Detection of the PSR J1741+1351 white dwarf companion with the Gran Telescopio Canarias

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Abstract. We report detection of the binary companion to the millisecond pulsar J1741+1351 with the Gran Telescopio Canarias. The optical source position coincides with the pulsar coordinates and its magnitudes are \( g' = 24.84(5) \), \( r' = 24.38(4) \) and \( i' = 24.17(4) \). Comparison of the data with the WD evolutionary models shows that the source can be a He-core WD with a temperature of \( \approx 6000 \) K and a mass of \( \approx 0.2M_\odot \). The latter is in excellent agreement with the companion mass obtained from the radio timing solution for PSR J1741+1351.

1. Introduction

Millisecond pulsars (MSPs) are neutron stars (NSs) that rotate particularly fast, having periods \( P < 30 \) ms. The canonical ‘recycling’ scenario assumes that MSPs are formed in binary systems where they spin up by transfer of mass and angular momentum from the secondary star [1, 2].

Optical observations of MSPs allow one to determine the nature and properties of their companions [3]. This provides additional constraints on binary system’s parameters which is important for understanding their formation and evolution. In most cases, companions are low-mass white dwarfs (WDs) [4]. These objects are faint and thus hardly detectable. Fortunately, the number of identifications gradually increases thanks to world’s largest sky surveys and ground-based telescopes [5, 6, 7].

The binary MSP J1741+1351 (hereafter J1741) was discovered with the Parkes radio telescope [8] and then detected in γ-rays by Fermi [9]. It is among the best timed MSPs. High-precision timing using 11-yr data set from the North American Nanohertz Observatory for Gravitational Waves provided measurements of the system inclination and masses of both the pulsar and its companion [10]. The system parameters are presented in table 1.

To study the properties of the J1741 companion, we performed deep optical observations with the Gran Telescopio Canarias (GTC). Here we report the results of the analysis of these data.
Table 1. Parameters of the PSR J1741+1351 system obtained from [10]. The distance $D_p$ is derived from the timing parallax of 0.6(1) mas. The dispersion measure distances $D_{\text{NE2001}}$ and $D_{\text{YMW}}$ were estimated using the YMW16 [11] and NE2001 [12] models of the Galactic electron density distribution, respectively. Numbers in parentheses are 1σ uncertainties related to the last significant digits quoted.

| Parameter                              | Value                  |
|----------------------------------------|------------------------|
| Right ascension $\alpha$ (J2000)       | 17$^h$41$^m$31$^s$.144731(2) |
| Declination $\delta$ (J2000)           | +13$^\circ$51'44''.12188(4) |
| Epoch (MJD)                            | 56209                  |
| Proper motion $\mu_\alpha = \dot{\alpha}\cos\delta$ (mas yr$^{-1}$) | -8.98(2) |
| Proper motion $\mu_\delta$ (mas yr$^{-1}$) | -7.42(2) |
| Spin period $P$ (ms)                   | 3.747154500259940030(7) |
| Period derivative $P$ (10$^{-20}$ s s$^{-1}$) | 3.021648(14) |
| Characteristic age $\tau$ (Gyr)        | 2                      |
| Orbital period $P_b$ (days)            | 16.335347828(4)        |
| Dispersion measure (DM, pc cm$^{-3}$)  | 24.2                   |
| Distance $D_{\text{NE2001}}$ (kpc)    | 0.9                    |
| Distance $D_{\text{YMW}}$ (kpc)       | 1.36                   |
| Distance $D_p$ (kpc)                   | 1.8$^{+0.5}_{-0.3}$    |
| Pulsar mass $M_p$ (M$\odot$)          | 1.14$^{+0.43}_{-0.25}$ |
| Companion mass $M_c$ (M$\odot$)       | 0.29$^{+0.05}_{-0.04}$ |
| System inclination $i$ (deg)           | 73$^{+3}_{-4}$         |

