THE MASS OF THE WHITE DWARF IN GW LIBRA

L. van Spaandonk1, D. Steeghs1, 2, T. R. Marsh1, and S. G. Parsons1

1 Astronomy and Astrophysics, Department of Physics, University of Warwick, Coventry CV4 7AL, UK; lvan-spaandonk@warwick.ac.uk
2 Harvard-Smithsonian for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA

Received 2010 February 24; accepted 2010 April 19; published 2010 May 6

ABSTRACT

We report a mass and rotational broadening ($v \sin i$) for the pulsating white dwarf (WD) component of the WZ Sge type Dwarf Nova GW Lib based on high-resolution Very Large Telescope spectroscopy that resolves the Mg ii 4481 Å absorption feature. Its gravitational redshift combined with WD mass–radius models provides us with a direct measurement of the WD mass of $M_1 = 0.84 \pm 0.02 M_\odot$. The line is clearly resolved and if associated with rotational broadening gives $v \sin i = 87.0 \pm 3.4$ km s$^{-1}$, equivalent to a spin period of 97 ± 12 s.

Key words: binaries: spectroscopic – novae, cataclysmic variables – stars: individual (GW Lib)

1. INTRODUCTION

The population of cataclysmic variables (CVs) provides an important sample of binary systems possessing homogeneous configurations of white dwarfs (WDs) accreting from near main-sequence donor stars. A CV initially evolves toward shorter orbital periods, but near a period of $\sim$75 minutes bounces back toward longer periods with its donor star turning into a degenerate brown dwarf. Recent CV searches, such as the significant harvest of CVs from Sloan Digital Sky Survey (Szkydy et al. 2009; Günsicke et al. 2009), are finally unearthing large numbers of systems at short orbital periods as expected from binary evolution considerations.

Reliable estimates for binary parameters are needed to place individual systems on their evolutionary tracks. The faintness of the low-mass donor stars in comparison to the WD and its accretion flow makes such parameter estimates difficult for short-period systems (e.g., WZ Sge; Steeghs et al. 2001, 2007), except in favorable cases where eclipse constraints can be exploited (Littlefair et al. 2006). Patterson (2001) has identified an indirect method of inferring binary mass ratios using the tidally driven superhump modulations in the light curves of CVs. Although promising, this furthermore highlights the need for suitable calibrator systems for which binary parameters can be accurately determined independently.

GW Lib is a short-period dwarf nova ($P_{orb} = 76.78$ minutes; Thorstensen et al. 2002) displaying the typical characteristics of a CV near its period minimum. Crucially, it was the first CV discovered to contain a pulsating WD (van Zyl et al. 2004), by analogy with field WD pulsators that lie in the instability strip for non-radial pulsations. So far, various methods to determine its system parameters have been exploited, including model fits to the WD absorption profiles, prominent in both the optical (Thorstensen et al. 2002) providing estimates for the WD $T_\text{eff}$ and log $g$. Asteroseismological models, combined with a UV-flux limit, suggest a WD mass of $M_1 = 1.02 M_\odot$ (Townsley et al. 2004). After its second recorded super-outburst in 2007 April (Templeton 2007), the superhump period suggests a mass ratio of $q = M_2/M_1 = 0.06$ (Kato et al. 2008) when combined with Patterson’s empirical relation (Patterson et al. 2005).

In this Letter, we explore the possibilities of using the gravitational redshift of the Mg ii absorption line reported in van Spaandonk et al. (2010) in combination with mass–radius relations to give an independent measurement of the mass and spin of the WD in GW Lib.

2. OBSERVATIONS AND REDUCTION

GW Lib was observed within the 69.D-0591 program at the 8.4 m Very Large Telescope (VLT), located at the Paranal Observatory in Chile as part of the European Southern Observatory, equipped with only the blue arm of the Ultraviolet and Visual Echelle Spectrograph (UVES; Dekker et al. 2000). We retrieved a total of 45 science frames obtained during 2002 May 16–17 covering 2.4 and 2.8 binary orbits on the respective nights. The reduction of the raw frames was conducted using the most recent standard recipe pipeline release of the UVES Common Pipeline Library recipes. The resultant optimally extracted spectra covered a wavelength range of 4020–5240 Å at a dispersion of 0.031 Å pixel$^{-1}$ and a spectral resolution of 0.10 Å (5.77 km s$^{-1}$) as measured from the skylines. The spectra were wavelength calibrated with one Thorium Argon arc per night. This calibration was tested against the two sky lines visible at 5197.92 Å and 5200.28 Å. The corresponding science frames were corrected for any remaining shifts. The residuals were scattered around zero with a maximum amplitude of 0.01 km s$^{-1}$. Next, heliocentric velocity corrections were applied to the individual frames to deliver spectra in a common heliocentric rest frame.

