Searching for optical companions to four binary millisecond pulsars with the Gran Telescopio Canarias

A. Yu. Kirichenko1,2*, A. V. Karpova2, D. A. Zyuzin2, S. V. Zharikov1, E. A. López3, Yu. A. Shibanov2, P. C. C. Freire4, E. Fonseca5, and A. Cabrera-Lavers6,7

1Instituto de Astronomía, Universidad Nacional Autónoma de México, Apdo. Postal 877, Baja California, México, 22800
2Ioffe Institute, Politekhnicheskaya 26, St. Petersburg, 194021, Russia
3Instituto de Investigación en Ciencias Físicas y Matemáticas, USAC, Ciudad Universitaria, Zona 12, Guatemala
4Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53131 Bonn, Germany
5Department of Physics & McGill Space Institute, McGill University, 3600 University Street, Montreal, QC, H3A 2T8, Canada
6Instituto de Astrofísica de Canarias, Vía Láctea s/n, E38200, La Laguna, Tenerife, Spain
7GRANTECAN, Cuesta de San José s/n, E-38712, Baja Baja, La Palma, Spain

Accepted 2020 January 8. Received 2020 January 7; in original form 2019 November 11

ABSTRACT

We report on multi-band photometric observations of four binary millisecond pulsars with the Gran Telescopio Canarias. The observations led to detection of binary companions to PSRs J1630+3734, J1741+1351 and J2042+0246 in the Sloan $g'$, $r'$ and $i'$ bands. Their magnitudes in the $r'$ band are $\approx 24.4, 24.4$ and $24.0$, respectively. We also set a $3\sigma$ upper limit on the brightness of the PSR J0557+1550 companion in the $r'$ band of $\approx 25.6$ mag. Combining the optical data with the radio timing measurements and white dwarf cooling models, we show that the detected companions are cool low-mass white dwarfs with temperatures and ages in the respective ranges of $(4–7)\times10^3$ K and 2–5 Gyr. All the detected white dwarfs are found to likely have either pure hydrogen or mixed helium-hydrogen atmospheres.

Key words: binaries: general – pulsars: individual: PSR J0557+1550, PSR J1630+3734, PSR J1741+1351, PSR J2042+0246

1 INTRODUCTION

Millisecond pulsars (MSPs) represent a subclass of radio pulsars that are characterised by short rotational periods ($P < 30$ ms) and low spin-down rates ($\dot{P} \sim 10^{-19} – 10^{-20}$ s s$^{-1}$). To date, about 400 MSPs have been detected\(^1\). According to the commonly accepted ‘recycling’ scenario, such objects are formed as ‘normal’ pulsars in binary systems and then are spun-up due to accretion of matter from companion stars (Bisnovatyi-Kogan & Komberg 1974; Alpar et al. 1982). Resulting systems have essentially circular orbits and ‘peeled’ companions, usually low-mass white dwarfs (WDs) (e.g. Tauris 2011). To explain binary MSPs with eccentric orbits, other formation channels are discussed such as the triple-system formation scenario and the direct formation via a delayed accretion-induced collapse of massive WDs (Tauris 2011; Portegies Zwart et al. 2011; Freire & Tauris 2014). Some other possibilities for the origin of these systems are discussed by Antoniadis (2014).

Under certain conditions, which are usually defined by
have triggered intensive studies with large optical telescopes (Bassa et al. 2016; Dai et al. 2017; Kirichenko et al. 2018; Beronya et al. 2019).

In this article we present the results of first deep optical observations of four binary MSPs with the Gran Telescopio Canarias (GTC): PSRs J0557+1550, J1630+3734, J1741+1351 and J2042+0246. The parameters of the systems and their previous studies are reviewed in Section 2. In Section 3 we provide a description of our optical observations and data reduction, and the results are presented in Section 4 and are discussed in Sections 4 and 5.

2 TARGETS

The parameters of the four MSP systems are collected in Table 1. For each of them, the orbital period ≥ 4 days together with the companion mass or its lower limit of ≥ 0.19 M⊙ derived from the radio timing imply that the companion is likely a WD. We have selected these systems for optical observations considering the WD nature of the companions and distances ≤ 2 kpc. Below we shortly describe previous studies of the targets.

PSR J0557+1550 was discovered in the PALFA Galactic plane survey using the Arecibo radio telescope (Scholz et al. 2015). The authors did not find any optical or infra-red counterpart to the pulsar in the SIMBAD database and concluded that the apparent visual magnitude of its companion has to be > 22.

PSRs J1630+3734 and J2042+0246 were discovered in the radio observations of Fermi unassociated sources (Ray et al. 2012; Sanpa-arsa 2016). The most recent timing analyses of these pulsars were performed by Sanpa-arsa (2016). After inspecting archival data from the Catalina Sky Survey with limiting visual magnitudes of 19.5 – 21.5, Salvetti et al. (2017) have reported non-detection of the PSR J1630+3734 companion.

