Limits on the Mass, Velocity and Orbit of PSR J1933–6211

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ABSTRACT

We present a high-precision timing analysis of PSR J1933–6211, a millisecond pulsar (MSP) with a 3.5-ms spin period and a white dwarf (WD) companion, using data from the Parkes radio telescope. Since we have accurately measured the polarization properties of this pulsar we have applied the matrix template matching approach in which the times of arrival are measured using full polarimetric information. We achieved a weighted root-mean-square timing residuals (rms) of 1.23 µs, 15.5% improvement compared to the total intensity timing analysis. After studying the scintillation properties of this pulsar we put constraints on the inclination angle of the system. Based on these measurements and on χ² mapping we put a 2-σ upper limit on the companion mass (0.44 M⊙). Since this mass limit cannot reveal the nature of the companion we further investigate the possibility of the companion to be a He WD. Applying the orbital period-mass relation for such WDs, we conclude that the mass of a He WD companion would be about 0.26 ± 0.01 M⊙ which, combined with the measured mass function and orbital inclination limits, would lead to a light pulsar mass ⩽ 1.0 M⊙. This result seems unlikely based on current neutron star formation models and we therefore conclude that PSR J1933–6211 most likely has a CO WD companion, which allows for a solution with a more massive pulsar.

Key words: pulsars: individual (PSR J1933–6211) – pulsars: kinematics – pulsars: general

1 INTRODUCTION

MSPs are rapidly rotating neutron stars that have spin periods shorter than ~30 ms. It is thought that they obtain their short spin periods from angular-momentum increases during mass transfer from their companions (Bisnovatyi-Kogan & Komberg 1974; Alpar et al. 1982). The majority of MSPs have WD companions which can be either massive CO or ONeMg WDs or lower-mass He WDs. CO or ONeMg WD companions are less common in binary MSPs (BMSPs), originating from intermediate-mass progenitor stars which transfer their envelope mass on a short time leaving a partly recycled MSP (with a spin period of a few tens of ms; Tauris 2011). In contrast, He WD companions are the most common and originate in low-mass X-ray binaries (LMXBs). Their time scale of evolution is long enough to allow significant amounts of matter to accrete onto the pulsar and to fully recycle them to spin periods of a few milliseconds.

PSR J1933–6211 was discovered in 2007 at the Parkes radio telescope in the high Galactic latitude survey (Jacoby et al. 2007). Soon after the discovery it was clear that the spin period was only 3.5 ms and the orbital period was 12.28 days, which in combination with the position of the pulsar in a spin period – period derivative (P–P) diagram, makes this system a typical example of a BMSP (Fig. 1). Pulsars that belong to this category, along with double neutron-star systems, are the most well-studied so far. If BMSPs are formed in an LMXB, their resulting He WDs follow a tight correlation between their mass and orbital period (Savonije 1987; Tauris & Savonije 1999). This relation can be a useful tool to probe the origin of a given BMSP and place constraints on the component masses of the system. In addition, their orbital eccentricity is also predicted to be correlated with their orbital period (Phinney 1992).
Based on equation of state and evolutionary models, the minimum allowed mass for rotating neutron stars is around 0.1–0.3 $M_\odot$ depending on their spin period (Colpi et al. 1993; Haensel et al. 2002). However, from current theories on stellar evolution and supernova (SN) explosion physics, minimum neutron star masses are expected to be larger than at least 1.0 $M_\odot$ (Timmes et al. 1996). Direct pulsar mass measurements can be achieved with post-Keplerian parameter measurements through timing (Lorimer & Kramer 2012). These measurements require an eccentric, tight system, with preferably an edge-on orbit orientation. In edge-on orbits, Shapiro-delay detection is often possible. Shapiro delay is a time-delay that arises from the photon's passage through the gravitational field of the companion star. This effect is strongest in edge-on orbits and is typically sharply peaked, with the largest delays inflicted on observations at time of superior conjunction. Efforts to measure the Shapiro delay (and thereby the companion and pulsar masses) therefore typically benefit from intense observations around superior conjunction, although full orbital coverage is typically needed to break covariances with other orbital parameters (Freire & Wex 2010).

