PEERING INTO THE DARK SIDE: MAGNESIUM LINES ESTABLISH A MASSIVE NEUTRON STAR IN PSR J2215+5135

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ABSTRACT

New millisecond pulsars (MSPs) in compact binaries provide a good opportunity to search for the most massive neutron stars. Their main-sequence companion stars are often strongly irradiated by the pulsar, displacing the effective center of light from their barycenter and making mass measurements uncertain. We present a series of optical spectroscopic and photometric observations of PSR J2215+5135, a “redback” binary MSP in a 4.14 hr orbit, and measure a drastic temperature contrast between the dark/cold ($T_N=5660^{+260}_{-480}$ K) and bright/hot ($T_D=8980^{+470}_{-280}$ K) sides of the companion star. We find that the radial velocities depend systematically on the atmospheric absorption lines used to measure them. Namely, the semi-amplitude of the radial velocity curve of J2215 measured with magnesium triplet lines is systematically higher than that measured with hydrogen Balmer lines, by 10%. We interpret this as a consequence of strong irradiation, whereby metallic lines dominate the dark side of the companion (which moves faster) and Balmer lines trace its bright (slower) side. Further, using a physical model of an irradiated star to fit simultaneously the two-species radial velocity curves and the three-band light curves, we find a center-of-mass velocity of $V_2=412.3^{+5.0}_{-2.7}$ km s$^{-1}$ and an orbital inclination $i=63.9^{+2.4}_{-2.5}$. Our model is able to reproduce the observed fluxes and velocities without invoking irradiation by an extended source. We measure masses of $M_1=2.27^{+0.17}_{-0.15}$ M$_\odot$ and $M_2=0.33^{+0.03}_{-0.02}$ M$_\odot$ for the neutron star and the companion star, respectively. If confirmed, such a massive pulsar would rule out some of the proposed equations of state for the neutron star interior.

Keywords: pulsars: general — pulsars: individual (PSR J2215+5135) — stars: neutron — binaries: general — stars: variables: general — X-rays: binaries

1. INTRODUCTION

New millisecond pulsars (MSPs) in compact binaries (orbital period $P_{\text{orb}}\lesssim 1$ d) are being discovered with the advent of the Fermi large area telescope (LAT; Atwood et al. 2009). Their companion or secondary stars are light ($\lesssim 0.1$ M$_\odot$ in the so-called redbacks) or ultralight ($\lesssim 0.01$ M$_\odot$ in the black widows), and in some cases they are strongly irradiated by the pulsar wind and high-energy radiation powered by the neutron star’s rotational energy loss ($\dot{E}$). Furthermore, three of the nearly twenty known redback MSPs have shown transitions between the radio-pulsar and accretion-disk states, which has provided a long-sought link between MSPs and low-mass X-ray binaries (LMXBs; Archibald et al. 2009; de Martino et al. 2013; Papitto et al. 2013; see Linares 2014 for a review of redback states).

Most of these new compact binary MSPs are relatively nearby ($\lesssim 4$ kpc) and far from the Galactic plane ($\gtrsim 5^\circ$), where interstellar extinction is low. This allows for sensitive optical spectroscopic observations and dynamical studies of the companion star in its orbit around the pulsar, and offers a new opportunity to measure the mass of spun-up “recycled” neutron stars (e.g., Romani & Shaw 2011; Kaplan et al. 2013; Crawford et al. 2013). However, as we discuss in the present work, the effects of irradiation on the measured radial velocities must be carefully taken into account in order to avoid systematic uncertainties.

PSR J2215+5135 (J2215 hereafter) was discovered as a 2.61-ms MSP in radio searches of the LAT source 1FGL J2216.1+5139 (i.e., 2FGL J2215.7+5135 or 3FGL J2215.6+5134), and to date has the shortest $P_{\text{orb}}$ among Galactic field redbacks ($P_{\text{orb}}\lesssim 4.14$ hr; Hessels et al. 2011). Even though this system has been observed so far only in the (disk-free, rotation powered) pulsar state, Linares (2014) found a relatively high X-ray luminosity $L_X\sim 10^{32}$ erg s$^{-1}$, suggesting J2215 as a candidate for future transitions to an accreting state. Optical photometry revealed a $V=20.2–18.7$ mag counterpart with orbital variability typical of strongly irradiated systems (Breton et al. 2013; Schroeder & Halpern 2014). Modelling the optical lightcurves (LCs) can determine the inclination of the orbit which, together with the precise ephemerides obtained from pulsar timing, may allow a full orbital solution and a neutron star mass measurement (e.g., van Kerkwijk et al. 2011). However, the orbital parameters for J2215 presented by van Kerkwijk et al. (2011) differ by a large amount, yielding inconsistent neutron star masses $M_{\text{NS}}$ in the range 1.6–2.5 M$_\odot$.

We present here the results of a new set of observations of J2215 taken in 2014 with three different tele-
scopes (Section 2), including the 10.4-m *Gran Telescopio Canarias* (GTC). These reveal an extreme temperature contrast between the cold/dark (“night”) and hot/bright (“day”) faces of the secondary star (Section 3.1). In order to place tighter independent constraints on $M_{NS}$ and to investigate systematic effects on dynamical studies of this new class of pulsars, we carefully measure the spectral type and radial velocity of the companion along the orbit (Sec. 2.3).

We find that the apparent radial velocities of J2215 depend on both the spectral range and the reference/template spectrum used to measure them (Sec. 3.2). In Section 4, we model jointly the observed LCs and radial velocities, including for the first time dynamical information of the cold/dark side of the companion. We find a new orbital solution (Sec. 4.2) with an extremely massive neutron star (Sec. 5.3). We discuss these results in Section 5 as well as the implications for dynamical studies in compact binaries with strong irradiation. Section 6 contains a summary of our main results and conclusions.

![Figure 1.](image)

**Figure 1.** *Top:* Optical light curves of J2215 in three bands, as indicated. Data points show our 2014 IAC-80 & WHT observing campaign and lines (solid, dotted and dashed) show the 2010-2011 results from Schroeder & Halpern (2011). Error bars on the top right corner show the uncertainty on the magnitude calibration (Sec. 2.1) errors on differential magnitude are plotted but smaller than the symbols. *Middle:* Color variation along the orbit showing redder/colder emission around light minimum (orbital phase 0). *Bottom:* Radial velocity curve from our WHT-ISIS spectra, calculated by cross-correlating the full spectra (red and blue arms) with an F5 template. The averages used for optimal subtraction are shown with gray-shaded rectangles (Sec. 2.3).