PSR J1741+1351 was discovered with the Parkes radio telescope (Jacoby et al. 2007) and the first Shapiro delay measurements for this pulsar were performed by Freire et al. (2006). It was also detected in γ-rays with the Fermi telescope (Espinoza et al. 2013). Using the 11-yr data set from the North American Nanohertz Observatory for Gravitational Waves (NANOGrav), Arzoumanian et al. (2018) measured masses of both PSR J1741+1351 and its companion and the system inclination (see Table 1). Our optical detection of the companion with the GTC and its preliminary analysis have been briefly reported in a conference paper (Zyuzin et al. 2019).

Table 1. Parameters of the binary MSP systems studied in this Paper. Numbers in parentheses are 1σ uncertainties related to the last significant digits quoted. \( D_{\text{YM16}} \) is the DM-distance derived using the YMW16 (Yao, Manchester & Wang 2017) Galactic electron density model. \( D_p \) is the timing parallax distance.

| MSP         | J0557+1550 | J1630+3734 | J1741+1351 | J2042+0246 |
|-------------|------------|------------|------------|------------|
| Right ascension \( \alpha \) (J2000) | 05°57′31″49.18(9) | 16°30′36″46′0093(7) | 17°41′31″14′4731(2) | 20°42′11″00′2875(5) |
| Declination \( \delta \) (J2000) | 15°50′06″046(8) | 37°34′42″007(1) | 13°51′44″12′1884(8) | 02°46′14″397′2(7) |
| Galactic longitude \( l \) (deg) | 192.68 | 60.24 | 37.89 | 48.99 |
| Galactic latitude \( b \) (deg) | –4.31 | 43.21 | 21.64 | –23.02 |
| Proper motion \( \mu_\alpha \) (mas yr\(^{-1}\)) | –2.4(3.5) | –5.19(3.4) | –7.42(2) | –14.1(3.5) |
| Proper motion \( \mu_\delta \) (mas yr\(^{-1}\)) | –15.9(3.4) | –15.9(3.4) | –7.42(2) | –14.1(3.5) |
| Epoch (MJD) | 56346 | 56136 | 56209 | 56529 |
| Spin period \( P \) (ms) | 2.5563767076830(5) | 3.3181121293936(9) | 3.747154500259940030(7) | 4.53372670723282(3) |
| Period derivative \( \dot{P} \) (10\(^{-20}\) s s\(^{-1}\)) | 0.735(2) | 1.077(9) | 3.021648(14) | 1.403(6) |
| Characteristic age \( \tau = P/2\dot{P} \) (Gyr) | 5.5 | 4.9 | 2.0 | 5.1 |
| Orbital period \( P_O \) (days) | 4.8465590440(4) | 12.52502574(2) | 16.335347828(4) | 77.20098806(3) |
| Projected semi-major axis \( a \) (lt-s) | 4.0544597(8) | 9.039336(1) | 11.0033159(5) | 24.5699969(8) |
| Spin-down power \( \dot{E} \) (erg s\(^{-1}\)) | 1.7×10\(^{34}\) | 1.2×10\(^{34}\) | 2.3×10\(^{34}\) | 5.9×10\(^{33}\) |
| Dispersion measure (DM, pc cm\(^{-3}\)) | 102.6 | 14.2 | 24.2 | 9.3 |
| Distance \( D_{\text{YM16}} \) (kpc) | 1.83 | 1.19 | 1.36 | 0.64 |
| Timing parallax (mas) | – | – | 0.6(1) | – |
| Distance \( D_p \) (kpc) | – | – | 1.8\(^{+0.5}_{-0.3}\) | – |
| Companion mass \( M_c \) (M⊙) | ≥ 0.2\(^b\) | ≥ 0.24\(^b\) | 0.22\(^{+0.05}_{-0.03}\) | ≥ 0.19b |
| Pulsar mass \( M_p \) (M⊙) | – | – | 1.14\(^{+0.23}_{-0.25}\) | – |
| System inclination \( i \) (deg) | – | – | 73\(^{+2}_{-1}\) | – |
| References\(^c\) | [1] | [2] | [3] | [2] |

\(^a\)In the case of the NE2001 model (Cordes & Lazio 2002), the distances \( D_{\text{NE2001}} \) are 2.92 (J0557+1550), 0.94 (J1630+3734), 0.9 (J1741+1351) and 0.83 (J2042+0246) kpc.

\(^b\)A minimum companion mass is calculated assuming the inclination angle of the binary orbit \( i = 90° \) and the pulsar mass \( M_p = 1.4M_\odot \).