In the cases that neither the orbit is relativistic nor the inclination of the system is high, indirect limits on the mass can be derived from the mass function. The mass function defines a relation between the Keplerian parameters with the system inclination angle and the system masses. Unlike Keplerian parameters that can be accurately measured through timing, the inclination angle and companion mass are very difficult to measure directly. In cases of close, massive WDs, optical observations, in combination with WD cooling models, may reveal the mass of the companion. When no direct measurements are feasible, pulsar timing can still be used to derive limits on the masses and orbital parameters. In those cases where the companion is a He WD, a mass estimate can be obtained from the correlation between WD mass ($M_{\text{WD}}$) and orbital period ($P_b$).

Strong scintillation of the pulsar signal can be a big observational challenge. Scintillation, which has as a result that the observed signal intensity varies, is caused by inhomogeneities and turbulence in the interstellar plasma. How strong this phenomenon is, depends on the size of inhomogeneities, the distance of the pulsar, the observing frequency and the peculiar velocity. PSR J1933–6211, having a low dispersion measure of 11.520(2) pc cm$^{-3}$, is expected to scintillate strongly at 1.3 GHz frequency (Rickett 1977). Scintillation time scale analysis can be used in order to measure the transverse velocity of the pulsar. Scintillation transverse velocity is an interstellar medium effect that is caused by the pulsar’s orbital velocity, the proper motion, Earth’s orbital motion, the velocity of the scattering screen and the peculiar velocity. Transverse velocity measurements allow us to put...
In this paper we present an updated timing analysis and mass limits for PSR J1933–6211. The observations and data reduction are described in Section 2, while the overall timing solution and the pulsar’s usefulness for pulsar timing arrays (PTAs) are discussed in Section 3. Our attempts to measure the mass of this pulsar were seriously hampered by strong scintillation around the time of superior conjunction. An analysis of these scintillation measurements is given in Section 4. Next, we present the pulsar’s proper motion and transverse velocity in Section 4.1. Constraints on the mass of the pulsar – and the implications for binary evolution models, are outlined in Section 5, followed by some concluding remarks in Section 6.

2 OBSERVATIONS AND DATA REDUCTION

Our observations of PSR J1933–6211 were performed with the Parkes 64-m radio telescope. The total span is \(\sim 10\) years divided into two epochs of \(\sim 1\) year of observations each (Fig. 3). In the first epoch the pulsar is observed as part of the high Galactic latitude survey follow-up observations (Jacoby et al. 2007). These archival data, bibliically available, were recored with the Caltech Swinburne Parkes Recorder 2 (CPSR2) coherent dedispersion backend (Hotan et al. 2006) that provides two dual-polarization bands of 64 MHz, each centered on 1341 and 1405 MHz respectively. Each of the bands was split into 128 frequency channels using a polyphase filterbank.

The aim of the second epoch of observations was to precisely measure the orbital parameters of the system and the masses. The observations were performed with the CASPSR backend (Hickish et al. 2016), which provides a 256-MHz bandwidth, centered at 1382 MHz, resulting in a significant increase in sensitivity. All the observations were taken at wavelength of 21cm with the central beam of the Parkes multibeam receiver (Staveley-Smith et al. 1996).

Since one of our goals is to measure the system masses we picked our observations strategy in a way that we were sensitive to Shaprio-delay detection. This phenomenon maximally affects pulse arrival times at superior conjunction. Superior conjunction is the point in the orbit where the pulsar is behind its companion. Consequently we defined our observing strategy to have uniform coverage through 75% of the orbit, but increased observing cadence during the 25% of the orbit surrounding superior conjunction. The length of a typical observing scan was 30min.

We divided each observation into 15-min segments. Each of these 15-min sub-integrations were weighted by their signal-to-noise ratio (S/N) before the segments were integrated in time and frequency. The observations that provided the best S/N were combined and von Mises functions were fitted in order to create an analytic template. We followed the same procedure to create templates for each of the two backends for which the data were available. We measured the pulse times-of-arrival (ToAs) with two different methods. In the first method we correlated the analytic templates with the observations by applying goodness-of-fit statistics in the frequency domain (Taylor 1992) and in the second method we applied the matrix template matching approach for which we used the full polarization information of the pulsar signal in the template.

In order to optimise the sensitivity of our analysis, we performed full polarimetric calibration following the methods described by (van Straten 2004, 2013). Specifically, a time-dependent receiver model was derived from long-track observations of PSR J0437–4715 following the polarimetric calibration-modelling technique described by van Straten (2004). This solution was then applied to the PSR J1933–6211 data using the measurement-equation template-matching technique of van Straten (2013). The Stokes parameters in the calibrated data follow the conventions defined by van Straten et al. (2010).