No standard was observed in the correct settings on the nights and as no master response curve exists for the non-standard setup used, the frames were not flux calibrated. The exposure time was 500 s giving a signal to noise of $\sim$6.5 per spectrum. Details of the observations can be found in Table 1 while Figure 1 shows the average spectrum of GW Lib on May 16. Prominent features are the Balmer disk emission lines on top of broad absorption troughs from the WD, visible due to the low-mass accretion rate in the system. He i is also seen in emission as is He ii at 4685.75 Å.

Our pre-outburst, intermediate resolution spectra of GW Lib showed Mg ii at 4481.21 Å in absorption (see Figure 2; van Spaandonk et al. 2010). The archival VLT/UVES data confirm the presence of this line and thanks to the superior spectral resolution combined with the low inclination of the system shows it to be unblended from the nearby He i emission at 4471 Å. We measure an EW of $0.25 \pm 0.01$ Å (similar to $0.24 \pm 0.03$ Å in 2004) and an FWHM of 1.35 ± 0.04 Å.
3. GRAVITATIONAL REDSHIFT FOR Mg II

In low-accretion rate dwarf novae, the luminosity of the accretion disk is low enough to show the broad absorption features of the WD and can even show the narrow absorption features of metal lines due to freshly accreted gas. These lines open a window to probe the WD atmosphere directly and give independent measurements of stellar parameters. For lines formed near the primary, a gravitational redshift is expected, introduced in the deep gravitational potential of the WD (Eddington 1924; Greenstein & Trimble 1967; Sion et al. 1994). A measurement of the gravitational redshift in the rest frame of the binary could provide the WD mass directly when combined with mass–radius models (e.g., Eggleton’s relation as quoted in Verbunt & Rappaport 1988). This method has previously been used in CVs in the cases of U Gem (Long & Gilliland 1999), VW Hyi (Smith et al. 2006), and WZ Sge (Steeghs et al. 2007).

In the case of GW Lib, the directly measured redshift of the magnesium line ($v_{\text{Mg II}}$) needs to be rectified for several contributions in order to get the true gravitational redshift induced by the WD only ($v_{\text{grav}}(\text{WD})$). These corrections consist of the systemic velocity ($\gamma$) of the binary system and the effects of the gravitational potential from the donor star ($v_{\text{grav}}(\text{donor})$). Hence, the gravitational redshift due to the WD is given by

$$v_{\text{grav}}(\text{WD}) = v_{\text{Mg II}} - v_{\text{grav}}(\text{donor}) - \gamma.$$

We will discuss the various contributions and measurements independently. First, all 45 spectra of the two nights were individually continuum normalized and then binned into 20 equally spaced orbital phase bins to increase signal-to-noise ratio (S/N).

3.1. $v_{\text{Mg II}}$

To measure the redshift of the magnesium line to the best precision and minimize any orbital effect, we compared several methods.
4481.126 Å with a transition probability of $\log(gf) = 0.7367$, 4481.150 Å with $\log(gf) = -0.5643$, and 4481.325 Å with $\log(gf) = 0.5818$. The variables for the fit are the common offset (for all three lines) and the common FWHM to provide a good fit to the blue wing of the absorption feature. The peak height is also a common variable but scaled according to the various transition probabilities. This gives a best fit with a mean offset of $35.2 \pm 1.1$ km s$^{-1}$, an FWHM of $1.32 \pm 0.08$ Å, and a common absorption line depth of $2 \pm 0.1\%$.

Second, we fixed the FWHM and peak of the Gaussians to these values and checked the individual spectra for orbital variability. Unfortunately, the S/N is too low to give good individual fits (individual 1σ errors on the offset are $\sim 8$ km s$^{-1}$) nor can we phase-lock this motion to the ephemeris of the system as determined in van Spaandonk et al. (2010) due to the uncertainty in the period. The resultant radial velocity curve suggested motion, and a formal sine fit delivered a semi-amplitude of $K = 13 \pm 2$ km s$^{-1}$. To rectify for any orbital motion, we removed any measured shift compared to the mean from individual spectra.

A uniform orbital average was constructed to minimize any effects caused by varying S/N over the orbital period, and finally we refit this last average with our triple Gaussian fit with variables the common offset, the common FWHM, and the weighted peak as described before (see the inset of Figure 1).