\(^c\)Parameters are obtained from [1] – Scholz et al. (2015), [2] – Sanpa-arsa (2016) and [3] – Arzoumanian et al. (2018) (see also https://data.nanograv.org for current values).
3 OBSERVATIONS AND DATA REDUCTION

The fields of PSRs J0557+1550, J1630+3734, J1741+1351 and J2042+0246 were observed\(^2\) in June, September and October 2018 under clear sky conditions using the Optical System for Imaging and low-intermediate Resolution Integrated Spectroscopy (OSIRIS\(^3\)) instrument at the GTC. OSIRIS consists of two CCDs and provides a field of view (FoV) of 7.8 arcmin × 7.8 arcmin and a pixel scale of 0.254 arcsec. To avoid affection by bad pixels, 5 arcsec dithering between the individual exposures was used in all observing programmes. In addition, short 20 s exposures of each pulsar field in the \(r'\) band were obtained to avoid saturation of bright stars that were further used for precise astrometry. The details of the observations are presented in Table 2.

We performed standard data reduction, including bias subtraction and flat-fielding, using the Image Reduction and Analysis Facility (IRAF) package. The cosmic rays were removed from each individual exposure with the L.A.Cosmic algorithm (van Dokkum 2001). For each field and filter, the individual images were then aligned to the best quality image and combined. The four targets were exposed on CCD2 providing a FoV of 3.9 arcmin × 7.8 arcmin. All necessary astrometry and photometry calibrations were performed focusing on this part of the detector.

The astrometric solutions for the four pulsar fields were computed using the short exposures. Sets of 16–30 relatively bright stars from the Gaia DR2 catalogue (Gaia Collaboration et al. 2016, 2018) detected with the signal-to-noise ratio \(> 20\) were used as the WCS references. Their position uncertainties on the images and catalogue uncertainties were \(\lesssim 50\) mas and \(\lesssim 1\) mas, respectively. OSIRIS contains geometrical distortions increasing with the distance from the detector aim-point where the targets were exposed. This hampers the accurate astrometric transformation. To minimise distortion effects, the reference stars for PSRs J0557+1550, J1741+1351 and J2042+0246 fields were selected within 1 arcmin of the target positions, numbering 23, 19 and 16, respectively. For PSR J1630+3734, which has the largest Galactic latitude, there are no sufficient suitable reference objects in its immediate vicinity, and we used 30 stars within 4 arcmin of its position. In addition, to obtain the astrometric fits, we have followed the ‘general’ scheme (linear terms plus distortion) described in the OSIRIS User Manual\(^4\). We used the CCMAP routine, which includes the frame shift, rotation and scale factor defined as recommended in the manual. Formal rms uncertainties of the resulting astrometric fits are presented in Table 3. They are compatible with the position uncertainties of reference stars on the images. Selection of a larger amount of reference stars as well as choosing their different sets did not change the solutions significantly. The resulting solutions were applied to the combined images.

The photometric referencing was obtained using Sloan standards SA 104-428, SA 110-232 and SA 112-805 from Smith et al. (2002) observed during the same nights as our targets in all respective bands. To determine the magnitude zero-points, we used their measured magnitudes and the mean OSIRIS atmosphere extinction coefficients \(k_r = 0.15 \pm 0.02, k_i = 0.07 \pm 0.01\) and \(k_g = 0.04 \pm 0.01\). To verify the obtained calibration, we have compared the magnitudes of several stars in the pulsar fields against those in the Sloan Digital Sky Survey (SDSS) and Pan-STARRS DR1 catalogues for all bands. In most of the cases, the OSIRIS and the catalogue magnitudes were consistent within uncertainties. The only discrepancy of \(\sim 0.1\) mag was found for the \(g'\)-band magnitudes of the PSR J1741+1351 field stars, implying a slightly variable transparency during the night of observations, and we have taken it into account in our calculations. The resulting zero-points are presented in Table 2.

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\(^2\) Programmes GTC4-18AMEX and GTC20-18BMEX, PI A. Kirichenko

\(^3\) http://www.gtc.iac.es/instruments/osiris/

\(^4\) http://www.gtc.iac.es/instruments/osiris/media/OSIRIS-USER-MANUAL_v3_1.pdf
4 RESULTS AND DISCUSSION

The resulting ~23 arcsec × 23 arcsec $r'$-band images of the four pulsar fields are presented in Figure 1. The crosses correspond to the pulsar positions obtained from the radio timing and shifted according to proper motions to match the epoch of the optical observations, where respective information on the proper motion is provided. The astrometric uncertainties are negligible in the spatial scale of the optical images.