2. **Observations, Reduction and Analysis**

2.1. **Photometry**

We obtained phase-resolved photometric observations of PSR J2215+5135 with the IAC-80 and William Herschel (WHT) telescopes at the Teide and Roque de los Muchachos observatories, respectively, on four different nights (see Table 1). The IAC-80 images were taken on 2014 August 2–3 with the Teide observatory light improved camera (CAMELOT; 0.30 arcsec pixel$^{-1}$) using the SDSS filters g' and r', an exposure time of either 420s or 600s and a binning of 2x2 pixels in order to optimize the signal-to-noise ratio (S/N). The WHT images were taken on 2014 August 11 (contemporaneous with our WHT-ISIS spectra) and September 1, with the auxiliary-port camera (ACAM; 0.25 arcsec pixel$^{-1}$ in imaging mode) using the SDSS filters g', r' and i', an exposure time of 60s and a window of 501x501 pixels around the source in order to reduce readout time (readout and filter change resulted in deadtime of 6-9s per exposure).

All images were debiased and flat-fielded using standard *iraf* routines. We then performed aperture photometry using the ULTRACAM pipeline, a variable source extraction radius (set to 1.5–1.7 times the seeing) and a nearby stable non-saturated reference star. The resulting differential magnitudes are relative to a nearby star in the field and thus insensitive to thin clouds or moderate atmospheric variability (yet the observing conditions were generally good). The absolute flux (apparent magnitude) calibration was done using a nearby AAVSO-APASS star, with uncertainties of 0.05 mag (r') and 0.1 mag (g', i'), and checked against other nearby stars from the USNO-B1 catalog. We also compared these reference star magnitudes with those given by the PANSTARRS catalog, and found only a significant difference in the r' band, with a shift of +0.16 mag with respect to the APASS values that we use. We verified that this has no impact on any of the results reported in this work; in particular, the parameters reported in Section 4 are all consistent within the errors when using the PANSTARRS instead of the APASS calibration. Figure 1 (top) shows the J2215 LCs folded at the orbital period.

2.2. **Spectroscopy**

We observed J2215 with the WHT and GTC telescopes on 2014 August 11 and November 14–15, respectively, in order to obtain medium resolution spectra of the companion star and measure its spectral type and velocity along the orbit. For the WHT-ISIS spectra we chose the R600B (blue arm) and R600R (red arm) gratings centered at 4500 Å and 6400 Å, respectively. The slit width was set to 1", resulting into a resolution of 105–130 km s$^{-1}$ (R~2600) and 65–80 km s$^{-1}$ (R~4000) for the blue and red arms, respectively. At the GTC we used OSIRIS in its long-slit spectroscopy mode, with the R2000B VPH gratings and a slit width of 1", resulting into a resolution of 145–160 km s$^{-1}$ (R~2000). With this campaign we obtained 17 WHT-ISIS and 21 GTC-OSIRIS spectra covering the full 4.14-hr orbit with some redundancy and with exposure times of 900 s and 935 s, respectively (i.e., exposing each spectrum for about 6% of the J2215 orbit; see Table 1).

After applying bias and flat corrections to the trimmed
images within IRAF, we extracted the spectra and subtracted sky background using the optimal extraction method within STARLINK/PAMELA to account for the significant tilt. The GTC-ISIS spectra were calibrated in wavelength using interspersed arc spectra (CuNe, CuAr) extracted from the same source extraction regions, taken once every two source spectra. A set of well identified arc lines were satisfactorily fitted with a 4th order polynomial to produce the wavelength scale (47 and 31 lines in the blue and red arms, resulting into an rms amplitude of residuals of 0.05 Å and 0.02 Å, respectively). We adjusted the same polynomial function to all arc spectra and interpolated in time between adjacent arcs to calibrate the science spectra, thereby accounting for the significant (~1 Å) drift due to instrument flexure. The GTC-OSIRIS wavelength calibration was done using one set of arcs taken on the second night, fitting the pixel-wavelength relation with a 4th order polynomial (19 lines giving residuals with an rms amplitude of 0.06 Å). The resulting wavelength calibration was checked and refined using the OI sky line at 5577 Å, which allowed us to correct for residual (~10 km s\(^{-1}\)) shifts in the wavelength solution.

2.3. Spectral analysis

In order to measure the radial velocity and temperature of the companion star in J2215 throughout the orbit, we applied within MOLLY the cross correlation and optimal subtraction techniques, respectively. As both techniques require comparison spectra (or templates hereafter), we built a library of main-sequence stellar templates with spectral types between O4 and M0 (see Appendix A). The continuum level of all 38 source and 33 template spectra was normalized with a spline fit, and subtracted.

After binning to a same heliocentric velocity scale, excluding telluric lines and broadening the template spectra to the source spectral resolution (Sec. 2.2), each source and template spectra were cross correlated to find their relative velocity, allowing shifts between -700 and +700 km s\(^{-1}\). The resulting radial velocity curves (RVCs) from the GTC and WHT spectra were fitted with a sine function V=G+Ksin[2π(t-T\(_0\))/P\(_{\text{orb}}\)], where V and G are the radial and systemic velocities, K is the semi-amplitude of the RVC, t is the middle time of each spectrum, T\(_0\) is the time of inferior conjunction of the secondary which defines the orbital phase \(\phi=0\) and P\(_{\text{orb}}\) is the orbital period. Having checked that the best-fit period is consistent with (but less precise than) the orbital period from pulsar timing, this parameter was subsequently fixed at the pulsar timing value P\(_{\text{orb}}=0.1725021049[8]\) d.

Using the orbital parameters above, we corrected for the systemic velocity and orbital motion and shifted all source spectra to the reference frame of each template. In order to increase the S/N, we averaged 4–6 source spectra around \(\Phi=0\pm0.15\) and \(\Phi=0.5\pm0.125\). We then performed an optimal subtraction using the full GTC spectral range, i.e., subtracted the templates scaled by a factor f\(_{\text{tmpl}}\) from the source averaged spectra, adjusting f\(_{\text{tmpl}}\) to minimize the residual scatter. This is a quantitative way of matching the observed absorption lines from J2215 to a set of templates with known spectral types and temperatures (Marsh et al. 1994).

Because J2215 becomes very faint around \(\Phi=0\) (r>20 mag; Fig. 4 where the cold face of the companion star dominates), the corresponding ISIS spectra have low S/N. The tightest constraints on the spectral type and radial velocities come from the higher S/N GTC spectra, so we focus the rest of our analysis on those. Only one out of the 21 GTC spectra could not be included in the analysis due to the very low (<100 at peak) number of counts collected.

Table 1: Summary of optical observations of PSR J2215+5135.

| Telescope   | Instrument (configuration) | Bandwidth ( Å ) | Date (evening) | Time (UT) | Exposures (nr. x duration) | Orbital phase | Airmass | Seeing (") |
|-------------|-----------------------------|-----------------|---------------|-----------|-----------------------------|---------------|---------|------------|
| IAC-80 (80 cm) | CAMELOT (bin 2x2) | g',r' | 2014-08-02 | 22:53-04:01 | 4x420s | 0.4-1.6 | 1.47-1.09 | 1.1-2.5 |
| IAC-80 (80 cm) | CAMELOT (bin 2x2) | g',r' | 2014-08-03 | 23:32-03:52 | 30x420s | 0.3-1.3 | 1.32-1.09 | 0.4-0.7 |
| WHT (4.2 m) | ACAM (win. 501 x 501) | g',r',i'| 2014-08-11 | 22:15-00:03 | 95x60s | 0.4-0.8 | 1.48-1.18 | 0.7-1.6 |
| WHT (4.2 m) | ACAM (win. 501 x 501) | g',r',i'| 2014-09-01 | 23:17-02:06 | 149x60s | 0.4-1.0 | 1.13-1.09 | 0.8-1.4 |

*Effective wavelength of the photometric filters or approximate wavelength range covered by the spectra, in Angstroms.
Appendix A, the Balmer and Mg-I radial velocities allow us to track different parts of the irradiated companion throughout its orbit around the pulsar.