2. Observations and data reduction

The observations of the J1741 field (Proposal GTC4-18AMEX, PI A. Kirichenko) were carried out in June 2018 in the Sloan $g'$, $r'$ and $i'$ bands with the GTC/OSIRIS ([http://www.gtc.iac.es/instruments/osiris](http://www.gtc.iac.es/instruments/osiris)) instrument. The detector field of view was 7'8$\times$7'8 and the plate scale was 0.254 arcsec pixel$^{-1}$. Dithered science frames were taken, with total exposure times of 3, 3.5 and 2.76 ks for the $g'$, $r'$ and $i'$ filters, respectively. A short 20 s exposure was obtained in the $r'$ band to avoid saturation of bright stars that were further used for precise astrometry.

The data reduction, including bias-subtraction and flat-fielding, was performed with the Image Reduction and Analysis Facility (IRAF) package. The reduced individual science frames were aligned to a best-seeing frame and combined for each filter. The average seeing of the combined images were 0'084, 1'005, and 0'082 for the $g'$, $r'$ and $i'$ filters, respectively. The astrometric solution were computed using a set of 11 stars from the Gaia DR2 catalogue [13]. The formal $r$ms uncertainties of the astrometric fit are 0'05 in RA and Dec for all the bands. The photometric calibration, we used the standard stars SA 112,805 and SA 104,428 observed during the same night as the target. The derived photometric zeropoints are $z_{g'} = 28.76(2)$, $z_{r'} = 28.99(1)$ and $z_{i'} = 28.55(1)$. The values were obtained by comparing the standard star magnitudes from [14] with their instrumental magnitudes, corrected for the finite aperture and atmospheric extinction. We used the atmospheric extinction coefficients ([http://www.iac.es/adjuntos/cups/C0ps2014-3.pdf](http://www.iac.es/adjuntos/cups/C0ps2014-3.pdf)) $k_{g'} = 0.15(2)$, $k_{r'} = 0.07(1)$ and $k_{i'} = 0.04(1)$.
Figure 1. 20′′×20′′ GTC/OSIRIS $r'$-band image of the J1741 field (left) and its enlarged 4′′×4′′ section within the dashed rectangle containing the pulsar (right). The solid circle with a radius of 0′′.15 shows the 3σ position uncertainties of the pulsar radio position.

Figure 2. Colour-magnitude (left) and colour-colour (right) diagrams with various WD cooling tracks. Solid black (DA) and dashed light-blue (DB) lines show the cooling tracks for WDs with hydrogen and helium atmospheres, respectively [15, 16, 17, 18], with masses 0.3–0.8 $M_\odot$ (spaced by 0.1 $M_\odot$). Solid purple (DA*) lines show the models from [19] for He-core WDs with hydrogen atmospheres and masses of 0.1869, 0.2026 and 0.2495 $M_\odot$. Masses increase from upper to lower curves. Cooling ages in the left panel and temperatures in the right panel are indicated by different symbols. The location of the J1741 presumed companion is marked by the red star: the upper one is for the maximum distance estimate $D_p$ and the lower one is for the minimum distance estimate $D_{NE2001}$. The source colours for different distances are very close, so in the right panel we combined results for $D_p$ and $D_{NE2001}$. The data for WD companions of other pulsars listed in the legend are also shown (see [20] for details and references).
3. Results and discussion

In figure [1] we show sections of the J1741 field in the $r'$ band. The pulsar coordinates at the epoch of our observations (MJD 58274) corrected for its proper motion (table [1]) are $\alpha = 17^h41^m31^s14.1245(8)$ and $\delta = +13^\circ 51'44''0.0799(1)$. Its position uncertainty is shown in the image by the circle which also accounts for the astrometric referencing uncertainty. A star-like source (hereafter Source C) perfectly overlapping with the pulsar position is clearly seen and it is also detected in other bands.