In the fields of PSRs J1630+3734, J1741+1351 and J2042+0246 in all bands we firmly detect star-like objects, whose coordinates coincide with the pulsar positions (see also Table 3). To calculate the probability of an accidental coincidence of pulsar positional regions with unrelated field objects, we have used the Poisson distribution $P = 1 - \exp(-\pi \sigma R^2)$, where $\sigma$ and $R$ correspond to the surface number density of stars with a similar magnitude and the astrometric accuracy, respectively. Considering magnitudes in a range of 19–25, in all cases this probability does not exceed $\approx 10^{-2}$. For this reason, below we consider the detected objects as optical binary companions of the MSPs. Two of them, companions to PSRs J1741+1351 and J2042+0246, show star-like profiles, while the PSR J1630+3734 companion profile is more complex. The point spread function (PSF) subtraction of this source using the IRAF/DAOPHOT ALLSTAR routine has revealed a faint slightly extended underlying object located about one arcsec north-east from the source maximum peak. It is enlarged in the left bottom corner of the right upper panel of Figure 1, where the companion was subtracted. The PSF photometry and iterative PSF subtraction were applied both to the companion and this source to measure their magnitudes and positions. The underlying object...
Optical companions to four binary MSPs

Table 3. Astrometric and photometric information for the MSP systems and the interstellar reddening in their direction. Reddening, intrinsic colours and absolute magnitudes are provided for the latest published distance estimations, i.e. DM distances for PSRs J0557+1550, J1630+3734 and J2042+0246 based on the YMW16 model and the timing parallax distance for PSR J1741+1351 (see Table 1). \( \alpha_p \) and \( \delta_p \) are the pulsars' coordinates for the epoch of the GTC observations (errors include uncertainties of the radio positions and proper motion which are negligible in comparison with the rms uncertainties of the GTC astrometric fits). \( \alpha_c , \Delta \alpha_c \) and \( \delta_c , \Delta \delta_c \) are coordinates of the optical companions on the images and their rms uncertainties.

| MSP          | J0557+1550 | J1630+3734 | J1741+1351 | J2042+0246 |
|--------------|------------|------------|------------|------------|
| \( \alpha_p \) (J2000) | 05\,°57\,′\,31\,″4918(9) | 16\,°30\,′\,36\,″468(2) | 17\,°45\,′\,31\,″141245(8) | 20\,°42\,′\,11\,″0800(4) |
| \( \delta_p \) (J2000) | 15\,°50\,′\,06\,″046(8) | 37\,°34\,′\,42\,″00(2) | 13\,°51\,′\,44\,″0799(1) | 02\,°46\,′\,14\,″53(2) |
| \( \alpha_c \) (J2000) | – | 16\,°30\,′\,36\,″475 | 17\,°45\,′\,31\,″144 | 20\,°42\,′\,11\,″005 |
| \( \delta_c \) (J2000) | – | 37\,°34\,′\,41\,″92 | 13\,°51\,′\,43\,″95 | 02\,°46\,′\,14\,″46 |
| rms \( \Delta \alpha_c \), arcsec | 0.05 | 0.02 | 0.05 | 0.04 |
| rms \( \Delta \delta_c \), arcsec | 0.04 | 0.02 | 0.05 | 0.05 |
| \( g' \) | – | 25.43(4) | 24.74(5) | 24.96(4) |
| \( r' \) | >25.6 | 24.44(4) | 24.38(4) | 23.97(2) |
| \( i' \) | – | 24.17(4) | 24.17(4) | 23.58(3) |
| \( E(B - V) \) | 0.19\,±\,0.03 | 0.00\,±\,0.01 | 0.12\,±\,0.01 | 0.07\,±\,0.02 |
| \( A_g' \) | 0.00\,±\,0.01 | 0.42\,±\,0.01 | 0.26\,±\,0.07 | 0.18\,±\,0.05 |
| \( A_r' \) | 0.48\,±\,0.07 | 0.00\,±\,0.01 | 0.30\,±\,0.01 | 0.14\,±\,0.03 |
| \( t' \) | – | 0.00\,±\,0.01 | 0.22\,±\,0.01 | 0.14\,±\,0.03 |
| \( g' - r' \) | – | 0.99\,±\,0.07 | 0.24\,±\,0.07 | 0.93\,±\,0.10 |
| \( r' - i' \) | – | 0.27\,±\,0.06 | 0.13\,±\,0.04 | 0.35\,±\,0.07 |
| \( M_{r'} \) | >13.8 | 14.06 \,±\,0.04 | 12.80\,±\,0.44 | 14.76\,±\,0.05 |
| Effective temperature \( T_{\text{eff}}, \text{K} \) | \( \lesssim 5.0 \times 10^3 \) | \( \sim 4 \times 10^3 \) | \( (6-7) \times 10^3 \) | 4.49(14) \,×\,10^3 |
| Cooling age \( t, \text{Gyr} \) | \( \gtrsim 1.5 \) | \( \sim 2-5 \) | \( \sim 1-2 \) | 5.6\,±\,0.9 |

\( ^{a} \)In the directions to PSRs J1630+3734 and J2042+0246 the reddening is the same for the DM distance estimations provided either by the YMW16 or NE2001 models. For J1741+1351 \( E(B-V) \) does not vary for \( D > 0.9 \) kpc.

is detected at about 3\( \sigma \) significance in the \( r' \) and \( i' \) bands with a magnitude of \( \approx 26.5 \) and is not detected in the \( g' \) band down to the \( \approx 27.5 \) magnitude limit. Its relation to the pulsar companion remains unclear. It is likely that the object is a hint of a distant galaxy. The resulting observed magnitudes of the proposed companions are presented in Table 3.