This gives a final measurement of $v_{\text{grav, WD}} = 35.8 \pm 1.5$ km s$^{-1}$. The line has an FWHM = $1.30 \pm 0.05$ Å. We have tested the accuracy of our measurement by following different recipes for combining and averaging the spectra, but note that the uncertainty on the gravitational redshift is dominated by the S/N and resolution of the data and not the specific recipe used.

3.2. $v_{\text{grav}}$(donor)

The first correction is due to the influence of the gravitational potential of the donor on the magnesium line. However, the expected low mass of the donor star ($\sim 0.05 M_{\odot}$) gives only a small correction of $0.06 \pm 0.02$ km s$^{-1}$ near the WD surface, effectively negligible given the measurement uncertainty.

3.3. The Systemic Velocity $\gamma$

From simultaneous double Gaussian fits to the double peaked Hβ and Hγ disk lines, combined with radial velocity curve fits provide a systemic velocity of $-12.3 \pm 1.2$ km s$^{-1}$ and a semi-amplitude of $K_{\text{disk}} = 36.4 \pm 1.8$ km s$^{-1}$. These values are consistent with previously derived values (Thorstensen et al. 2002; van Spaandonk et al. 2010).

As we measure $\gamma$ from disk lines, we need to take into account that this emission is red-shifted both by the WD and the donor star. As $v_{\text{grav}}$ is reciprocal to the distance, the amount we have to account for is minimal at the edge of the disk, $R_{\text{outer, disk}} = 2.2 \times 10^8$ m (Equation 2.61 of Warner 1995) giving a minimal correction to $v_{\text{grav}}$ of 1.7 km s$^{-1}$. A more realistic value comes from the projected Keplerian velocity at the edge of the disk $K_{\text{disk}} \sim 200$ km s$^{-1}$ (from the location of the disk ring in Doppler maps and the estimate for $i$, see van Spaandonk et al. 2010) which gives a Kepler speed of $v_{\text{disk}} = K_{\text{disk}}/\sin i \sim 1070$ km s$^{-1}$ and corresponds to a $v_{\text{grav}} = v^2/c \sim 3.8$ km s$^{-1}$. Including the transverse Doppler redshift (at half the strength of the gravitational redshift), the total gravitational redshift at the location of the disk lines amounts to $5.7 \pm 1.6$ km s$^{-1}$. The gravitational potential of the donor star has an effect of only $0.08 \pm 0.02$ km s$^{-1}$ at a distance of $\sim 3 \times 10^8$ m. Hence the total $v_{\text{grav}}(\text{disk}) = 5.8 \pm 1.6$ km s$^{-1}$.

The $\gamma$ from the disk lines combined with the above correction should be consistent with the $\gamma$ suggested by the radial velocity curve from the donor star (corrected for the effects of the gravitational potential at its surface). From the Ca ii emission line in the $I$ band we previously found $\gamma = -13.1 \pm 1.2$ (van Spaandonk et al. 2010), the correction at the surface of the donor star is $0.34 \pm 0.15$ km s$^{-1}$ from the donor star and $1.4 \pm 0.2$ km s$^{-1}$ from the WD (again including the transverse Doppler shift). Thus, we have $\gamma_{\text{disk}} = (-12.3 \pm 1.2) - (5.8 \pm 1.6) = -18.1 \pm 2.0$ and $\gamma_{\text{donor}} = (-13.1 \pm 1.2) - (1.7 \pm 0.3) = -14.8 \pm 1.2$. Both estimates for $\gamma$ are indeed consistent and with similar precision. Hence, we have used $\gamma_{\text{disk}}$ as it is derived from the same data set.

3.4. The Implied WD Mass

Combining all values we find for the final gravitational redshift:

$$v_{\text{grav}}(\text{WD}) = (35.8 \pm 1.5) - (0.06 \pm 0.02)$$
$$= (35.8 \pm 1.5) - (-18.1 \pm 2.0) = 53.8 \pm 2.5 \text{ km s}^{-1}.$$ 

When combined with theoretical and empirical models for the mass–radius relationship for WDs, this gives a direct measurement of the WD mass. The models we used are Eggletons zero-temperature mass–radius relation as quoted by Verbunt & Rappaport (1988) and several appropriate non-zero temperature models for GW Lib from Fontaine et al. (2001). We plot these models in Figure 2 together with the $M_1(R)$ line demanded by our measured $v_{\text{grav}}$. Accommodating the intersections between non-zero temperature models we find that $M_1 = 0.84 \pm 0.02 M_{\odot}$.