The cross correlation of two broad lines may yield ambiguous results if the profiles are not exactly the same. The matching wings can give two maxima in the cross correlation function, at velocities which differ from that measured using the line core (“double peaked” cross correlation functions). On close inspection of J2215’s RVCs, we found that this introduces strong artificial deviations from a sinusoidal function around phase 0.5, only when using Balmer lines and templates of spectral type earlier than F (i.e., when both source and template spectra are dominated by broad lines). For this reason, we include only spectral types later than F0 in our results for the Balmer-line RVCs (Section 3.2).

3. RESULTS

3.1. Temperature of the hot and cold sides

The optical flux from J2215 varies smoothly along the orbit (no flares are detected in the 60s cadence data), with one clear maximum and minimum per orbital cycle and a peak-to-peak amplitude of almost two magnitudes (g’, B bands). We find that the orbital LCs (Fig. 1) are stable over timescales of years, comparing our 2014 observations with the 2010-2011 data presented by Schroeder & Halpern (2014, converting their BVR magnitudes into the SDSS g’r’i’ system following Jordi et al. 2006). The ∼0.4 mag change in the [g’−r’] color reveals hotter emission at maximum light (Φ_orb=0.5). The RVC of the companion shows a large amplitude (K∼400 km s−1) and changes sign near the
maximum and minimum light ($\Phi_{\text{orb}}=0.5$ and 0, respectively), as can be seen already from the WHT spectra (Fig. 1) and as first reported by Romani et al. (2015). These properties are indicative of a companion star that is strongly irradiated by the pulsar throughout the compact 4.14 hr orbit.

![Figure 4](image)

**Figure 4.** Equivalent width (EW) of all (green diamonds), Balmer (blue squares) and Mg-I (red circles) absorption lines in the GTC spectra of J2215, as a function of orbital phase.

The J2215 spectra around $\Phi_{\text{orb}}=0.5$ (Figures 2 and 3) show strong Balmer lines (H1 through H9) consistent with an A5 star, as well as numerous yet weaker metallic (Ca/Fe/Mg) lines. Around $\Phi_{\text{orb}}=0$, when the companion star presents its cold face to the observer, Balmer lines are much weaker and narrower while Mg-I triplet lines are stronger. Hence the equivalent widths (EW) of Balmer and Mg-I lines are anticorrelated along the orbit, as shown in Figure 4. The optimal subtraction analysis (Sec. 2.3) gives a clean measurement of the temperature and spectral type of the companion star, independent of the measured colors (which may be contaminated by non-stellar light). We find drastic changes between the irradiated and cold sides of the companion star. This is shown qualitatively in Figures 3 and 2, where the J2215 GTC and WHT spectra are compared to A5 and G5 templates degraded to the same resolution.

Figure 5 shows our quantitative results: the reduced chi squared resulting from the optimal subtraction method (Sec. 2.3) for templates with a broad range of spectral types (O–M). We thereby measure a spectral type $A5 \pm 2$ for the brightest spectra (i.e., A3-A7 at $\Phi_{\text{orb}}=0.5$) and G5+5 at the faintest end (G0-K0 at $\Phi_{\text{orb}}=0$; Romani et al. 2015 report similar yet slightly earlier spectral types of A2 and G0 around phase 0.5 and 0, respectively, but no errors are quoted). These correspond to effective temperatures for the cold (“night”) and hot (“day”) sides of $T_N=5660_{-380}^{+260}$ K and $T_D=8080_{-280}^{+470}$ K, respectively (Pecaut & Mamajek 2013). We thus find a drastic temperature contrast between opposite sides of the companion star, where the hot/day side is about 2400 K or 40% hotter than it would be without irradiation. The best match scale factors are $f_{\text{veil}}\approx 0.8$ at both superior and inferior conjunction, suggesting a contribution from non-stellar light (veiling) of about 20% in this GTC-OSIRIS 4000–5300 Å band (which corresponds approximately to filter g’).

### 3.2. Radial velocities: magnesium vs. Balmer lines

We find that the radial velocities and K values depend systematically on the set of lines or spectral range used to measure them. Namely, as we show in Figure 6 the semi-amplitude of the Mg-I line RVC ($K_{\text{Mg}}$, red circles) is always ~10% higher than the semi-amplitude of the Balmer line RVC ($K_{\text{Balmer}}$, blue squares). Using the same G5 template yields $K_{\text{Balmer}}=382.8_{-4.7}^{+4.7}$ km s$^{-1}$ and $K_{\text{Mg}}=420.2_{-6.2}^{+6.2}$ km s$^{-1}$.

In Figure 7 we present two extreme cases: RVCs of J2215 calculated using Balmer lines (blue symbols) and Mg-I-triplet lines (red symbols; see Sec. 2.3 for the exact wavelength ranges). In both cases the radial velocities were measured by cross correlating the J2215 spectra with templates.
Figure 7. Radial velocity of the companion star in J2215 in its orbit around the pulsar, as measured by cross-correlation with a G5 template using i) Balmer lines (blue points) and ii) MgI triplet lines (red points; Sec. 3.2). Left: Blue dashed and red solid lines show the sinusoidal fits to the Balmer and MgI RVCs, respectively (the best-fit systemic velocity was subtracted in both cases). Sine fit residuals are shown in the bottom panel. Right: Best fit and residuals from our xrbcurve model of a nearly Roche lobe filling irradiated star (Sec. 4).

Most RVCs are reasonably well fitted with a pure sinusoidal function (reduced chi-squared \( \lesssim 2 \)). There are, however, deviations noticeable in the sine fit residuals (Fig. 7), especially in the Balmer line RVCs (spectral types earlier than F1 were not used in the Balmer line cross correlation analysis, see Sec. 2.3). The fitted K values were verified in a model independent way by measuring the peak to peak semi-amplitude of the RVC: the two maximum and minimum radial velocities were averaged, subtracted and divided by two. The results were always consistent with the K values presented in Figure 6.

Using the full ensemble of lines, on the other hand, yields intermediate values of the RVC semi-amplitude (green triangles in Fig. 6) \( K_{\text{All}}=398.8 \pm 2.3 \text{ km s}^{-1} \) for a G5 template). We also find a clear systematic dependence with the template’s spectral type when using the full spectral range: a monotonic increase of \( K_{\text{All}} \) towards later (cooler) spectral types. We conclude that, when measuring radial velocities in strongly irradiated systems such as J2215, the spectral range and reference spectra must be chosen carefully in order to measure the pulsar mass accurately (see Section 5 for further discussion).

