Optical identification of the binary companion to the millisecond PSR J2302+4442 with the Gran Telescopio Canarias

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ABSTRACT

We report detection of the binary companion to the millisecond pulsar J2302+4442 based on the deep observations performed with the Gran Telescopio Canarias. The observations revealed an optical source with $r' = 23.33\pm0.02$ and $i' = 23.08\pm0.02$, whose position coincides with the pulsar radio position. By comparing the source colour and magnitudes with the white dwarf cooling predictions, we found that it likely represents a He or CO-core white dwarf with the pulsar radio position. Following the discovery in the timing campaign with the Nançay, Jodrell Bank and Green Bank telescopes (Cognard et al. 2011). Table 1 summarises the parameters of the pulsar system.

1 INTRODUCTION

Among ~2600 pulsars currently listed in the ATNF Pulsar Catalogue, there are over 300 pulsars with very short rotational periods ($P < 30$ ms). These are so-called millisecond pulsars (MSPs) that are believed to have been spun up through the recycling process, i.e. through angular momentum transfer by accretion from main-sequence companions during their low and intermediate X-ray binary stages (Bisnovatyi-Kogan & Komberg 1974, Alpar et al. 1982). The majority of the known MSPs are observed in binary systems, and, depending on the initial conditions, the nature of the companion star can be diverse. In most of the cases, however, the companion represents a He white dwarf (WD) (see, e.g., Tauris et al. 2011).

Observations of binary MSP systems allow for measurements of their fundamental parameters such as masses of both pulsar and companion star. In some cases this can be achieved through radio timing measurements of the Shapiro delay (Shapiro 1964). However, such measurements can be significantly hampered in case of long MSP system orbital periods, extending the observational time spans to decades. In this case, optical observations can be used for independent measurements of the WD companion mass by comparing the photometric and/or spectroscopic results with the WD evolutionary tracks. On the other hand, the optical detectability highly depends on the distance to a particular MSP system.

In this respect, a significant contribution to the MSP population was made by the Fermi γ-ray telescope detections and the follow-up radio searches (Ray et al. 2012). To date, γ-ray MSPs represent over 40 per cent of more than 200 γ-ray pulsars detected with Fermi (Guillemot et al. 2016), and about 20 per cent of all known MSPs. The advantage of the Fermi pulsars is that most of them are nearby objects (Saz Parkinson & Fermi LAT Collaboration 2013) and their faint optical binary companions are expected to be easily detected with large-aperture optical telescopes.

The millisecond PSR J2302+4442 ($P = 5.19$ ms, $P = 13.9 \times 10^{-21}$) has been discovered in the Nançay Radio Telescope follow-up observations of unidentified Fermi γ-ray sources and later studied during the timing campaign with the Nançay, Jodrell Bank and Green Bank telescopes (Cognard et al. 2011). Table 1 summarises the parameters of the pulsar system. Following the discovery in the radio, the γ-ray pulsations were also found in the Fermi data. In addition, a tentative pulsar X-ray counterpart with the 0.5–8 keV flux of $\sim 4 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ was found in the XMM-Newton
Table 1. Parameters of the PSR J2302+4442 system. The pulsar period and age are derived from Cognard et al. (2011) and the period derivative is from Arzoumanian et al. (2018). The pulsar coordinates for the MJD 56279 epoch and the proper motion values are from Matthews et al. (2016) and Guillemot et al. (2016), respectively. The system orbital parameters are taken from Fonseca et al. (2016).

| P (ms) | 5.192324646411(7) |
| 13.9×10^{-21} |
| τ (yr) | 6.2×10^{9} |
| α_{2000} | 23^{0+2}_{-0.4}6_{-6}^{+978}(3) |
| δ_{2000} | +44^{0+2}_{-0.2}22_{-0928}^{+1028}(3) |
| i (deg) | 103.40 |
| b (deg) | -14.00 |
| μ_α (mas y^{-1}) | -0.05(13) |
| μ_δ (mas y^{-1}) | -5.85(12) |

Keplerian elements

| P_0 (days) | 125.93529697(13) |
| x (lt-s) | 51.4299676(5) |
| i (deg) | 54^{+1}_{-3} |
| e | 0.000503021(17) |

observations of the Fermi field conducted prior to the radio pulsar identification (Cognard et al. 2011).

Using a nine-year dataset from the North American Nanohertz Observatory for Gravitational Waves, Fonseca et al. (2016) have tentatively detected a Shapiro timing delay in the PSR J2302+4442 system. However, given the large orbital period P_0, only a small fraction of the Shapiro-delay signal was sampled and only a rough estimate on the pulsar companion mass m_c = 2.3^{+1.3}_{-1.2} M_⊙ was provided. The nature of the companion star thus remains unclear.