As the PSR J0557+1550 companion is undetected in the only available \( r' \) band, we have estimated a 3\( \sigma \) upper limit on its brightness in this band (see Table 3).

To calculate the absolute magnitudes and intrinsic colours of the optical companions, we used the 3D map of interstellar dust reddening \( E(B-V) \) which is based on PAU-STARRS 1 and 2MASS stellar photometry and Gaia parallaxes (Green et al. 2019)\(^5\). Using distances to the pulsars from Table 1, we obtained the corresponding \( E(B-V) \) colour excesses (Table 3). They were then converted to the extinction corrections \( A_{g',r',i'} \) for all the bands utilising coefficients provided by Schlafly & Finkbeiner (2011). The resulting corrections, absolute magnitudes and intrinsic colours are presented in Table 3.

As we noted in Sect. 2, the companions to the pulsars are likely WDs. To verify this, we compared the obtained absolute magnitudes and reddened colours with the cooling models of helium-core WDs with hydrogen-atmospheres (Althaus et al. 2013)\(^6\) and CO-core WDs with hydrogen and helium atmospheres (known as the Bergeron models; Holberg & Bergeron 2006; Kowalski & Saumon 2006; Tremblay et al. 2011; Bergeron et al. 2011)\(^7\). The corresponding colour-magnitude and colour-colour diagrams are presented in Figure 2, where evolutionary sequences for WDs of different classes are shown by different line types. The positions of the detected companions in the diagrams, particularly in the colour-magnitude diagram, depend on the accepted distances to the pulsars. To account for different possibilities, for each pulsar we show at least two positions, corresponding to the DM-distances based on the NE2001 and YMW16 Galactic electron density distribution models (see Table 1). For PSR J1741+1351, we also include the point corresponding to the parallactic distance from Arzoumanian et al. (2018). Bellow we analyse the results obtained for each object.

4.1 PSR J0557+1550

PSR J0557+1550 was observed only in the \( r' \) band and no optical source was detected at its radio position down to \( r' \gtrsim 25.6 \) mag. Comparison of the lower limit on \( M_{r'} \) (see Table 3, \( D_{\text{YMW16}} = 1.83 \) kpc) with the cooling models for a hydrogen-atmosphere WD with the minimum companion mass \( \approx 0.2 \text{M}_\odot \) implies the age \( t \gtrsim 1.5-3 \) Gyr and the WD effective temperature \( T_{\text{eff}} \lesssim (4.6-5.0) \times 10^3 \) K. The respective values for the distance \( D_{\text{NE2001}} = 2.92 \) kpc, which is based

\( ^{5} \) http://argonaut.skymaps.info/

\( ^{6} \) http://evolgroup.fcaglp.unlp.edu.ar/TRACKS/tracks_heliumcore.html

\( ^{7} \) http://www.astro.umontreal.ca/~bergeron/CoolingModels.

MNAT 000, 1–10 (2019)
Figure 2. Colour-magnitude (top) and colour-colour (bottom) diagrams with various WD cooling tracks and data for WD companions to different MSPs listed in the legend. Purple dash-dot-dotted lines (DA*) show evolutionary tracks by Althaus et al. (2013) for helium-core WDs with masses 0.1821, 0.2724 and 0.4352M⊙. Solid green (DA) and grey dotted (DB) lines show models for CO-core WDs with hydrogen and helium atmospheres, respectively, (Holberg & Bergeron 2006; Kowalski & Saumon 2006; Tremblay et al. 2011; Bergeron et al. 2011) with masses 0.2, 0.6 and 1.0M⊙. Dashed blue and brown lines are tracks for WDs with mixed atmospheres (log(He/H) = 1.0 and 4.0, respectively) and masses 0.2, 0.6 and 1.0M⊙. Masses increase from upper to lower tracks. WDs’ ages (top) and effective temperatures (bottom) are shown by different symbols. The positions of the PSRs’ J1630+3734, J1741+1351 and J2042+0246 companions are shown by different symbols as indicated in the legend. In the top panel, for each source its positions are shown for different DM distance estimates (provided by the YMW16 and NE2001 models); for the PSR J1741+1351 companion the position corresponding to the timing parallax distance is also indicated (see Table 1). We also indicate their positions at various additional distances derived using reddening values from the dust map by Green et al. (2019). The distances are marked by the numbers in kpc units. Since their colours do not change significantly with the distance, in the lower panel the results are presented for the distances from Table 1.
on the NE2001 model, are $M_\gamma > 12.6$, $t \gtrsim 1–2$ Gyr and $T_{\text{eff}} \lesssim (5.7 – 6.3) \times 10^3$ K.