The systemic velocities that we find are all in the 40–70 km s\(^{-1}\) range, showing only small changes with spectral range or template spectral type. Averaging the results for spectral types G0-K0 we find \( G=49.0 \pm 2.5(\text{stat}) \pm 8.0(\text{syst}) \text{ km s}^{-1} \) (where the statistical and systematic errors correspond to the standard deviation of the full range and of all three spectral ranges, respectively). From the same sine fits we find an epoch of zero phase (companion at inferior conjunction) of \( T_0=56976.9501 \pm 0.0003(\text{stat}) \pm 0.0008(\text{syst}) \) MJD (TDB), which we use together with the radio pulsar timing \( P_{\text{orb}} \) (Sec. 2.3) in order to compute orbital phases.
4. MODELLING

In order to obtain the most reliable masses and orbital parameters, we modelled simultaneously the photometric three-band LCs and the Mg-triplet and Balmer-line RVCs, using the XRBCURVE model. The model, described in the following, has been successfully applied to LCs and RVCs of neutron star and black hole X-ray binaries (Shahbaz et al. 2000, 2003, 2017, for more details).

4.1. Binary parameters and irradiation

XRBCURVE includes a nearly Roche-lobe-filling secondary star heated by high-energy photons from the compact object and an accretion disk (not included in this case since no disk emission lines are detected). The binary system's geometry is determined by the orbital inclination \( i \), the mass ratio \( q = M_2/M_1 \) (where \( M_1 \) and \( M_2 \) are the masses of the neutron star and secondary star, respectively), and the Roche lobe filling factor of the secondary star, \( f \). The orbital period \( P_{\text{orb}} \), the radial velocity semi-amplitude of the secondary star's barycenter \( K_2 \) and the distance to the source in kpc \( D \) set the scale of the system. The light arising from the secondary star depends on its mean, unperturbed effective temperature \( T_2 \) and the gravity darkening exponent \( \beta \).

The additional light due to irradiation is given by the irradiation efficiency \( \eta = \frac{L_{\text{irr}}}{\dot{E}} \), which we define in ac-
cordance with previous work as the ratio of the heating luminosity (L_{irr}, assuming isotropic emission by an irradiating point source at the compact object) to the spin-down luminosity of the pulsar (E\dot{P}=5.29\times10^{34}\text{~erg}\text{~s}^{-1}, Breton et al. 2013). We calculate the resulting increase in the local effective temperature due to the irradiating external source assuming that all irradiating flux is thermalized (Shahbaz et al. 2003). We use NEXTGEN model-atmosphere fluxes (Hauschildt et al. 1999) to determine the intensity distribution on the secondary star and a quadratic limb-darkening law with coefficients taken from Claret (2000), to correct the intensity. Based on the observed mid-G spectral type for the secondary star (Sec. 3), we fix \beta at 0.10 (Lucy 1967).

To model the RVs, we assume that the whole secondary star contributes to both Balmer and MgI-triplet lines, including the inner/irradiated face. This is based on the corresponding EWs, which follow those expected from an A5–G5 star (Fig. 1). We set the Balmer and MgI-triplet absorption line strengths according to the effective temperature of each surface element of the star. Using our template spectra, we determine the EW versus temperature relationship for the same exact wavelength ranges used in measuring the RVs (Appendix A) see Fig. 13. The line strengths for each surface element on the star are then calculated using its temperature and the EW-temperature relation. Finally, radial velocities are calculated from the model line profile, averaged among all surface elements visible at each orbital phase.

In determining the binary parameters, we use a Markov chain Monte Carlo (MCMC) method convolved with a differential evolution fitting algorithm (DREAM; see Shahbaz et al. 2017; Vrugt 2016). We use a Bayesian framework to determine our binary model parameters (Gregory 2005). We include the projected semi-major axis of the pulsar orbit measured from radio timing observations (a = a_1 \sin i=0.46814[1] light-seconds; Abdo et al. 2013) as an independent constraint on q and K_2 (q=K_2 P_{orb} / 2\pi c; where c is the speed of light) using a Gaussian prior. Our MCMC fitting makes use of flat prior probability distributions for the rest of model parameters. We use 20 individual chains to explore the parameter space and 40000 iterations per chain. We reject the first 500 iterations and only include every 10th point.

We use a reddening of E(B-V)=0.38 mag, which we calculate from the X-ray absorbing column density towards J2215, N_H=2.1\times10^{21}\text{~cm}^{-2} (Gentile et al. 2014) using the conversion from (Predehl & Schmitt 1995). Because N_H is in turn estimated from the measured pulsar dispersion measure (He et al. 2013), we verified the accuracy of the reddening towards J2215 in different ways. The total Galactic N_H in the direction of J2215 is 40% higher (Kalberla et al. 2003), although this may include additional absorbing material in the line of sight. Our value of E(B-V)=0.38 mag is consistent with that measured from IR dust maps in the same direction (0.35+/-0.02 mag, Schlegel et al. 1998). In order to quantify the possible impact on the measured pulsar mass, we repeated the LC and RV fits with E(B-V) left as a free parameter, with a flat prior. Reassuringly, this yields the same value M_1\approx2.3 M_\odot, and a value of E(B-V) fully consistent with (less than one sigma from) the one we use.

We also compute the line-of-sight temperature at orbital phases 0.0 and 0.5 which represent the cold/night (T_N) and hot/day (T_D) temperatures of the secondary star. Using the spectral type measurements explained above, we impose temperature constraints on T_N (5280–5920 K, corresponding to a spectral type G5+5) and T_D (7800–8550 K, corresponding to a spectral type A5+2). Comparing with previous models of J2215 (Table 2), we conclude that our quantitative independent constraints on T_N and T_D are critical in order to find a good solution. From our measured f_{veil}=0.8 (Sec. 3.1), it is clear that there is an extra light component that veils the observed light from the secondary star. To allow for this wavelength-dependent veiling we include an extra flux component in the model LCs, f_g, f_r, and f_i in the g, r and i band, respectively. We also allow for possible uncertainties in the absolute flux calibration of the light curves, by including a wavelength-dependant magnitude offset in the same bands.

The model parameters that determine the shape and amplitude of the optical LCs, and RVs are t, f_g, f_r, f_i, K_2 and the extra flux components f_g, f_r, and f_i. There are also a number of extra parameters: the phase shift for the LCs and RVs (discussed below) as well as the systemic velocities for the MgI-triplet and the Balmer-line radial velocity curves (which we set to be the same). The g, r, i-band LCs were phase folded and averaged into 37, 37 and 28 orbital phases, respectively. The MgI-triplet and Balmer-line RVs contain 20 data points each (Sec. 2.5 for details). Given that there are five different data sets with different numbers of data points, to optimize the fitting procedure we assigned relative weights to them. After our initial search of the parameter space, which resulted in a good solution, we scaled the uncertainties in each data set (i.e., the LCs and the RVs) so that the total reduced \chi^2 of the fit was \sim1 for each data set separately. The MCMC fitting procedure was repeated to produce the final set of parameters, which were used to determine M_1 and M_2.