Based on the polarized pulse shape (see Fig. 2), we performed the analysis of van Straten (2006), which suggests a theoretical \(\sim \) 25% improvement in ToA precision, depending on the degree of polarization and the variability of the polarization vector as a function of pulse phase, can be obtained if ToAs were derived by using the full polarization information (instead of deriving ToAs from the total-intensity profile only, as is common in pulsar timing). To verify this result, we derived two sets of ToAs: one set based on the total-intensity profile and one based on the full polarimetric polarization, using the van Straten (2006) timing method. In the remainder of the paper we use full polarimetric polarization residuals unless otherwise stated.

The resulting phase-connected full polarimetric polarization ToA residuals are presented in Fig. 3. The comparison with the total-intensity residuals led to an overall improvement of 15.5% in timing residuals and 20% in ToAs uncertainty.

The packages that were used for the analysis described...
Table 1. The timing data characteristics, as observed with two different observing systems.

| Data range (MJD) | Data range (Gregorian) | Number of ToAs | Central frequency (MHz) | Bandwidth (MHz) | Average ToA uncertainty (µs) | EFAC | Weighted rms timing residual (µs) |
|------------------|-----------------------|----------------|-------------------------|----------------|-------------------------------|------|-------------------------------|
| CPSR2            | 52795.7–53301.4       | 2003 Jun.–2004 Oct. | 52 | 1341/1405 | 2 x 64 | 3.686 | 0.8/1.4 | 1.254 |
| CASPSR           | 55676.0–56011.0       | 2011 Apr.–2012 Mar. | 96 | 1382 | 256 | 3.393 | 0.9 | 1.057 |

1 These values correspond to the mean ToA uncertainty for 15-min integration time observations. For more typical 1-hour integrations, the ToA uncertainty (and timing RMS) should decrease by up to a factor of two.

Figure 3. The timing residuals at 20 cm as a function of orbital phase, using the CPSR2 (circles) and CASPSR (stars) data.

Table 2. The timing parameters of the system that correspond to the best-fit residuals.

| General information |
|---------------------|
| MJD range           | 52795 - 53301 |
| Number of ToAs      | 148 |
| Weighted rms timing residual (µs) | 1.23 |

| Measured Quantities |
|---------------------|
| Right ascension, α (J2000) | 19:33:32.4268(5) |
| Declination, δ (J2000) | −62:11:46.876(1) |
| Proper motion in α, μα (mas yr⁻¹) | −5.54(7) |
| Proper motion in δ, μδ (mas yr⁻¹) | 10.7(2) |
| Total proper motion (mas yr⁻¹) | 12.1(2) |
| Spin frequency, ν (Hz) | 282.212361528(2) |
| Spin down, ν (×10⁻¹6 Hz s⁻¹) | −3.0828(7) |
| Dispersion measure, DM (pc cm⁻³) | 11.52(2) |
| Orbital period, P_b (d) | 12.8194067183(8) |
| Time of ascending node, T_asc (MJD) | 53000.4952524(2) |
| Projected semi-major axis, a_p (lt-s) | 12.2815745(3) |
| η = e sinω (× 10⁻⁶) | 1.36(4) |
| κ = e cosω (× 10⁻⁶) | −0.32(3) |

| Derived Quantities |
|---------------------|
| Epoch of periastron passage, T_b (MJD) | 53004.17(5) |
| Longitude of periastron, ω (deg) | 103(1) |
| Orbital eccentricity, e | 12.1(2) |
| Mass function, f(M_p) | 0.0121034(2) |

2-σ limits from χ² mapping

| Assumptions |
|-------------|
| Clock correction procedure | TT(BIPM(2013)) |
| Solar system ephemeris model | DE421 |
| Binary model | ELL1 |
| Note: Figures in parentheses are the nominal 1-σ TEMPO2 uncertainties in the least-significant digits quoted. |

3 TIMING SOLUTION AND HIGH-PRECISION POTENTIAL

A total of 148 ToAs were formed in order to measure the orbital, spin characteristics and the astrometry of PSR J1933–6211. Since the eccentricity of the system is very low, we applied the ELL1 model (Lange et al. 2001), for which the eccentricity, e, the epoch and the longitude of periastron passage, T_b and ω respectively, are replaced by the Laplace-Lagrange parameters, η = e sinω and κ = e cosω and the time of the ascending node passage T_asc.

