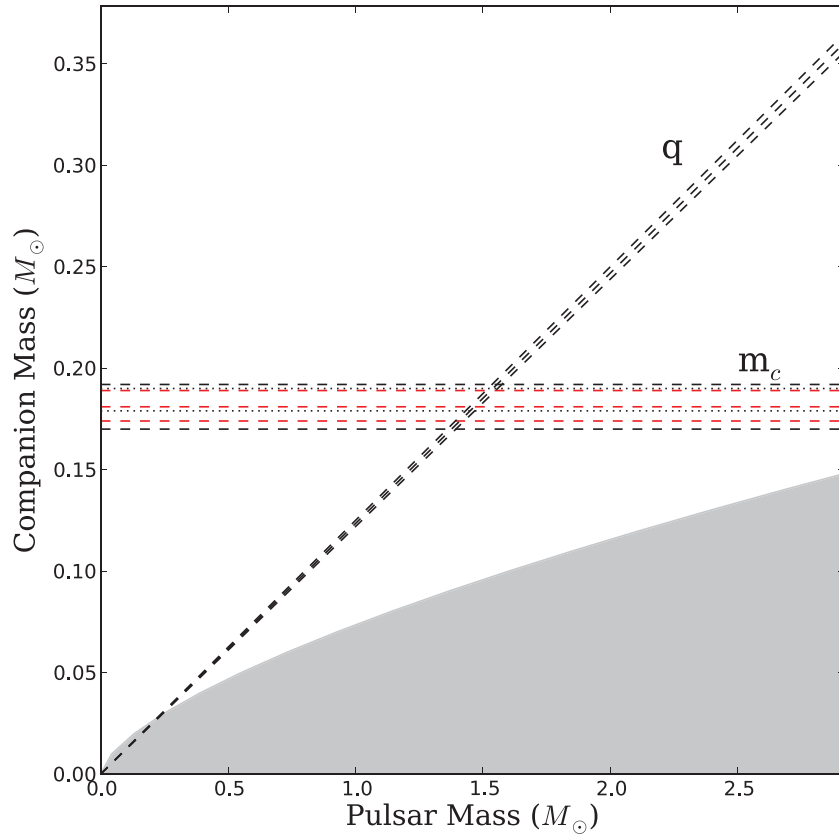
The above analysis demonstrates that with the current set of observations it is difficult to constrain the cooling age of the WD, since this depends on both the thickness of the WD envelope and the metallicity of its progenitor. Future, more precise constraints on the parallax, and consequently on the radius, might help to discriminate between different cases.

#### 4.9 3D velocity and Galactic motion

In Section 2 we computed the two components of the transverse velocity based on the parallax and proper motion estimates from radio timing measurements of the pulsar. Combined with the systemic radial velocity  $\gamma = -42 \pm 16 \text{ km s}^{-1}$  from the optical observations of the WD (Table 1), we have the full 3D velocity and can compute the Galactic path back in time (as was done for PSR J1012+5307 by Lazaridis et al. 2009). For our calculations we have used the Galactic potential of Kenyon et al. (2008), verifying our results with those of Kuijken & Gilmore (1989) and Paczynski (1990). We infer that the PSR J1738+0333 system has an eccentric orbit with a Galactocentric distance between 6 and 11 kpc, and an oscillating  $Z$ -motion with an amplitude of 1 kpc and a (averaged) period of 125 Myr. We also calculated the peculiar velocity of the system with respect to the local standard of rest at every transition of the Galactic plane ( $Z = 0$ ) during the last 4 Gyr, and find that it ranges between 70 and 160 km s<sup>-1</sup>. We will discuss this further in Section 5.1.

### 5 RAMIFICATIONS

In Table 2 we list the properties of the system derived in previous sections, and in Fig. 5 we show our constraints on the masses. In what follows we discuss the ramifications of our work for stellar and binary astrophysics.



**Figure 5.** Constrains on the masses derived from our observations. The shaded region is excluded because it would require  $\sin i > 1$ . Our constraint on the mass ratio is indicated by diagonal lines, and that on the WD mass by horizontal lines, with the red ones giving the central value and  $1\sigma$  uncertainties using the mass–radius relation of Panei et al. (2000), the black dashed ones the  $1\sigma$  range inferred using the models of Panei et al. (2007) and the black dotted the  $1\sigma$  limit based on Serenelli et al. (2001).