4.2. Model results and comparison with previous work

Our physical model fits simultaneously the Balmer and MgI RVs of J2215 (Figure 7, right) as well as the optical LCs in three bands (Figure 8), with a global reduced \chi^2 of 1.30 for 126 d.o.f. Small residuals are apparent in the LC fits (especially near \Phi_{orb}=0.8) and in the RV fits (at \Phi_{orb}=0.5). We show in Figure 9 the parameter distributions from our XRBCURVE fits to J2215. All model parameters are well constrained, and the overall agreement between the data and model is good. Our best-fit D=2.9+0.1 kpc is fully consistent with the 3 kpc value found independently from the MSP dispersion measure (Hessels et al. 2011).

Table 2 presents our best-fit values and their 1-sigma uncertainties, compared to previous studies of J2215. First, as already pointed out by Romani et al. 2015, previous attempts at determining orbital parameters exclusively based on photometric measurements and modelling are unsuccessful (Schaefer & Halpern 2014; see also Breton et al. 2013). This is clear, e.g., from the K_2 velocities predicted by those photometric fit results, inconsistent with our measured values (Table 2). Thus we
conclude that, at least in the presence of strong irradiation, dynamical information is required in order to find a reliable orbital solution.

Second, the orbital inclination depends strongly on the temperatures of both sides of the companion. Indeed, a larger temperature contrast between both sides requires a smaller inclination angle to produce the observed peak to peak magnitude difference. Our temperature constraints on the model are taken from quantitative temperature measurements at $\Phi_{\text{orb}}=0.0$ and 0.5 (Sec. 4.3), and lead to a robustly determined $i=63.9^\circ \pm 2.4^\circ$. Therefore, independent constraints on the temperature at different orbital phases are also needed to find a robust solution.

Third, we have shown that a point-source irradiation binary model can fit satisfactorily the J2215 data, in clear contrast with previous results (Romani et al. 2015; Romani & Sanchez 2016). This discrepancy might be also due to the different temperature constraints, but a more detailed comparison is warranted. In any case, our results show that irradiation from an extended shock is not required to explain the optical properties of J2215.

On the other hand, all four models do agree on the filling factor, showing a nearly Roche-lobe filling companion in J2215. We find an additional non-stellar flux contribution in the range 0.035–0.07 mJy in all three bands (g, r and i), between 2 and 10 times fainter than the companion star (at $\Phi_{\text{orb}}=0$ and 0.5, respectively). This extra non-variable flux component, with a rather flat spectral slope, might be due to synchrotron emission from an intrabinary shock, but at present this interpretation remains tentative. We can also rule out the presence of a quiescent disk (as suggested by Schroeder & Halpern 2014), based on the absence of broad hydrogen and helium emission lines regularly associated with disks.

Our best-fit model predicts a projected rotational velocity for the companion of $V_{\text{sin}i}=103\pm1$ km s$^{-1}$. Applying an optimal subtraction (Sec. 2.3) of the MgI triplet region around $\Phi_{\text{orb}}=0$, with a G5 template broadened in steps of 10 km s$^{-1}$ up to 210 km s$^{-1}$, we measure $V_{\text{sin}i}=180\pm20$ km s$^{-1}$ (with a limb darkening coefficient $u=0.8$) and $V_{\text{sin}i}=165\pm15$ km s$^{-1}$ (with no limb darkening, $u=0$). Thus, taking into account the uncertainty on the amount of limb darkening, our current observational constraints put $V_{\text{sin}i}$ in the range 150–200 km s$^{-1}$. However, better spectral resolution spectra are required to measure this accurately and compare it to our model prediction (our GTC data have a resolution of 160 km s$^{-1}$; Sec. 2.2). Finally, our best-fit value of $\eta$ implies a very high $L_{\text{irr}}=[1.5^{+0.3}_{-0.2}] \times 10^{35}$ erg s$^{-1}$. An irradiating luminosity three times higher than the spin-down energy budget might be explained by e.g. beaming/anisotropy of the pulsar wind (e.g., Philippov et al. 2015).

The flux distribution along the surface of the companion star is shown in Figure 10, a by-product of our best-fit model of J2215. These maps illustrate the drastic irradiation or 'heating' effects of the pulsar wind and high-energy emission on the temperature distribution of the secondary star. Besides producing a strong temperature gradient between opposite sides (which we measure in Sec. 3.1), such strong heating shifts the effective center of the secondary star (“center of light”) away from its center of mass. Because the strength of the lines varies throughout the surface of the star, this shift is different for different absorption lines. This in turn results in significant distortion of the integrated line profiles as well as the corresponding RVCs (e.g., Philips et al. 1999; Shabnaz et al. 2000). Thus our model provides a natural explanation for the systematic difference in K velocities that we find and report in Section 3.2.

4.3. On orbital phase shifts and systematics

Our model allows for phase shifts in the LC and both RVCs, which may arise physically from e.g. asymmetric heating of the companion star. The best-fit values for the phase shifts in the Balmer RVC, the MgI RVC and the LCs are, respectively: $\Delta \Phi_{\text{Balmer}}=0.018\pm0.003$, $\Delta \Phi_{\text{MgI}}=0.0002\pm0.0039$ (i.e., consistent with 0 within 1-sigma) and $\Delta \Phi_{\text{K}}=0.0082\pm0.0007$ (where the quoted errors are again 1-sigma statistical). Similar LC phase shifts $<0.01$ have been reported for J2215 (Schroeder & Halpern 2014; Romani et al. 2015; Romani & Sanchez 2016), and interpreted as evidence for asymmetric heating from an intra-binary shock.

However, since the model does not take into account errors on the orbital phases, one must consider carefully the systematic uncertainty on $\Phi_{\text{orb}}$ before interpreting such phase shifts. If we used the pulsar timing reference epoch to calculate $\Phi_{\text{orb}}$ (which dates from 2009-12-21, from Abdo et al. 2013), we should include the orbital period derivative $P_{\text{orb}}$ (not doing so would yield a propagated uncertainty to our 2014-08-02 epoch of 0.02 orbital cycles). But assuming a constant $P_{\text{orb}}$ over a 5-yr timespan is problematic, since redbacks and black widows are known to show large, erratic changes in $P_{\text{orb}}$ on timescales of years (e.g., Archibald et al. 2013). Instead, we use our own spectroscopic reference time (T0, see Section 3.2) with a systematic uncertainty of 0.0008 d, which corresponds to a systematic uncertainty on $\Phi_{\text{orb}}$.
Figure 10. Flux maps of the companion star in J2215 from our best-fit XRBcurve model, seen at different orbital phases (as indicated along the top axis). Flux units are arbitrary. Three different sets of maps are presented, for: continuum g-band emission (top panels), MgI triplet absorption lines (middle) and Balmer absorption lines (bottom). The different distribution of lines throughout the surface is evident, and due to the strong irradiation effects (see text for details). The center of light depends strongly on the line or spectral range chosen.