Using aperture photometry, we obtained the Source C magnitudes $g' = 24.84(5)$, $r' = 24.38(4)$ and $i' = 24.17(4)$. To correct these values for the interstellar extinction, we used the dust map [21] and distances to J1741 (table [1]). We got the reddening $E(B-V)$ of 0.10(3) and 0.13(2) for the minimum and maximum distance estimates. $E(B-V)$ was then transformed to the extinction correction values using coefficients from [22]. For $D_{NE2001} = 0.9$ kpc, the resulting intrinsic colours and absolute magnitude are $(g' - r')_0 = 0.36(14)$, $(r' - i')_0 = 0.15(10)$ and $M_{g'} = 14.38(8)$, while for $D_p = 1.8^{+0.5}_{-0.3}$ kpc – $(g' - r')_0 = 0.33(11)$, $(r' - i')_0 = 0.13(8)$ and $M_{r'} = 12.80^{+0.46}_{-0.59}$.

To check whether Source C is a WD, we compared its colours and magnitudes with the WD cooling tracks from [19, 15, 16, 17, 18] which are shown in figure [2]. Indeed, according to the diagrams, Source C is likely a WD with a temperature of about 6000 K. This estimate is appropriate for the whole possible distance range of J1741 (table [1]) since the reddening does not vary significantly. However, various distances imply different WD masses and ages. The minimum distance suggests a WD with a mass of $> 0.4$ M$_\odot$ and age of 2–5 Gyr while the maximum one – a WD with a mass of 0.2–0.3 M$_\odot$ and age of 1–2 Gyr. The former case is not compatible with the radio timing measurement of the companion mass $M_c = 0.22(5)$ M$_\odot$ for J1741 while the latter one is in a good agreement with it. This supports the distance to the pulsar based on the timing parallax and implies that its companion is a DA He-core WD.

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References

[1] Bisnovatyi-Kogan G S and Komberg B V 1974 Soviet Astronomy 18 217
[2] Alpar M A, Cheng A F, Ruderman M A and Shaham J 1982 Nature 300 728–730
[3] van Kerkwijk M H, Bassa C G, Jacoby B A and Jonker P G 2005 Binary Radio Pulsars (ASP Conf. Series vol 328) ed Rasio F A and Stairs I H (San Francisco: Astronomical Society of the Pacific) p 357
[4] Tauris T M 2011 Evolution of Compact Binaries (ASP Conf. Series vol 447) ed Schmidtobreick L et al. (San Francisco: Astronomical Society of the Pacific) p 285
[5] Bassa C G et al. 2016 MNRAS 455 3806–3813
[6] Kirichenko A Y et al. 2018 MNRAS 480 1950–1955
[7] Karpova A V, Zyuzin D A, Shibanov Y A, Kirichenko A Y and Zharikov S V 2018 PASA 35 e028
[8] Jacoby B A, Bailes M, Ord S M, Knight H S and Hotan A W 2007 ApJ 656 408–413
[9] Espinoza C M et al. 2013 MNRAS 430 571–587
[10] Arzoumanian Z et al. 2018 ApJS 235 37
[11] Yao J M, Manchester R N and Wang N 2017 ApJ 835 29
[12] Cordes J M and Lazio T J W 2002 NE2001 I. A New Model for the Galactic Distribution of Free Electrons and its Fluctuations Preprint astro-ph/0207156
[13] Gaia Collaboration et al. 2018 A&A 616 A1
[14] Smith J A et al. 2002 AJ 123 2121–2144
[15] Holberg J B and Bergeron P 2006 AJ 132 1221–1233
[16] Kowalski P M and Saumon D 2006 ApJ 651 L137–L140
[17] Tremblay P E, Bergeron P and Gianninas A 2011 ApJ 730 128
[18] Bergeron P et al. 2011 ApJ 737 28
[19] Panei J A, Althaus L G, Chen X and Han Z 2007 MNRAS 382 779–792
[20] Beronya D M et al. 2019 MNRAS 485 3715–3720
[21] Green G M et al. 2018 MNRAS 478 651–666
[22] Schlafly E F and Finkbeiner D P 2011 ApJ 737 103