### 4.2 PSR J1630+3734

In the colour-colour diagram, the PSR J1630+3734 companion shows a $\approx 2\sigma$ error displacement to bluer colour indices from the tracks of WDs with pure hydrogen or helium atmospheres (DA*, DA and DB tracks; see the bottom panel of Figure 2). The shift is not related to uncertainties of the DM distance as the extinction in the PSR J1630+3734 direction is very low (see Table 3) and does not affect the source intrinsic colours.

It is known that models of ultra-cool WDs with mixed He/H atmospheres show bluer ($g' – r'_0$) colours as opposed to those of WDs with pure hydrogen or helium atmospheres (e.g. Parsons et al. 2012). As an example, in Figure 2 we also present the cooling tracks for CO-core WDs with mixed atmospheres (for $\log(\text{He}/\text{H}) = 1.0$ and 4.0). The position of the PSR J1630+3734 companion is in accord with these tracks. Unfortunately, respective tracks for helium-core WDs are not available and at the current stage the determination of the presumed He/H ratio in the WD atmosphere is not possible. If the source is indeed a WD with a mixed atmosphere, its temperature and age are $\sim 4 \times 10^3$ K and $\sim 2–5$ Gyr, respectively. We note, however, that the $\sim 2\sigma$ displacement to bluer colour indices does not exclude the pure hydrogen or helium atmospheres, but makes them less plausible.

### 4.3 PSR J1741+1351

The temperature of the PSR J1741+1351 companion, assuming its WD nature and taking into account the intrinsic colour indices (see Figure 2), is about $(6–7)\times 10^3$ K. This estimation is independent of any considered distance from Table 1 as $E(B – V)$ along the pulsar line of sight and the intrinsic colours of the companion vary only slightly within the expected distance range $\sim 0.1–2.3$ kpc. The radio timing analysis by Arzoumanian et al. (2018) provides the parallax distance to the pulsar $1.8^{+0.5}_{-0.3}$ kpc and the companion mass $M_\gamma = 0.22(5)$ M⊙. The corresponding derived absolute magnitude and colour index of the companion are $M_\gamma = 12.80^{+0.44}_{-0.61}$ and $(r' – i'_0) = 0.13^{+0.06}_{-0.10}$. They are consistent with a hydrogen or helium atmosphere WD with a mass of $0.2–0.3$ M⊙ which is in agreement with the mass measurement from the radio timing. The respective WD cooling age is 1–2 Gyr (see Figure 2). The DM distance $D_{\text{YMW16}} = 1.36$ kpc based on the YMW16 model implies a helium or mixed He/H atmosphere WD with similar mass and age ranges, 0.2–0.5 M⊙ and 1–2 Gyr, respectively. In contrast, the smaller DM distance $D_{\text{NE2001}} = 0.9$ kpc requires an older ($\sim 2–5$ Gyr) and

Recently, Freire et al. (in preparation) have reported measurements of the PSR J1741+1351 system parameters based on new radio observations with high cadence in combination with publicly available data provided by NANOGrav (Demorest et al. 2013). They confirmed and improved the value for the companion mass $M_\gamma = 0.227^{+0.013}_{-0.014}$ M⊙, provided the estimations on the pulsar mass $M_p = 1.19^{+0.10}_{-0.11}$ M⊙ and the parallactic distance $1.22^{+0.13}_{-0.11}$ kpc, however these are still preliminary. The new parallactic distance is marginally

![Figure 3. Colour-magnitude diagrams with WD cooling sequences. The dash-dot-dotted purple line (DA*) shows the track for a helium-core WD with a mass of 0.239 M⊙ (Althaus et al. 2013), solid green (DA) and black dotted (DB) lines – for CO-core WDs with masses of 0.2 M⊙ with hydrogen and helium atmospheres, respectively (Holberg & Bergeron 2006; Kowalski & Saumon 2006; Tremblay et al. 2011; Bergeron et al. 2011), the dashed brown line – for a WD with mixed atmosphere ($\log(\text{He}/\text{H}) = 4.0$) and a mass of 0.2 M⊙. The positions of the PSR J1741+1351 optical companion are shown by triangle symbols for different distance estimates indicated in the legend. The pink stripe corresponds to the source ($r' – i'_0$) colour in the case of the maximum extinction in the pulsar direction.](image1)

![Figure 4. Constraints on the effective temperature and mass for the PSR J2042+0246 WD companion. The contours show the 68.3% and 95.5% confidence levels. 1D likelihoods are shown in the top and side panels. Dashed lines indicate the median values and dash-dotted lines are the 1σ confidence intervals.](image2)
consistent with the DM distance $D_{\text{DM,16}} = 1.36$ kpc and implies that the PSR J1741+1351 companion may have a mixed atmosphere. In Figure 3 we present a colour-magnitude diagram with selected evolution tracks for WDs with different atmosphere compositions (DA, DB, and He/H) and masses that are close to the companion mass. At the distance $D = 1.22$ kpc, the companion perfectly agrees with a WD with a mixed He/H atmosphere.