5. DISCUSSION

5.1. Measuring masses: An empirical K correction

In a careful study of the strongly irradiated companion star of PSR J2215+5135, we find that the radial velocities depend systematically on the spectral features and spectral range used to measure them (Sec. 3.2). Thanks to the high-quality GTI optical spectra, we show that magnesium lines yield semi-amplitudes of the RVC that are always higher than those inferred from hydrogen Balmer lines or from an undetermined blend of lines. We argue that this new systematic effect arises from the extreme contrast between the the cold and heated sides of the companion star, for which we measure temperatures of $T_N=5660^{+280}_{-380}$ K and $T_D=8080^{+470}_{-280}$ K, respectively (Sec. 3.1). Under these circumstances, Balmer lines trace the hot face of the companion star of J2215 in its orbit around the pulsar, while MgI triplet lines trace its cold, unperturbed face.

We modelled both RVCs and the optical LCs in three bands, and found the center of mass velocity to be $K_2=412.3^{+5.0}_{-5.0}$ km s$^{-1}$ (Sec. 3). Because the center of light of the Mg-I lines yields higher velocities ($K_{Mg}=K_2+\Delta K$, $\Delta K > 0$), it is slightly shifted outwards from the center of mass of the companion. Using the simple expression for the center-of-light displacement $\Delta R/a=\Delta K/(K_2^2(1+q))$ (Wade & Horne 1988) and our best-fit orbital parameters (Table 2), we estimate $\Delta R_{Mg}/R_{RL2} \simeq +0.11$ (i.e., about 11% of the Roche lobe radius of the companion). Balmer lines, on the other hand, suffer from a stronger inwards displacement of the center of light, which can yield to systematic errors in dynamical mass measurements if not corrected. We estimate this displacement as above using the measured $K_{Balmer}$, and find $\Delta R_{Balmer}/R_{RL2} \simeq -0.24$ (i.e., a 24% shift relative to $R_{RL2}$).

Given the large ($\sim 10\%$) differences in the measured K values and the $M_1 \propto K^3$ relation, this has important consequences for the measured pulsar masses. For instance, using the different measured K values and our best-fit orbital solution (Sec. 4) yields inconsistent values for the neutron star mass: $M_1=1.88^{+0.16}_{-0.16} M_\odot$ (from $K_{Balmer}=382.8^{+4.7}_{-4.7}$ km s$^{-1}$) and $M_1=2.49^{+0.23}_{-0.23} M_\odot$ (from $K_{Mg}=420.2^{+6.2}_{-6.2}$ km s$^{-1}$). Thus we find that, in the presence of strong irradiation, the systematic error on K may be equally or more important than the uncertainty on the orbital inclination, $i$.

To circumvent this and reduce drastically the systematics on K measurements, we have put forward a new method: we measure K velocities using different sets of lines in order to “bracket” the center-of-mass velocity of the companion star. We have deemed as optimal the Balmer and MgI triplet lines (Sec. 2.3) which provide a lower and an upper limit on $K_2$, respectively. These could in principle be replaced by other sets of lines that
trace the movement of both the cold/dark and irradiated/bright sides of the star. While the traditional “K correction” relies on model assumptions or on the transient nature of irradiation in some systems (Sec. 5.2), our method provides a direct way of quantifying this correction from the same spectra of the irradiated companion star.

To our knowledge, the only similar studies in the literature involve a combination of emission and absorption lines in white dwarf binaries (e.g., Parsons et al. 2010; Rodriguez-Gil et al. 2015). Our method relies exclusively on absorption lines from the star’s atmosphere, thus eluding the uncertainty sometimes associated with the exact site where Balmer/HeI/Bowen emission lines are formed. This “empirical K correction” is of particular relevance for the emerging population of MSPs in compact binaries, and it should also be applicable in the broader context of semi-detached binaries with strong irradiation/heating effects.

In summary, our findings show that metallic lines in general and MgI lines in particular offer a much less distorted view of the center of mass of the secondary star, opening a new way to measure masses in strongly irradiated compact binary MSPs. In the relevant temperature and spectral type range for J2215 and most redback and black widow companions (spectral types A through M), Balmer lines are more sensitive to temperature than MgI triplet lines (see Appendix A Fig. 13). Indeed, when going from a spectral type A5 to a G5, the EW of Balmer lines decreases by a factor \( \approx 7 \) (48 → 7 Å), whereas the EW of MgI triplet lines increases by a smaller factor \( \approx 3 \) (1.52 → 4.75 Å). This may explain why the effects of irradiation are more drastic on Balmer absorption lines than on metallic lines.

5.2. A broader look at irradiation: K correction and deep heating

Irradiation in compact binaries has been studied in the context of black hole and neutron star low-mass X-ray binaries (LMXBs) as well as white dwarf (WD) binaries (dwarf novae, DN, post-common envelope binaries, PCEBs and asynchronous polars, AP). In those systems, irradiation proceeds mostly through X-ray and UV photons from a hot white dwarf or innermost accretion disk. The ratio of the maximum irradiating flux at the companion’s surface (near the inner Lagrangian point) over the companion’s intrinsic unperturbed flux provides a good way to quantify the importance of irradiation in close binaries: \( f_{irr} = \frac{L_{irr}}{L_2 R_2^2}. \) The effects of irradiation on the measured K velocities, on the other hand, are typically parameterized in terms of the so-called K correction, which we define as the ratio between observed and center-of-mass K values: \( k_f = \frac{f_{irr}}{k_2}. \) This correction is estimated in the literature in a number of different ways, e.g., by comparing outburst and quiescence K values (Hessman et al. 1984) or by simulating and fitting RVCs with irradiation models (Wade & Horne 1988; Phillips et al. 1999; Muñoz-Darias et al. 2005).

In some cases (compact LMXBs in outburst, very hot WDs), chromospheric/fluorescent emission lines are formed on the inner face of the companion star, leading to a lower limit on the center of mass velocity semi-amplitude \( K_2 \) (i.e., \( f_{irr} < 1 \)). This is the case of Bowen fluorescence lines in LMXBs. It is interesting to compare J2215 with the accreting millisecond pulsars (AMPS) SAX J1808.4–3658 and XTE J1814–338, with Bowen-line outburst K corrections of \( f_{irr} = 0.90 \) and 0.81, respectively (Cornelisse et al. 2009; Wang et al. 2017). These are analogous to (and possibly evolutionary precursors of) black widow and redback MSPs. Assuming an irradiating luminosity in outburst \( L_X \approx 10^{36} \text{ erg s}^{-1} \), we estimate their maximum ratio of irradiating to intrinsic flux and find extreme values, \( f_{irr} \approx 10^{-10} \). 