3.5. System Parameters and WD Spin

Kato et al. (2008) reported the detection of superhump modulations in GW Lib. Combining this with the period from Thorstensen et al. (2002) and the improved superhump excess–mass ratio relation given by Knigge (2006), the implied mass ratio of the system is $q = 0.060 \pm 0.008$. We previously determined the projected radial velocity of the donor star, $K_2$ in van Spaandonk et al. (2010). Thus with an independent determination of $M_1$ from this Letter, we can solve the system parameters for GW Lib under these constraints and list these in Table 2.

If one assumes that the width of the Mg ii absorption line is dominated by rotational broadening, its FWHM can constrain the spin period of the WD. The FWHM of the absorption line fit is measured to be $1.30 \pm 0.05$ Å which corresponds to a $v \sin i$ of $87.0 \pm 3.4$ km s$^{-1}$ at this wavelength. Assuming $i$ is close to the value giving in Table 2, this translates into a rotation speed of $448 \pm 24$ km s$^{-1}$ at the surface of the WD. For a WD of mass $0.84 \pm 0.02 M_{\odot}$ and a radius for $(6.95 \pm 0.15) \times 10^8$ cm this results in a spin period of the WD of $97 \pm 12$ s.

4. DISCUSSION

We have measured the gravitational redshift of the Mg ii absorption line in high-resolution echelle spectra of GW Lib
Table 2

System Parameters for GW Lib

| Parameter | Value |
|-----------|-------|
| P (minutes) | 76.78 ± 0.03 |
| M (M⊙)    | 0.84 ± 0.02 |
| q          | 0.060 ± 0.008 |
| K₂ (km s⁻¹) | 100.8 ± 7.1 |
| K₁ (km s⁻¹) | 6.25 ± 0.4 |
| M₂ (M⊙)    | 0.050 ± 0.007 |
| v₁ (km s⁻¹) | 30.8 ± 0.5 |
| v₂ (km s⁻¹) | 513.4 ± 4.8 |
| i (°)      | 11.2 ± 0.4 |
| Pspin(s)   | 97 ± 12 |

During quiescence. Assuming an origin in the photosphere of the accreting WD, we combined this redshift with non-zero temperature mass–radius relations for WDs to derive a WD mass of 0.84 ± 0.02 M⊙. Combining this independent measurement with other constrains confirms that GW Lib is a low-mass ratio system observed at very low inclination (Table 2). Because the Mg ii line was well resolved in our data, we could also estimate the spin period of the WD to be 97 ± 12 s if we assume the width of the line to be dominated by rotational broadening.

Our mass value is significantly below the 1.02 M⊙ lower limit derived by Townsley et al. (2004). However, their choice of preferred solution was largely driven by the WD size as implied by the measured UV flux. Szkody et al. (2002) fitted WD models to UV spectra of GW Lib. Two different single temperature solutions were explored: d = 171 pc (M₁ = 0.6 M⊙/vgrav ~ 29 km s⁻¹) and d = 148 pc (M₁ = 0.8 M⊙/vgrav ~ 49 km s⁻¹) respectively. These solutions can be corrected to the latest parallax distance of 100±13 pc (J. R. Thorstensen 2009, private communication—improvement of the distance in Thorstensen et al. 2002). At this distance, the observed UV flux implies a radius of 5 × 10⁸ cm (for a WD temperature of 14,700 K). However, such a small radius intersects the mass–radius relations at 1.07 M⊙ (Figure 2, horizontal solid line) and was indeed the reason Townsley et al. (2004) ruled out their lower mass solutions. Such a massive WD would result in vgrav ~ 95 km s⁻¹, much larger than our measured redshift would suggest. We note that Szkody et al. (2002) fail to find a good single temperature fit and claim the best fit arises fitting a dual temperature model to the spectrum, allowing for a cooler zone that would place GW Lib within the ZZ Ceti instability strip for pulsating single WDs. However, the UV-flux versus implied WD radius then becomes a less clear-cut argument given the freedom of two temperatures and the surface coverage split between the two. We note that the reverse has been seen in U Gem where the UV-flux places the WD at a lower mass than the gravitational redshift suggests (Long & Gilliland 1999; Long et al. 2006).