We fit for pulsar parameters using least-squares fitting in order to minimize the differences between measured ToAs and the expected arrival times derived from the analytical model (Edwards et al. 2006). A phase offset was fitted between the CPSR2 and the CASPSR data account for any difference in instrumental delays. We further multiplied the ToA uncertainties with error-scaling-factors (EFACs) of 0.8 and 1.4 for the data correspond to the two CPSR2 polarization bands and 0.9 CASPSR data respectively. These factors account for any possible underestimation of the ToA uncertainties, as described in Verbiest et al. (2016). We note that the phase offset between the backends is only 1.71 µs. Given this small offset, the fact that the timing model fits both sub-sets equally well and that the fit worsens considerably when an integer number of pulse-periods get either added or subtracted from this offset value, clearly indicates that phase-connection was achieved across the 6-year gap.

The TT(BIPM(2013)) terrestrial time standard and the DE421 solar system ephemeris were used in order to convert from topocentric to barycenter arrival times.

The resulting timing parameters that correspond to our best-fit residuals (Fig. 3) are presented in Table 2. The tim-
ing analysis led to significant measurements of the proper motion, the spin and spin-down and the keplerian parameters of the system. All these well measured parameters led us to further investigate the geometry and the origin of the system.

With a weighted rms of only 1.23 μs, PSR J1933–6211 is a good candidate to be added in the Pulsar Timing Array (PTA) projects that aim to detect gravitational waves in the nHz regime as its timing rms compares well to that of most sources in the international PTA (Verbiest et al. 2016).

3.1 Mass constraints from timing

The lack of a Shapiro delay detection and precise post-Keplerian parameter measurements, \( \dot{\omega} \) and \( P \), has as a result that with the current timing direct system-mass measurements are not possible. Instead, we derived constraints on the masses and orientation of the system by mapping the goodness-of-fit (as determined by the \( \chi^2 \) value of the fit) over a four-dimensional grid covering the companion mass \( M_c \), the inclination angle of the system \( i \), the longitude of the ascending node \( \Omega \) and the distance to the system \( D \). At each pixel of this four-dimensional grid, these four parameters were held fixed, as were the post-Keplerian parameters \( \dot{\omega} \) and \( P \) that were derived from these. (Note while the distance does not enter in the post-Keplerian parameters, it was used to determine the parallax, which was kept fixed, and it entered in the calculation of the Kopeikin terms that define \( i \) and \( \Omega \); Kopeikin (1995, 1996)). Our grid had a step size of 0.01 M⊙ in \( M_c \), 0.01° in \( i \), 1° in \( \Omega \) and 20 pc in distance, so our results (see Table 2) are quantised at these levels.

In Fig. 4 our results are presented, with 95% confidence limit on the companion mass. The lower limit for the WD mass (0.1 M⊙) comes directly from the mass function, evaluated for an edge-on system, provided that the pulsar mass is > 0.0 M⊙. These limits do not allow us to identify the companion star as either a He or CO WD. In Section 5 we revisit this question based on some alternative, more theoretical, approaches.

3.2 Characteristic age

The age of pulsars is key for evolutionary models. But in order to measure it precisely we should know the pulsar’s spin period at birth and the braking index. In order to approximate this problem we make some assumptions: the initial period of a pulsar is much lower than the one that we measure today, and the pulsar loses energy due to magnetic dipole radiation with a constant B-field (braking index equal to 3). We can then estimate the characteristic age \( \tau \):

\[
\tau = \frac{P}{2 \dot{P}},
\]

which is only a rough estimate of the real age (see below).

PSR J1933–6211 has a very low spin period derivate, as derived from timing (see Table 2). For pulsars with such low spin period derivate, effects like the Shklovskii effect and Galactic acceleration can have a significant impact on the observed spin period derivate. In order to calculate more accurately the characteristic age we measured the contribution of these kinematic effects in \( \dot{P} \) and we measured them.

Both effects are quite small in PSR J1933–6211, the Shklovskii effect that is calculated from:

\[
\left( \frac{\dot{P}}{P} \right)_{\text{Shk}} = 2.43 \times 10^{-21} \frac{\mu^2}{(\text{mass yr}^{-1})} \frac{d}{(\text{kpc})},
\]

is 1.8(3) \( \times 10^{-19} \) s s\(^{-1}\).