In other cases (DNe and BHCs in outburst), absorption lines are partially quenched on the inner face of the companion due to irradiation, so that the effective center of light for these lines is shifted towards the outer face and they provide an upper limit on \( K_2 \) (i.e., \( f_{irr} > 1 \)). Even though stellar atmospheres with external heating are poorly understood, the reduced absorption line strength is often attributed to the reduced vertical temperature gradient in the presence of an external UV/X-ray photon flux. This is the case of the WD binaries Z Cha, U Gem and SSCyg, with \( f_{irr} \) estimated at 1.03, 1.04 and 1.26, respectively (Wade & Horne 1988; Friend et al. 1990; Hessman et al. 1984). For these systems we find mild irradiation, with estimated \( f_{irr} \) values in the range 0.1–3. The BHC GRO J1655-40 on the other hand, with \( f_{irr} \approx 1.16 \), has a relatively luminous F6IV companion star which also leads to a mild \( f_{irr} \approx 7 \) (Phillips et al. 1999; Oroz & Bailyn 1997).

In our case (J2215) and in compact binary MSPs in general, the relativistic pulsar wind and gamma-ray emission are the dominant sources of irradiation. These feature typical spin-down luminosities \( E = 10^{34}–10^{35} \text{ erg s}^{-1} \) and gamma-ray luminosities \( L_{\gamma} \) about ten times lower. Their X-ray luminosities are two to five orders of magnitude lower than \( \dot{E} \) and are thus less important in terms of irradiation (\( L_X = 10^{30}–10^{32} \text{ erg s}^{-1} \); Linares 2014; Gentile et al. 2014). Indeed, J2215 has \( L_X = 1.2 \times 10^{32} \text{ erg s}^{-1} \) (0.5–10 keV), \( L_{\gamma} = 1.4 \times 10^{34} \text{ erg s}^{-1} \) (0.1–100 GeV) and \( \dot{E} = 5.3 \times 10^{34} \text{ erg s}^{-1} \) (Linares 2014; Acero et al. 2015; Breton et al. 2013) respectively; for a 2.9 kpc distance). Our measured radial velocity amplitudes \( K_{\text{Balmer}} \) and \( K_{\text{MgI}} \) together with the center-of-mass velocity from our best-fit model (K2) imply K correction factors for J2215 of \( f_{irr} = 0.928 \) and \( f_{irr} = 1.109 \), respectively. In other words, the K values measured using Balmer and MgI lines are 7.2% lower and 1.9% higher, respectively, than the true center-of-mass K2.

For comparison, the K correction inferred by van Kerkwijk et al. (2011) for the black widow pulsar...
This can be understood qualitatively from the two terms entering $f_{\text{corr}}$, which have opposite trends: $R_2^2/a^2$ is lower in black widows (lower irradiating flux due to smaller solid angle), but $L_{\text{irr}}/L_2$ is higher compared to redbacks (as the black widow companions are less luminous).

Using our orbital solution (which gives $R_{\text{RL2}}/a=0.23$), our best-fit value of $L_{\text{irr}} \simeq 3 \times \dot{E}$, and a companion luminosity $L_2 \simeq 5.3 \times 10^{32}$ erg s$^{-1}$ (from our best-fit $T_2=5630$ K and $R_2=0.39$ R$_\odot$), we estimate $f_{\text{corr}} \sim 15$. In other words, the irradiating flux at the companion’s heated face is up to 15 times higher than the intrinsic stellar flux. Compared with UV and X-ray photons, Gamma-ray photons and relativistic particles from the pulsar wind are expected to penetrate deeper into the companion atmosphere. This leads to deep/internal heating of the companion’s inner surface, so it is not surprising to find no emission lines in J2215, and no quenching of absorption lines either (Fig. 1).

Furthermore, we have shown that J2215 could harbor the most massive pulsar known to date. Our best-fit model yields a very massive neutron star with $M_1=2.27^{+0.17}_{-0.15}$ M$_\odot$, and a well-constrained inclination of $i=63.9^{+2.4}_{-2.7}$ (see Figure 11). This is more massive than the previous well-established record holder (2.01 M$_\odot$, Antoniadis et al. 2013), at the 97% confidence level. The results of Romani et al. (2013) Romani & Sanchez (2016) are clearly at odds, although their nearly edge-on model (with a neutron star mass of 1.6 M$_\odot$) has no uncertainties reported and admittedly fails to describe the data. In a previous study of the original black widow pulsar, van Kerkwijk et al. (2011) found a pulsar mass similarly high (2.40±0.12 M$_\odot$). The main advances of the method we have presented here are: i) an empirical K correction, based on radial velocities measured with two different sets of lines (Sec. 5.2); and ii) independent constraints on the temperature imposed on the model, based on absorption line strengths (Sec. 6.3). We argue that these two new advances make our results more robust compared to previous work (van Kerkwijk et al. 2011; Romani et al. 2013; Romani & Sanchez 2016). There may still be unknown or highly uncertain systematic effects, however, biasing the best-fit model inclination and thus the dynamical mass measurements (see, e.g., the discussion in van Kerkwijk et al. 2011 their Section 4).

We therefore conclude that, if confirmed with an independent measurement of the orbital inclination, the massive neutron star in J2215 may place new constraints on the equation of state at supra-nuclear densities. This would push the limits of the most massive neutron stars in our Galaxy, setting a lower limit of 2.3 M$_\odot$ to their maximum mass. Since particle interactions in the core provide the pressure necessary to halt its collapse, the maximum mass of a neutron star places independent constraints on how these particles interact (Lattimer & Prakash 2007). For instance, exotic forms of matter such as hyperons or deconfined quarks have been proposed to exist in the central parts of a neutron star, yet they can hardly account for a neutron star as massive as the one we find in J2215 (see also Özel & Freire 2010).

With new Galactic MSPs being currently discovered at a rate of 10-30 per year (Lorimer 2018), the neutron star mass range will be explored further in the next decade, and is likely to continue widening. We have shown here that in the study of strongly irradiated pulsar companions, a controlled measurement of temperatures and velocities throughout the orbit is possible with current instruments, and key to finding a robust dynamical solution. Our novel technique, which combines velocity measurements with different absorption lines, temperature measurements and physical modeling of the binary, should provide a path forward for dynamical mass measurements in this growing population.