As Townsley et al. (2004) warn, no WD rotation was included in their asteroseismological models and therefore their derived parameters (M₁, Macc, M) may need to be revisited given our estimate of the spin period of the WD in GW Lib. A Pspin ≤ 97 ± 12 s should give rise to rotationally split modes. van Zyl et al. (2004) conducted a thorough campaign with a baseline of over 4 years to find these modes in the power spectrum of GW Lib. The extensive search revealed a possible doublet around the 230 s mode with a frequency difference between the components of 0.79 μHz. If this doublet originates from the rotation splitting of an l = 1 mode, the WD would have a spin period of ~7.3 days which is much longer than expected for the WD in a CV. Approached from the other side, if a similar mode is split as a result of a rotation period of ~100 s, the frequency difference would be ~0.5 mHz and should be visible in the power spectrum. Note that for the proposed spin period, the first-order approximation for frequency splitting is no longer valid and the splitting would become asymmetric.

From both GW Lib’s and U Gem’s comparison between WD mass found by gravitational redshift and the constraints from the UV-flux we can conclude that the measurement of the gravitational redshift through WD absorption lines gives in principle a good measurement of the WD mass in CVs, but is not always fully consistent with other constraints. Nonetheless, it suggests photospheric absorption lines in the atmospheres of accreting WDs can be a viable tool for mass measurements, in particular for low-mass accretion rate CVs where the light from the WD dominates and especially for low i systems.

For GW Lib itself, we are still dependent on a number of assumptions in order to solve its system parameters. To properly align all methods, we need to revisit the mass from asteroseismology taking into account the effects of rotation and see if a WD model with a mass of 0.84 M⊙ at the latest distance can be fitted to the UV data with reasonable temperatures. To be able to calculate a direct mass ratio, a determination of K₁ from the Mg ii should be possible through high S/N phase-resolved spectroscopy. If furthermore matched with an solid ephemeries using the emission from the donor star (giving K₂ and γ), a fully consistent and accurate WD mass for this prototypical accreting WD pulsator is entirely feasible.

D.S. acknowledges an STFC Advanced Fellowship. T.R.M. was supported by an STFC Rolling Grant. Based on observations made with ESO Telescopes at the Paranal Observatory under program ID 69.D-0591.

REFERENCES

Dekker, H., D’Odorico, S., Kauff, A., Delabre, B., & Kotzlowski, H. 2000, Proc. SPIE, 4008, 534
Eddington, A. S. 1912, MNRAS, 84, 308
Fontaine, G., Brassard, P., & Bergeron, P. 2001, PASP, 113, 409
Gänsicke, B. T., et al. 2009, MNRAS, 397, 2170
Greenstein, J. L., & Trimble, V. L. 1967, ApJ, 149, 283
Kato, T., Machara, H., & Monard, B. 2008, PASJ, 60, L23
Knigge, C. 2006, MNRAS, 373, 484
Littlefair, S. P., Dhillon, V. S., Marsh, T. R., Gänsicke, B. T., Southworth, J., & Watson, C. A. 2006, Science, 314, 1578
Long, K. S., Brammer, G., & Froning, C. S. 2006, ApJ, 648, 541
Long, K. S., & Gilliland, R. L. 1999, ApJ, 511, 916
Patterson, J. 2001, PASP, 113, 736
Patterson, J., et al. 2005, PASP, 117, 1204
Sion, E. M., Long, K. S., Szkody, P., & Huang, M. 1994, ApJ, 430, L53
Smith, A. J., Haswell, C. A., & Hynes, R. I. 2006, MNRAS, 369, 1537
Steeghs, D., Marsh, T., Knigge, C., Maxted, P. F. L., Kuulkers, E., & Skidmore, W. 2001, ApJ, 562, L145
Steeghs, D., Howell, S. B., Knigge, C., Gänsicke, B. T., Sion, E. M., & Welsh, W. F. 2007, ApJ, 667, 442
Szkody, P., Gänsicke, B. T., Howell, S. B., & Sion, E. M. 2002, ApJ, 575, L79
Szkody, P., et al. 2009, AJ, 137, 4011
Templeton, M. R. 2007, AAVSO Alert Notice, 349, 1
Thorstensen, J. R., Patterson, J., Kemp, J., & Vennes, S. 2002, PASP, 114, 1108
Townley, D. M., Arras, P., & Bildsten, L. 2004, ApJ, 608, L105
van Spaandonk, L., Steeghs, D., Marsh, T. R., & Torres, M. A. P. 2010, MNRAS, 401, 1857
van Zyl, L., et al. 2004, MNRAS, 350, 307
Verbunt, F., & Rappaport, S. 1988, ApJ, 332, 193
Warner, B. 1995, Cataclysmic Variable Stars (Cambridge: Cambridge Univ. Press)