### 5.1 Kinematics

PSR J1738+0333 has a velocity of  $85 \pm 17 \text{ km s}^{-1}$  with respect to the local standard of rest that corotates with the Galaxy ( $Z = 0$ ) at the distance of the pulsar. The latter compares well with the mean transverse velocity for the bulk of MSPs with measured proper motions (e.g.  $\sim 85 \text{ km s}^{-1}$  according to Hobbs et al. 2005). Our semi-quantitative analysis in Section 4.8 shows that the system’s velocity varies as much as  $150 \text{ km s}^{-1}$  over the course of its Galactic orbit. Based on the simplified potential of Kenyon et al. (2008) used herein, PSR J1738+0333 has a peculiar velocity between 70 and  $160 \text{ km s}^{-1}$  when it crosses the Galactic plane ( $Z = 0$ ). Thus, assuming that the system had a small peculiar motion before the supernova (SN) explosion, the systemic velocity after the formation of the neutron star must have been in that range. This is consistent with an SN explosion with a small, or even negligible, kick (Nice & Taylor 1995; Tauris & Bailes 1996).

### 5.2 Evolutionary history

MSPs with low-mass helium WD companions are expected to form through mainly two different channels depending on the initial separation of the progenitor binary (e.g. Tauris 2011, and references therein). The initial separation of the progenitor binary determines the evolutionary status of the donor star at the onset of the Roche lobe overflow (RLO).

(i) *Case A RLO.* For systems with initial periods short enough to initiate mass transfer on the main sequence, it is expected that

magnetic braking (aided to some extent by gravitational radiation) drives the system to shorter periods, resulting in a compact binary in an orbit which is close to being perfectly circular (the eccentricity,  $e < 10^{-5}$ ). These systems were first studied in detail by Pylyser & Savonije (1989).

(ii) *Case B RLO.* For progenitors with larger initial separations the mass transfer is expected to start at a later phase, since the star fills its Roche lobe only during shell hydrogen burning, while moving-up the red-giant branch. In this case the orbit will diverge resulting in a wider binary. Interestingly, for systems following this path, there are two theoretical predictions that can be verified observationally: the first is a correlation between the orbital period and the mass of the WD companion which results from the unique relation between the radius of the giant donor and the mass of its core which eventually forms the WD (Savonije 1987). The second is a correlation between the orbital eccentricity and the orbital period (Phinney 1992) arising because the turbulent density fluctuations in the convective envelope – of which the size increases in more evolved stars (wider orbits) – do not allow for a perfect tidal circularization.

The critical period that separates diverging from converging systems (often called bifurcation period) is expected to be  $\sim 1 \text{ d}$ ; however its precise value depends on the treatment of tidal interactions and magnetic braking (e.g. Pylyser & Savonije 1989; van der Sluys, Verbunt & Pols 2005; Ma & Li 2009) and is still a subject of debate. The residual eccentricity in binaries with radiative donors (i.e. those binaries that evolve to tight converging systems) should be

closer to zero compared to binaries in wider orbits but it is difficult to estimate by how much, as pointed out by Phinney & Kulkarni (1994).

With a current orbital period of 8.5 h, PSR J1738+0333 is most likely the fossil of the former case (Case A RLO). However it is interesting to note that our mass estimate and the non-zero eccentricity derived in Paper II pass both tests for the latter case mentioned above (Case B RLO) that predict  $m_c = 0.18 \pm 0.01 M_\odot$  (Tauris & Savonije 1999) and  $e \sim 4 \times 10^{-7}$ , respectively (deduced by extrapolating the Phinney 1992, relation to the observed period). This apparent agreement seems to be confirmed not only for PSR J1738+0333 but also for the other short-period LMWD binaries with measured masses (PSR J1012+5307, Lazaridis et al. 2009; PSR J0751+1807, Nice, Stairs & Kasian 2008), as well as low-mass WD companions to non-degenerate stars (e.g. van Kerkwijk et al. 2010; Breton et al. 2012). Since companion masses in converging systems are not expected to follow these relations; we cannot exclude a coincidence, but the matches seem to suggest that there is a grey zone with properties from both cases – something which should help improve our as yet rather simplified models of these systems.