The Galactic acceleration contribution is defined by:

\[
\left( \frac{\dot{P}}{P} \right)_{\text{Gal acc}} = \frac{\alpha_s \sin b}{c} - \cos b \left( \frac{\Theta_0}{c R_0} \right) \left( \cos \beta + \frac{\beta}{\sin^2 \beta + \beta^2} \right),
\]

where the Galactic distance of the solar system: \( R_0 = 8.34 \) kpc, the circular rotation speed of the Galaxy at \( R_0 \): \( \Theta_0 = 240 \) km s\(^{-1}\) (Reid et al. 2014), \( l \) the Galactic latitude and \( \beta = (d/R_0) \cos b - \cos l \). It is measured to be: 9.6(6) \( \times 10^{-20} \) s s\(^{-1}\). The resulting characteristic age after taken into account these effects is 14.6(4) Gyr, which exceeds the Hubble time. Such large characteristic ages have been pointed out before (Camilo et al. 1994), and are caused by the fact that the spin period derivate is too small to cause rapid changes in the pulsar spin period, so we observe the pulsar almost at its birth \( P \) and \( P \) values (Tauris et al. 2012), and thus eq. 1 above brakes down since it assumes \( R_0 \ll P \), where \( R_0 \) is the birth spin period (after accretion). Instead, for MSP’s the value of \( \tau \) is a measure of its remaining lifetime as a radio pulsar.

4 SCINTILLATION MEASUREMENTS

During our observations we measured strong scintillation. The mean S/N for observations that are fully averaged in time and frequency and polarization calibrated, is 29, but reaches ~200 during scintillation maxima, for 15-min observation scans, a factor of almost seven stronger.

We managed to observe only two complete scintles due to the length of the scintillation time scale and the fact that the individual observations were conventionally ~30 minutes long. For the scintillation analysis we used only CASPSR data with 5-min integrations divided into 512 frequency
channels (over a 256-MHz bandwidth). For each observation we removed the band edges, which corresponds to 10% of the band. We manually cleaned the remaining Radio Frequency Interference (RFI) for the cases where it was needed.

In order to measure the scintillation time scale and bandwidth we fitted 1-D Gaussian functions to the frequency (respectively time) averaged intensity-series of the dynamical spectrum. The number of Gaussians that are used to fit the data has been decided through a Kolmogorov-Smirnov test by requiring the post-fit intensities to follow a Gaussian distribution with 95% certainty (see Fig. 5). In Table 3 we present the scintillation parameters for the two available scintles as derived from the method that we explained above.

The scintillation properties allow transverse velocity measurements. The comparison with theoretical transverse velocity and further inclination angle limits are presented below.

### 4.1 Transverse velocity and inclination angle limit

Various studies have investigated the space velocity of pulsars. Desvignes et al. (2016), after investigating 42 MSPs pulsars, concluded that the mean transverse velocities of MSPs is $92 \pm 10$ km s$^{-1}$, a factor of 4 lower than that of young pulsars (Hobbs et al. 2005). This difference can be understood from their dissimilar kick velocities at birth. Such a differentiation is thought to arise from a combination of different masses of the exploding stars forming neutron stars in isolation versus in close binaries (the latter being stripped prior to the explosion) and the absorption of the kick momentum in a binary system (Tauris & Bailes 1996). newborn pulsars are expected to receive a broad range of kicks – between 0 and more than 1000 km s$^{-1}$ (Janka 2016). The binaries that eventually give rise to MSPs, survived the SN kick, which could mean that the kick often was either small or fortuitously oriented.

Pulsar space velocities can be measured through scintillation properties of the pulsar. By assuming that the diffraction screen is located in the middle between the Earth and the pulsar and that the scattering medium is a uniform Kolmogorov medium, we calculate the scintillation speed from (Gupta et al. 1994):

$$V_{\text{SS}} = 3.85 \times 10^4 \frac{\sqrt{d(kpc)} \Delta \nu(MHz)}{f(GHz) \Delta t(s)},$$

where $d$ is the distance of the pulsar, $f$ is the observing frequency and $\Delta f$ and $\Delta t$ are the scintillation bandwidth and time scale (see Table 3).