Nevertheless, taking into account the formal distance and photometric measurements’ uncertainty, a WD with a pure hydrogen or helium atmosphere is rather less plausible than completely rejected. As we mentioned before, $E(B-V)$ in the pulsar direction does not vary for the distances $\geq 0.9$ kpc (Green et al. 2019) and the companion colours do not change with the distance either. The stripe in Figure 3 corresponds to the source intrinsic colour in case of the maximum $E(B-V)$. Pure hydrogen atmospheres of WDs provide higher luminosities and larger corresponding distances in a range of 1.5–2.7 kpc, whereas the mixed atmospheres require a distance between 1.1 and 1.52 kpc. Therefore, determining the distance to the system is critical to select the appropriate model of the companion atmosphere.

The DA and DB tracks in Figures 2 and 3 represent the CO-core WDs cooling models, while it is generally believed that low-mass WDs in MSP binaries have helium cores (Tauris 2011). Comparison of tracks for (DA*) helium-core and CO-core WDs with hydrogen atmospheres shows that at a given age and mass the latter ones are less luminous (van Oirschot et al. 2014). At ages $\geq 1$ Gyr for low-mass WDs the brightness difference becomes less than a half of a magnitude. As seen from Figure 3, for the specific masses the difference between the DA and DA* tracks is even smaller and is comparable to the derived uncertainty in the absolute magnitude of the companion.

4.4 PSR J2042+0246

As it was mentioned before, most of the WD companions to MSPs have a pure hydrogen atmosphere. Positions of the PSR J2042+0246 companion on the colour-magnitude and colour-colour diagrams in Figure 2 roughly correspond to a cool ($\approx 4500$ K) hydrogen-atmosphere WD with an age of $\sim 2$–5 Gyr, depending on the cooling model.

To better constrain the WD parameters for this system, we utilised the procedure described by Dai et al. (2017) and used the models for helium-core hydrogen-atmosphere WDs with masses of 0.1554–0.4352 $M_\odot$ and the CO-core hydrogen-atmosphere WDs with masses of 0.5–1.0 $M_\odot$. The models were interpolated in the mass–temperature plane within a mass range of 0.1554–1.0 $M_\odot$ and a temperature range of 3000–10000 K using a 7000 K grid. Then the likelihood of each model point was calculated according to formula (5) from Dai et al. (2017). We assumed the distance range between $D_{\text{DM,16}}$ and $D_{\text{NE2001}}$, i.e. 0.6–0.8 kpc. As a result, we derived a WD mass of $0.30_{-0.08}^{+0.07}$ $M_\odot$, a temperature of 4.49(14) x10$^3$ K and an age of 5.6$^{+0.9}_{-1.2}$ Gyr (the values correspond to the medians of the probability distributions and their 1σ uncertainties). The obtained constraints on the WD mass and temperature are presented in Figure 4.

The results show that the companion can indeed be a helium-core WD, as the derived mass lies within the mass range of the model set by Althaus et al. (2013). This mass is compatible with the lower limit $M_c > 0.19$ $M_\odot$ provided by the radio timing measurements (Table 1). The derived WD mass and the mass function 0.0026721258 $M_\odot$ obtained by Sampa-arsa (2016) yield a lower limit on the pulsar mass of $\geq 1.6$ $M_\odot$ assuming a ‘median’ orbit inclination of 60°. In a specific case of 90°, the lower limit is $\geq 2$ $M_\odot$. This is in agreement with the fact that in MSP-WD binaries neutron stars are on average more massive than in double pulsar systems, where the mass distribution of neutron stars shows a narrow peak around 1.35 $M_\odot$ (e.g., Linares 2019).

5 SUMMARY AND CONCLUSIONS

Using the GTC, we have performed optical observations of four binary MSPs. We have detected likely companions to PSRs J1630+3734, J1741+1351 and J2042+0246 and set the upper limit on the PSR J0557+1550 companion brightness in the $r'$ band, which is by $\sim 3.6$ magnitude deeper than the previous one (Scholz et al. 2015). The magnitudes and colours of the detected optical sources are consistent with the evolutionary sequences of low-mass WDs, confirming the results from the radio-timing measurements. Using the WD cooling sequences, we have constrained the parameters of the detected WD companions, including mass, temperature and age. The latter two are presented in Table 3.

Colours of the PSR J1630+3734 companion suggest a WD with a mixed He/H atmosphere. The companion has a temperature of about 4 x 10$^3$ K and age of $\sim 2$–5 Gyr.

The PSR J2042+0246 companion is consistent with an old ($\geq 5$ Gyr) helium-core hydrogen-atmosphere WD with a mass of 0.30$^{+0.07}_{-0.08}M_\odot$ and a temperature of 4.49(14) x10$^3$ K. Assuming a median orbit inclination of 60°, we estimate the minimum pulsar mass to be 1.6 $M_\odot$.