According to the NE2001 electron-density model (Cordes & Lazio 2002), the pulsar dispersion measure DM = 13.762 ± 0.006 pc cm^{-3} and the line of sight correspond to the distance of 1.18 kpc. The YMW16 model (Yao et al. 2017) assigns them a smaller distance of 0.86 kpc. Both estimates suggest the PSR J2302+4442 system as a promising target for optical observations. Based on the Swift’s Ultraviolet/Optical Telescope observations, only shallow optical and ultraviolet upper limits on the companion flux were established (Cognard et al. 2011).

Here we present deep optical observations of the PSR J2302+4442 system carried out with the Gran Telescopio Canarias (GTC) and report a likely identification of the pulsar binary companion. The details of observations and data reduction are presented in Sect. 2, the results and analysis are described in Sect. 3 and discussed in Sect. 4.

2 OBSERVATIONS AND DATA REDUCTION

The pulsar field was observed in the Sloan r' and i'-bands with the Optical System for Imaging and low-intermediate Resolution Integrated Spectroscopy (OSIRIS) at the GTC on September 16, 2017^3. The detector provides a plate scale of 0.254 arcsec/pixel (2×2 binning) and a field of view (FOV) of 7.8 arcmin × 7.8 arcmin consisting of two CCDs. The target source was exposed on CCD2. The observations were performed in dark time and under clear conditions, with seeing values in the range of 0.6–0.9 arcsec. To avoid possible affection by bad pixels, we used 5 arcsec dithering between the individual exposures in both bands.

We reduced the data using standard routines from the Image Reduction and Analysis Facility (IRAF) package. The individual images were bias-subtracted and flat-fielded. To stack the exposures together, we used 10 unsaturated field stars and the best-quality image as a reference in each band. The total integration times on the resulting combined r' and i'-band images were 3135 s and 2415 s with the mean airmass values of ~1.25 and ~1.13, respectively.

The astrometric solution was computed using a selection of 11 isolated, non-saturated field stars on the resulting r' and i'-images and their coordinates from the USNO-B1 astrometric catalogue. Formal rms uncertainties of the astrometric fit were ∆R < 0.098 arcsec and ∆Dec < 0.175 arcsec for both the r' and i'-band images. The fit residuals were consistent with the nominal catalogue uncertainty of 0.2 arcsec. The resulting conservative 1σ referencing uncertainty for the two images is ≤ 0.22 arcsec for RA and ≤ 0.27 arcsec for Dec.

As a photometric reference, the SA 110-232 Sloan standard (Smith et al. 2002) was observed in both bands the same night as our target. Using the measured magnitudes and the mean OSIRIS extinction coefficients k_r = 0.07±0.01 and k_i = 0.04±0.01, we determined the magnitude zero-points of 28.69(1) and 28.24(1) for the r' and i'-bands, respectively.

3 RESULTS

The fragments of the resulting r' and i'-band images are presented in Fig. 1. The centre of the circle corresponds to RA = 23^{0+2}_{-0.4}6_{-6}^{+978} and Dec = +44^{0+2}_{-0.2}22_{-0928}^{+1028}. The coordinates represent the pulsar radio timing position from Matthews et al. (2016) shifted in accordance with the pulsar proper motion reported by Guillemot et al. (2016). The circle radius of 0.81 arcsec corresponds to the 3σ pulsar position uncertainty that accounts for the optical astrometric referencing and proper motion uncertainties. In both r' and i'-band images we firmly detect a starlike source whose position with RA = 23^{0+2}_{-0.4}6_{-6}^{+978} and Dec = +44^{0+2}_{-0.2}22_{-0928}^{+1028} falls into the pulsar position uncertainty region. Based on the spatial coincidence, we consider that this source is related to the pulsar system. The probability to detect an unrelated object within the pulsar positional region can be derived as P = 1−exp(−πσR^2), where σ corresponds to the surface number density of stars with a similar magnitude and R is the astrometric accuracy. Considering an unrelated object with a magnitude of 19–25, in case of our FOV this probability is as low as ~0.002. Hence, we conclude that the source is a likely optical counterpart to the pulsar binary companion. We will hereafter refer to this object as the pulsar companion. Based on the aperture photometry performed on the resulting combined images, we estimated the companion magnitudes of r' = 23.33(2) mag and i' = 23.08(2) mag.

The pulsar parallax is poorly constrained (Matthews et al. 2016, Arzoumanian et al. 2018), therefore, for the following estimations we will use the 95 per cent confidence lower limit on the pulsar distance of 0.5 kpc that follows from the parallax measurements (see Arzoumanian et al. (2018)) and the upper limit of 1.0 kpc. The latter was estimated assuming the efficiency of conversion of spin-down power into γ-ray radiation, η = L_γ/E, to be 100 per cent.