The dispersion measure can give an estimate of the pulsar distance. We consider two such distances derived from two different models: the widely used NE2001 model (Cordes & Lazio 2002) and the most recent YMW16 model (Yao et al. 2017). The NE2001 model has been widely scrutinised whenever new pulsar distances were measured (see, e.g. Matthews et al. 2016; Desvignes et al. 2016), leading to the conclusion that for pulsars at low and medium Galactic latitudes this model gives a good distance prediction, comparable to pulsar parallax measurements. For PSR J1933–6211 with Galactic latitude of $-28.6315^\circ$ and a dispersion measure equal to 11.520(2) pc cm$^{-3}$ the model-predicted distance is 0.51(7) kpc, and 0.65 kpc based on NE2001 and YMW16, respectively. The scintillation speed that we measured based on NE2001 distance measurements is equal to 36(2) km s$^{-1}$.

The pulsar space velocity ($V_{\text{model}}$), that we measured through scintillation speed, is composed of the pulsar’s orbital velocity ($V_{\text{orb}}$), proper motion ($V_{\text{pm}}$), Earth’s velocity ($V_{\text{Earth}}$) and the velocity of the scattering screen ($V_{\text{SS}}$).

$$V_{\text{model}} = V_{\text{orb}} + V_{\text{pm}} + V_{\text{Earth}} + V_{\text{SS}}$$

The proper motion and the orbital velocity, that either added or subtracted to the proper motion, contribute the most to the pulsar space velocity, since $V_{\text{SS}}$ can be neglected (Gupta 1995) and $V_{\text{Earth}}$ is considered as constant throughout the observation. Since the pulsar is moving, as we observe it we track it in different positions on the sky, having as a result to detect differences in $V_{\text{SS}}$. By monitoring these changes in respect to orbital phase we can obtain useful information about the geometry of the system.

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Table 3. Scintillation parameters and the derived scintillation speed of the two complete scintles. Both observations were taken with the CASPSR backend at 1382 MHz central frequency with 256-MHz observing bandwidth divided into 512 channels and 5-min time resolution.

| Data       | 2011-05-03 | 2011-05-16 |
|------------|------------|------------|
| $\Delta t$ (min) | 181(5) | 108(5) |
| $\Delta f$ (MHz) | 358(8) | 155(8) |
| $V_{\text{SS}}$ based on NE2001 (km s$^{-1}$) | 34(3) | 38(3) |
| Orbital phase ($\phi$) | 0.2 | 0.2 |

Figure 5. Dynamic spectrum of a full scintle of PSR J1933–6211 as observed on 16th of May 2011. In the top and right plots, the S/N in each frequency channel and in each sub-integration, are presented respectively. The solid line corresponds to a Gaussian fitting line to our observation.
example, Lyne (1984) and Ord et al. (2002) measured the inclination angles of the PSR B0655+64 and J1141−6545 systems respectively, based on the orbital dependence of the scintillation speed. Unfortunately, based on our analysis, the fact that both scintles are detected at the same orbital phase (Table 3), didn’t allow us to perform a $\chi^2$ mapping in order to put constraints on the inclination angle of the system. Luckily, we can further investigate the geometry of the system based on the timing constraints on the longitude of the ascending node $\Omega$ (eq. 5). The scintillation speed based on our observations. Our unknowns are two: $\Omega$ and $i$. The measured orbital velocity depends only on the unknown inclination angle:

$$V_{\text{orb}} = \frac{2 \pi \, d_p}{\sin i \sqrt{T - e^2} \, P_b} = \frac{20.8868501(5)}{\sin i} \text{ km s}^{-1}. \quad (6)$$

Higher inclination angles correspond to lower orbital velocities and as a result to lower observed scintillation speeds. The highest probable orbital velocity that can be measured for this system, in the 0.2 orbital phase, is $\sim 120$ km s$^{-1}$ and the lowest is $\sim 2$ km s$^{-1}$.

The other unknown is $\Omega$ for which we have a 2-$\sigma$ limit through timing (see Table 2). Inside this $\Omega$ 2-$\sigma$ parameter space we find the $i$ values for which the $V_{\text{model}}$ is consistent to our scintillation speed based on our observations. Our results are presented in Fig. 6. The fact that two regions of $i$ are allowed, is due to the 180-degree ambiguity in $\Omega$, raised from the fact that we can not determine which of the two orbit nodes is the ascending node.

5 LIMITS ON THE SYSTEM MASSES

In addition to the timing-based constraints presented in Section 3.1, for LMXBs, there are theoretical relations between the orbital parameters and the pulsar and companion masses. We will now consider these theoretical models and their predictions, in order to investigate the nature of the white dwarf companion.