For the PSR J1741+1351 system, the optical data and the WD cooling predictions suggest that the temperature of the companion is about (6–7)x10$^3$ K regardless of the distance, and its age is $\sim 1$–2 Gyr. The latest parallactic and the $D_{\text{DM,16}}$ distance estimations imply that the WD in the PSR J1741+1351 binary may have a mixed H/He atmosphere.

Mixed atmospheres in WDs are generally unusual since, due to gravitational settling, pure hydrogen atmospheres are expected (e.g. Althaus & Benvenuto 2000). Indeed, most of the known WD companions to MSPs are known to have hydrogen atmospheres. There are, however, several exceptions: the likely ultra-cool companions to PSRs J0751+1807 (Bassa et al. 2006), J0740+6620 (Beronya et al. 2019) and J2017+0603 (Bassa et al. 2016), which may have pure helium or mixed atmospheres; the massive CO-core WD companion to the mildly recycled PSR B0655+64 (van Kerkwijk & Kulkarni 1995), which shows carbon lines in its spectrum. Based on the current data, it is possible that the companions to PSRs J1630+3734 and J1741+1351 can complement this set. In MSP binaries, WD hydrogen envelopes can be reduced due to irradiation by the pulsar wind following the cessation of the mass transfer (Ergma et al. 2001). Indeed, the above mentioned systems are close binaries ($P_0 \leq 5$ d) with a high pulsar spin-down power ($E \sim 10^{34}$ erg s$^{-1}$), and it is clear that they can follow this scenario. However, since PSRs J1630+3734 and J1741+1351 possess longer orbital periods, this explanation
is unlikely. To verify this we have obtained basic estimations on the companion flux and the flux of the pulsar wind irradiating the companion (see, e.g., Bassa et al. (2016)) for both systems. Indeed, the estimations yield a 1–2 orders of magnitude smaller irradiation fluxes in comparison with the companion ones implying that in case of PSRs J1630+3734 and J1741+1351 the irradiation could not have significantly altered the atmospheres of the companions.

Another possibility is that the WD companions to PSRs J1630+3734 and J1741+1351 have changed their atmospheric compositions from the hydrogen-rich to the helium-rich and back as they cooled down through the convective mixing stage (e.g. Chen & Hansen 2012): when the temperature decreases, the surface convection zone of hydrogen expands and can reach the underlying helium layer; then the convection brings helium to the surface. Moreover, other mechanisms changing a WD surface composition were proposed (e.g. Blouin et al. 2019, and references therein).

Finally, we find that the WD ages in the PSRs J0557+1550, J1741+1351 and J2042+0246 binaries are consistent with the characteristic ages of their pulsar companions (see Table 1). In contrast, the PSR J1630+3734 intrinsic characteristic age, $\tau_i$, corrected for the Shklovskii and Galactic potential effects, is $6.1\pm0.6$ Gyr (Sampa-arsa 2016), which is somewhat larger than the estimated cooling age of the WD companion. However, characteristic ages are rough estimations and can significantly deviate from the true pulsar ages (see, e.g., Lorimer & Kramer 2012). In addition, Tauris (2012) has shown that during the decoupling phase of the companion from its Roche lobe, rotational energy of the pulsar is dissipated. As a result, characteristic ages do not represent the true age of these neutron stars. For this reason, in case of PSR J1630+3734, we do not consider the WD and pulsar age inconsistency as a strong argument against the optical identification of the pulsar companion and present the WD cooling ages as independent estimations on the age of the binaries.

As the companions to PSRs J0557+1550, J1630+3734 and J2042+0246 are very cool, their future studies would mostly rely on broadband near-infra-red observations where hydrogen and helium WD atmospheres can be best resolved based on the spectral energy distribution (Blouin et al. 2019). For the warmer PSR J1741+1351 companion, optical/near-infra-red spectroscopy with large-aperture ground-based telescopes or with the James Webb Space Telescope might be feasible to get new information on this interesting system, whose pulsar appears to have an unusually low mass.

ACKNOWLEDGEMENTS

We thank the anonymous referee for the useful comments that allowed us to improve the manuscript. We also thank P. Bergeron for providing cooling tracks for WDs with mixed atmospheres. The work is based on observations made with the Gran Telescopio Canarias (GTC), installed at the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias, in the island of La Palma. IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under a cooperative agreement with the National Science Foundation. This work has made use of data from the European Space Agency (ESA) mission Gaia (https://www.cosmos.esa.int/gaia), processed by the Gaia Data Processing and Analysis Consortium (DPAC; https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement. This work also used public data from the North American Nanohertz Observatory for Gravitational Waves (NANOGrav; http://nanograv.org), which is designated as a “Physics Frontiers Center” by the National Science Foundation (award # 1430284). DAZ thanks Pirineu School of Theoretical Physics for hospitality. The work of AYuK, AVK and DAZ was supported by the Russian Foundation for Basic Research, project No. 18-32-00170 molA. The work of SVZ was supported by PAPIIT grants IN-100617 and IN-102120.

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Optical companions to four binary MSPs