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^3 For instrument features see http://www.gtc.iac.es/instruments/osiris/
^4 Proposal GTCMULTIPLE2A-17BMEX, PI A. Kirichenko
Figure 1. GTC/OSIRIS Sloan r’ (left) and i’-band (right) image fragments of the PSR J2302+4442 field. The blue circle shows 3\(\sigma\) radio timing pulsar position uncertainty for the epoch of our observations (see text for details). The black stripe on both images is a part of a spike of a saturated field star.

Figure 2. Colour-magnitude diagram with the available data for companions to different MSPs including PSR J2302+4442 and the WD cooling tracks. Solid lines represent model predictions for WDs with hydrogen atmospheres with masses 0.1869, 0.2026 and 0.2495 M\(\odot\) from Panei et al. (2007) (purple, labelled as DA*) and 0.3–0.8 M\(\odot\) (spaced at 0.1 M\(\odot\)) from Holberg & Bergeron (2006), Kowalski & Saumon (2006), Tremblay et al. (2011) and Bergeron et al. (2011) (blue, labelled as DA). Red dashed lines show tracks for WDs with helium atmospheres with masses 0.2–0.7 M\(\odot\) (spaced at 0.1 M\(\odot\)) from Bergeron et al. (2011) (labelled as DB). Masses increase from upper to lower curves. The cooling ages are marked along the tracks.

Using the interstellar dust reddening model by Green et al. (2015) and considering the pulsar distance range of 0.5–1.0 kpc, we obtained the reddening value E(B-V) = 0.16±0.03. Along with the conversion coefficients provided by Schlafly & Finkbeiner (2011), this leads to the extinction correction values A\(r’\) = 0.37±0.07 and A\(i’\) = 0.27±0.05. The corresponding companion dereddened magnitudes are r’ = 22.96±0.07 mag and i’ = 22.81±0.05 mag.

Aiming to check whether the PSR J2302+4442 companion, as in the most probable case, belongs to the WD population, we compared its r’-band magnitude against the WD cooling predictions from Holberg & Bergeron (2006), Kowalski & Saumon (2006), Tremblay et al. (2011), Bergeron et al. (2011) and Panei et al. (2007). The respective colour-magnitude diagram with absolute magnitudes is presented in Fig. 2. The parameters of companions to some other millisecond pulsars with known r’ and i’-band magnitudes are presented for comparison. These include PSR J0348+0432 (Antoniadis et al. 2013), PSR J1012+5307 (Nicasio et al. 1995), PSR J2317+1439 (Dai et al. 2017) and PSRs J0614–3329 and J1231–1411 (Bassa et al. 2016). The magnitudes of the sources were adopted both from the Sloan Digital Sky Survey (SDSS) archive (Abolfathi et al. 2017) and directly from the cited articles. The respective extinction correction values were calculated using the reddening models by Green et al. (2015) and Drimmel et al. (2003). The dereddened magnitudes were then transformed into the absolute magnitudes using the DM distances and, if provided, the model-predicted WD distances and the parallax distances. The absolute magnitude and reddening for PSR J2317+1439 from Dai et al. (2017) were recalculated based on...
as follows from the cooling models. The $r' - i'$ colour does not exclude the possibility that the WD can fall onto the DA cooling sequence in the upper part of the colour-colour diagram, where the collision-induced absorption of molecular hydrogen strongly enhances the opacity in the infrared and shifts the spectral energy distribution to bluer colour indices (see, e.g., Hansen (1998)). In this case the expected effective temperature of the WD would be $\leq 3000$ K. However, the corresponding $r'$-band absolute magnitude would then imply a distance of $\leq 230$ pc. Such inconsistency with the distance derived from the parallax measurements (Arzoumanian et al. 2018) excludes this possibility.

To set constraints on the WD mass and effective temperature, we followed the method described by Dai et al. (2017). We obtained a single WD cooling model by unifying the cooling predictions for WD masses of 0.19–0.25 $M_\odot$ from Panei et al. (2007) and 0.3–1.2 $M_\odot$ from Holberg & Bergeron (2006), Kowalski & Saumon (2006), Tremblay et al. (2011) and Bergeron et al. (2011). We interpolated this model on the mass-temperature plane within the ranges of 0.19–1.2 $M_\odot$ and 4000–11000 K using a 7000×7000 grid. For each point of the plane we then calculated the likelihood using Equation (5) from Dai et al. (2017). In Fig. 4 we present the mass-temperature plane with the resulting constraints on the WD mass and effective temperature and the respective 1D likelihoods with calculated median values of 0.52$^{+0.25}_{-0.19}$ $M_\odot$ and 6300$^{+1000}_{-800}$ K.