6. SUMMARY AND CONCLUSIONS

- We have identified, for the first time and thanks to GTC’s large collecting area, absorption lines from both sides of the irradiated companion star to PSR J2215+5135. We show that Mg-I triplet lines effectively trace the unheated “dark side” of the companion, while hydrogen Balmer lines trace its irradiated side. We are therefore able to bracket the center of

![Figure 11. Neutron star mass measurements in J2215, shown vs. orbital inclination. Dotted and dashed lines show the effects of using different sets of absorption lines to measure velocities (Secs. 5.2 and 6.1). The thick solid line shows our model K2 (Sec. 4). Our best-fit orbital solution (filled red circle) is compared with previous work (Schroeder & Halpern 2011; Romani et al. 2015 filled squares and triangles, respectively).)](image)

5.3. The mass of PSR J2215+5135

We have argued that our “empirical K correction” removes a critical systematic in irradiated systems: the difference between center of light and center of mass of the companion. In J2215, our $K_2=412.3\pm5.0$ km s$^{-1}$ yields a mass function of 1.2 M$_\odot$, an absolute lower limit on the pulsar mass. Combined with the tight constraints on q (Sec. 4 Abdo et al. 2013), this implies a minimum neutron star mass of 1.6 M$_\odot$. Thus we find that J2215 contains a neutron star more massive than the “canonical” 1.4 M$_\odot$ double neutron stars, adding to the growing number of such systems (Demorest et al. 2010; Antoniadis et al. 2013; Özel & Freire 2014).
mass velocity, placing both an upper and a lower limit on \(K_2\). This removes the systematic uncertainty on \(K_2\) in strongly irradiated systems due to the displacement of the center of light, traditionally incorporated in the so-called “K correction”.

- We argue that, beyond light curve modelling, accurate mass measurements in strongly irradiated binary systems require i) radial velocities, preferably measured using metallic lines; and ii) robust constraints on the temperatures of both sides of the companion.

- In particular, we find that the semi-amplitude of the radial velocity curve of J2215 measured with MgI lines is systematically higher than that measured with Balmer lines, by 10%.

- We measure temperatures for the cold and hot sides of \(T_{\text{cold}}=5660_{-380}^{+260} \text{ K}\) and \(T_{\text{hot}}=8080_{-280}^{+470} \text{ K}\), respectively.

- By modeling jointly both radial velocity curves and the light curves in three bands, while imposing the temperature constraints above, we find that J2215 has: i) a center-of-mass K velocity of \(K_2=412.3\pm5.0 \text{ km s}^{-1}\); ii) an inclination \(i=63.9^\circ\pm2.7^\circ\); iii) an apparent irradiating luminosity three times higher than its spin-down luminosity and iv) a companion close to filling its Roche lobe (filling factor 0.95). (Section 4.1).

- Our physical modeling can reproduce the measured fluxes and velocities without invoking extended irradiation, and yields only marginal evidence for asymmetric heating (in the form of orbital phase shifts).

- We thereby find that J2215 hosts a main-sequence G5 companion with \(M_2=0.33_{-0.03}^{+0.05} \text{ M}_\odot\) and a very massive neutron star with \(M_1=2.27_{-0.15}^{+0.17} \text{ M}_\odot\).

- Pending independent confirmation of the orbital inclination, our results strongly suggest that the maximum neutron star mass is at least \(\sim 2.3 \text{ M}_\odot\).

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APPENDIX

A STELLAR SPECTRAL LIBRARY FOR TEMPERATURE AND RADIAL VELOCITY MEASUREMENTS

We built library of main sequence stellar spectra (or “templates”) in order to measure spectral types (temperatures) and radial velocities (Section 4.2). We used 33 VLT-UVES spectra from the Paranal Observatory Project [Baguña et al. 2003], UVES-POP, initially re-binned to a 0.2 Å resolution, which cover the ~3000–10000 Å range. We normalized them to their continuum level by fitting a spline function, and excluded the gaps between echelle orders. We then subtracted each template’s radial velocity, measured by cross-correlating the Hα and Hβ line profiles with a Gaussian with FWHM = 100 km s\(^{-1}\), or two such Gaussians separated by 200 km s\(^{-1}\) in the broad line cases. These radial velocities were in good agreement with the values listed in the SIMBAD database. The resulting spectra are shown in Figure 12 broadened to match the spectral resolution of the GTC-OSIRIS spectra presented herein (160 km s\(^{-1}\); Sec. 2.2). We also calculated the EW of absorption lines in the templates, shown in Figure 13 which we use in our modelling of the Balmer line and MgI-triplet radial velocities (Section 4).

REFERENCES

Abdo, A. A., et al. 2013, ApJS, 208, 17
Acero et al., F. 2015, ApJS, 218, 23
Antoniadis, J., et al. 2013, Science, 340, 448
Archibald, A. M., Kaspi, V. M., Hessels, J. W. T., Stappers, B., Janssen, G., & Lyne, A. 2013, Submitted to ApJ; ArXiv 1311.5161
Archibald, A. M., et al. 2009, Science, 324, 1411
Atwood, W. B., et al. 2009, ApJ, 697, 1071
Baguña, S., Jehin, E., Ledoux, C., Cabanac, R., Melo, C., Gilmozzi, R., & ESO Paranal Science Operations Team. 2003, The Messenger, 114, 10
Breton, R. P., et al. 2013, ApJ, 769, 108
Casares, J., Cornelisse, R., Steeghs, D., Charles, P. A., Hynes, R. I., O’Brien, K., & Strohmayer, T. E. 2006, MNRAS, 373, 1235
Claret, A. 2000, A&A, 363, 1081
Cornelisse, R., et al. 2009, A&A, 495, L1
Crawford, F., et al. 2013, ApJ, 776, 20
de Martino, D., et al. 2013, A&A, 550, A89
Demorest, P. B., Pennucci, T., Ransom, S. M., Roberts, M. S. E., & Hessels, J. W. T. 2010, Nature, 467, 1081
Friend, M. T., Martin, J. S., Connon-Smith, R., & Jones, D. H. P. 1990, MNRAS, 246, 637
Gentile, P. A., et al. 2014, ApJ, 783, 69
Gregory, P. C. 2005, Bayesian Logical Data Analysis for the Physical Sciences: A Comparative Approach with 'Mathematica' Support (Cambridge University Press)
Hauschildt, P. H., Allard, F., & Baron, E. 1999, ApJ, 512, 377
He, C., Ng, C.-Y., & Kaspi, V. M. 2013, ApJ, 768, 64
Hessels, J. W. T., et al. 2011, in American Institute of Physics Conference Series, Vol. 1357, American Institute of Physics Conference Series, ed. M. Burgay, N. D’Amico, P. Esposito, A. Pellizzoni, & A. Possenti, 40–43
Hessman, F. V., Robinson, E. L., Nather, R. E., & Zhang, E.-H. 1984, ApJ, 286, 747
Horne, K., & Schneider, D. P. 1989, ApJ, 343, 888
Jordi, C., et al. 2006, MNRAS, 367, 290
Kalberla, P. M. W., Burton, W. B., Hartmann, D., Arnal, E. M., Bajaja, E., Morras, R., & Pöppel, W. G. L. 2005, A&A, 440, 775
Figure 12. Template library adapted from UVES-POP (Bagnulo et al. 2003) for temperature and radial velocity measurements. Normalized intensities are shifted for display, and the spectral type is noted along the right axis.

Figure 13. EW of absorption lines from our template spectra, in the three ranges used for radial velocity measurements: i) Balmer lines (blue squares); ii) MgI triplet (red circles) and the full GTC-OSIRIS range (green triangles). The dotted line shows the template temperature (right vertical axis; from Pecaut & Mamajek 2013). Three representative spectra are shown in the top panels, within the Hβ and MgI-triplet line region.