### 5.3 Pulsar mass and efficiency of the mass transfer

Regardless of the evolutionary path followed, the mass transfer rate was sub-Eddington (e.g. Tauris & Savonije 1999) and thus one would expect that a substantial fraction of the mass leaving the donor was accreted by the neutron star. For PSR J1738+0333, this is demonstrably false: the minimum mass of the donor star can be constrained from our WD mass estimate to be  $\gtrsim 1 M_\odot$  because the available time for evolution is limited by the Hubble time (minus the cooling age of the WD). The amount of mass lost by the donor is  $M_{\text{donor}} - M_{\text{WD}}$ , while the amount accreted by the pulsar is  $M_{\text{PSR}} - M_{\text{PSR}}^{\text{init}}$ , with the last term being the birth mass prior to accretion. For any realistic birth mass of the neutron star at the low end of its ‘canonical’ birth mass range ( $\gtrsim 1.20 M_\odot$ ), we find that more than 60 per cent of the in-falling matter must have escaped the system (after correcting for the conversion from baryonic mass to gravitational mass). This translates to an accretion efficiency of only  $\varepsilon < 0.40$ . This result confirms the findings of Tauris & Savonije (1999) who concluded that a substantial fraction of the transferred matter in low-mass X-ray binaries is lost from the system, even at sub-Eddington mass-transfer rates.

More constraining (but less stringent) estimates are also obtained for the 6.3 h orbital period binary, PSR J0751+1807 (Nice et al. 2008) for which we find  $\varepsilon \sim 0.1\text{--}0.3$ .

Possible mechanisms for mass ejection discussed in the literature include propeller effects, accretion disc instabilities and direct irradiation of the donor’s atmosphere from the pulsar (e.g. Illarionov & Sunyaev 1975; van Paradijs 1996; Dubus et al. 1999). Alternatively, the neutron star in PSR J1738+0333 might have formed via the accretion-induced collapse of a massive ONeMg WD (e.g. Nomoto & Kondo 1991). If the neutron star was formed towards the end of the mass transfer it would not have accreted much since its birth. A possible problem with the above mechanism, however, is that it is specific to pulsars, while similarly inefficient accretion has been found also for low-mass WDs with non-degenerate companions (e.g. Breton et al. 2012), suggesting the problem in our understanding is more general. Finally, we note that even major inefficiencies in the mass accretion process do not pose a problem for the recycling scenario: the accreted mass needed to spin-up a pulsar to an  $\sim 5$  ms period is only of the order of  $0.05 M_\odot$ .

## 6 CONCLUSIONS

The main result of this work is the determination of the component masses of the PSR J1738+0333 system and adds to the three previously known MSP-LMWD binaries with spectroscopic information [PSR J1012+5307, van Kerkwijk et al. (1996) and Callanan et al. (1998); PSR J1911–5958A, Bassa et al. (2006); PSR J1909–3744 (vK+12)].

Our mass estimates are derived independently of any strong-field effects and thus transform the PSR J1738+0333 system into a gravitational laboratory, which – due to its short orbital period, gravitationally asymmetric nature and timing stability – provides the opportunity to test the radiative properties of a wide range of alternatives to GR (see Paper II for details).

Based on our measurements of the component masses, GR predicts an orbital decay of  $\dot{P}_b = -2.77_{-0.19}^{+0.15} \times 10^{-14}$ . While the actual  $\dot{P}_b$  inferred observationally is still less precise than this prediction, it will eventually provide a precise test for the input physics of atmospheric and evolutionary models. Assuming the validity of GR, one can confront the spectroscopic WD mass estimate implied by the mass ratio and intrinsic orbital decay of the system and thus test the assumptions for stellar astrophysics and WD composition that were used to model the evolution of the WD. Additionally, this mass estimate, combined with parallax and absolute photometry, constrains independently the surface gravity of the WD. The current estimates on these parameters imply a surface gravity of  $\log g = 6.45 \pm 0.07$  dex. While this is formally more accurate than our spectroscopic constraint, it might still be dominated by systematics on the distance, arising from correlations between the parallax and DM variations (see Paper II for details).

Finally, the interpretation of the mass estimates within the context of our current understanding for binary evolution implies that a significant fraction of the accreted material during the LMXB phase is ejected by the system. The discovery and study of more similar systems in the future will allow further tests of this result.

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