To check whether our companion mass estimation can provide better constraints on other parameters of the pulsar system, we have used the probabilities of the pulsar Shapiro-delay parameters obtained from the NANOGrav nine-year dataset (Fonseca et al. 2016). The Shapiro delay for the PSR J2302+4442 system ranks among the weakest detections in the set, and only rough constraints on the companion mass and inclination angle of $m_p = 2.3^{+1.3}_{-1.7} M_\odot$ and $i = 54^{+14}_{-12}$ degrees were provided (see Fig. 5). We have combined our likelihoods on the companion mass with the probability map from Fonseca et al. (2016). The resulting constraints on the two parameters are shown in Fig. 5. Based on the new probability map, we have calculated the median value for the inclination angle of $i = 73^{+5}_{-6}$ degrees, where the errors correspond to $1\sigma$ uncertainties. Using the binary mass function and the resulting constraint on the inclination angle, we have then calculated the pulsar mass value of $m_p = 3.1^{+0.7}_{-0.6} M_\odot$.

4 SUMMARY AND DISCUSSION

The first deep optical observations of the PSR J2302+4442 field with the GTC/OSIRIS have allowed us to reveal a point source whose position coincides with the pulsar radio timing position and whose magnitudes are in agreement with a WD. We propose the source as a likely optical identification of the pulsar companion.

We have considered that the optical source can be related to stellar families other than the WDs. Based on its effective temperature, the source could belong to the subdwarf branch. However, the subdwarf absolute magnitudes and the object apparent magnitude would then imply an unreasonably high distance of $\sim 30$ kpc, placing it outside the galaxy. Its association with the main sequence would assign it even larger distance, thus ruling out any stellar nature other than WD. Although the extragalactic origin cannot be excluded based on the current information, it is very unlikely that the source represents a distant galaxy. These conclusions favour a true detection of the pulsar companion.

Assuming the companion is indeed a WD, we have put constraints on its mass of $0.52^{+0.25}_{-0.19}$ $M_\odot$ and temperature of 6300$^{+1000}_{-800}$ K.
Companion mass ($M \odot$) and dotted lines correspond to the median value and 1σ confidence levels. Lower panel: the resulting 1D likelihood for the inclination angle. Dashed lines represent the 1σ confidence levels.

Figure 5. Upper panel: constraints on the inclination angle and companion mass derived by Fonseca et al. (2016) from the radio timing alone (red contours) and after combining the radio timing and photometric analysis (blue contours). Contours represent 1σ, 2σ and 3σ confidence levels. Lower panel: the resulting 1D likelihood for the inclination angle. Dashed and dotted lines correspond to the median value and 1σ confidence levels, respectively.

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K using the WD evolutionary tracks. The derived parameters imply that the companion belongs to the population of He or CO-core WDs. By the orbital period $P_o$, the pulsar period $P_s$, and the companion mass $m_c$, the PSR J2302+4442 system is found to fit in well the $P_s-m_c$ and $P_o-m_c$ distributions of the known binary MSPs (see, e.g., Fig.8 of Manchester (2017)). It resides among other systems with a similar companion mass, $P_s \sim 4-6$ ms and $P_o \sim 30-300$ days. On the other hand, considering the PSR J2302+4442 companion represents a He-core WD, its mass can be predicted based on the ($P_o$, $M_c$) correlation introduced by Tauris & Savonije (1999). The correlation is estimated using the models of low-mass X-ray binaries and in case of our $P_o$ gives the range of 0.34–0.37 $M_\odot$, depending on the chemical composition of the donor star. Our constraint on the WD mass is consistent with this prediction, supporting a genuine association with the PSR J2302+4442 system.

Combining our estimation on the companion mass with the radio timing measurements, we have obtained new constraints on the binary system inclination angle of $i = 73.4^\circ$ degrees and the pulsar mass of $m_p = 3.1_{-0.3}^{+0.5} M_\odot$. The latter represents a more accurate constraint on the pulsar mass as compared to the radio timing estimations alone and it is also consistent with the range of 1.37–2.01 $M_\odot$ found in precise mass measurements of recycled pulsars (Ozel & Freire 2016).

In order to reveal the fundamental parameters of the companion, photometry in other bands, optical spectroscopy and parallax measurements are needed. Spectroscopic observations will allow one to set more stringent constraints on its atmospheric parameters, temperature and surface gravity. Despite the fact that the source is relatively faint, optical spectroscopy is still feasible with the 8–10 meter class telescopes. Combined together with the precise distance measurements, it can potentially lead to the mass determination both for the companion and the neutron star.

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