5.1 Orbital eccentricity

Phinney & Kulkarni (1994) found a relationship between the orbital eccentricity and orbital period for cases where the pulsar is formed after stable mass transfer in an LMXB from a red giant filling its Roche lobe. For orbital periods of 12.8 days, the 95% lower limit on the eccentricity as predicted from this model is significantly higher than the value that we derived from timing (Table 2). This discrepancy is caused by the uncertainty in input physics applied for the modeling, i.e. related to tidal interactions and convection in the outer layers of the progenitor star. As a result, there is a large scatter in eccentricities for observed BMSPs with a given orbital period (cf. Fig. 4 in Tauris et al. (2012)).

5.2 Orbital period – WD mass relation

Different studies have investigated the relationship between the orbital period and the companion mass in MSP – WD binaries which originate from LMXBs (Savonije 1987; Rappaport et al. 1995; Tauris & Savonije 1999; Istrate et al. 2014). This relation has its basis in a correlation between the radius of a low-mass red-giant star and the mass of its degenerate He core.

Numerical stellar evolution calculations have been done by Tauris & Savonije (1999) to investigate this relationship for LMXBs with wide orbits (> 2 days). Based on computations of dynamically stable mass transfer in LMXBs, they obtained a relationship between the orbital period and the WD mass for different chemical compositions of the donor star. Based on this analysis, the derived WD mass varies from 0.251 to 0.277 $M_{\odot}$ (Table 4).

The mass of the WD is related to the mass of the neutron star ($M_{ns}$) and the orbital inclination angle ($i$) through the mass function:

$$f(M) = \frac{(M_{ns} \sin i)^3}{(M_{ns} + M_{wd})^2}, \quad (7)$$

In Fig. 7 we present this relation for three different WD masses, see Table 4 above. The derived upper limit for the neutron star mass is 0.96 ± 0.08 $M_{\odot}$. This very low pulsar mass limit, can be even lower if we combine it with the inclination angle limit: $i < 80^\circ$, as calculated based on the

Table 4. WD mass estimates assuming different chemical compositions of its progenitor star, based on the orbital period – WD mass relation for He WD companions (Tauris & Savonije 1999) and given that $P_0 = 12.8$ d for PSR J1933−6211.

| Population | WD mass ($M_{\odot}$) |
|------------|----------------------|
| I          | 0.251                |
| I & II     | 0.264                |
| II         | 0.277                |

Figure 6. Pulsar mass – companion mass diagram. The grey areas indicate inclination angles excluded with 1-$\sigma$. With the solid lines the inclination angle 1-$\sigma$ limits for this system are presented, as measured based on the scintillation speed. With the dotted lines the error is presented. Our two sets of solutions arise from the fact that we can not determine which of the two nodes is the ascending node.
In a close orbit, the mass of the remnant CO WD can be as low as 0.33 M⊙. In case of IMXBs, the main sequence (i.e. undergoing core hydrogen burning) the RLO begins when the progenitor of the WD is still on.

The two scintles that we observed allowed us to determine the scintillation parameters of the system. This information lead us to transverse velocity measurements of 26(2) km s⁻¹. Based on χ² mapping, the Keplerian parameters, measured through timing, and the transverse velocity we put limits on the inclination angle of the system. We concluded that the inclination angle is likely lower than ∼80°.

The lack of Shapiro delay, ω and ρ′ measurements prevents direct mass measurements. For this reason, we performed χ² mapping in order to put limits on the WD mass. Our 2-σ upper limit for the WD mass is 0.44 M⊙. This limit corresponds to 2.2 M⊙ as an upper pulsar mass limit for a high inclination angle. Based on this limit, we cannot distinguish between the possibility of a CO or a He WD. For this reason, we further investigated the possibility that the companion is a He WD. These type of MSP systems are very well studied. Based on the orbital period – WD mass relationship resulting from LMXB evolution (Tauris & Savonije 1999), we derived an upper limit for the pulsar mass of 0.96 ± 0.08 M⊙. Therefore, we conclude that if PSR J1933–6211 has indeed a He WD companion, then the mass of the pulsar is very light – in fact, too light to be consistent with current stellar evolution and SN explosion physics modeling. We therefore, conclude that the companion of PSR J1933–6211 is most likely a CO WD, and therefore this system has an origin in an IMXB system, somewhat similar to the BMSP J1614–2230.

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