Publications of the Astronomical Society of Australia (PASA), Vol. 35, e028, 5 pages (2018).

doi:10.1017/pasa.2018.21

Optical Identification of the Millisecond Pulsar J0621+2514

A. V. Karpova[1,3], D. A. Zyuzin[1], Yu. A. Shibanov[1], A. Yu. Kirichenko[1,2] and S. V. Zharikov[2]

[1]Ioffe Institute, Politekhnicheskaya ul., 26, St. Petersburg, 194021, Russia
[2]Instituto de Astronomía, Universidad Nacional Autónoma de México, Apdo. Postal 877, Ensenada, Baja California 22800, México
[3]E-mail: annakarpova1989@gmail.com

(RECEIVED April 10, 2018; ACCEPTED May 9, 2018)

Abstract

Using the SDSS and Pan-STARRS1 survey data, we found a likely companion of the recently discovered binary γ-ray radio-loud millisecond pulsar J0621+2514. Its visual brightness is about 22 mag. The broadband magnitudes and colours suggest that this is a white dwarf. Comparing the data with various white dwarfs evolutionary tracks, we found that it likely belongs to a class of He-core white dwarfs with a temperature of about 10 000 K and a mass of $\lesssim 0.5\,\mathrm{M}_\odot$. For a thin hydrogen envelope of the white dwarf, its cooling age is $\lesssim 0.5$ Gyr which is smaller than the pulsar characteristic age of 1.8 Gyr. This may indicate that the pulsar age is overestimated. Otherwise, this may be explained by the presence of a thick hydrogen envelope or a low metallicity of the white dwarf progenitor.

Keywords: binaries: close – pulsars: individual: PSR J0621+2514

1 INTRODUCTION

Millisecond pulsars (MSPs) form a special subclass of radio pulsars which is characterised by short ($P < 30$ ms) rotational periods, relatively small magnetic fields ($B \sim 10^8 - 10^{10}$ G), and low spin-down rates ($\dot{P} \sim 10^{-20} - 10^{-19}$ s s^{-1}). To date, about 350 MSPs have been discovered. This number is approximately 13% of the total number of known pulsars[1]. It is believed that short spin periods are caused by the accretion of matter from a donor star (Bisnovatyi-Kogan & Komberg 1974; Alpar et al. 1982). This 'recycling' hypothesis is consistent with the fact that most MSPs are found in binary systems. The hypothesis is strongly supported by discoveries of transient MSPs which show switching between the accretion and radio MSP stages, PSR J1023+0038, XSS J12270−4859, and PSR J1824−2452I (Archibald et al. 2009; Bassa et al. 2014; Roy et al. 2015; Papitto et al. 2013).

Observed MSPs companions belong to various stellar classes: main sequence (MS) stars, white dwarfs (WDs), non-degenerate or partially degenerate stellar cores, and neutron stars (NSs) (e.g., Manchester 2017). This depends on initial parameters of the progenitor binary system, e.g., the mass of the donor star, the orbital separation, the environments where the system forms (e.g., the Galactic disc or a globular cluster), etc. The 'fully' recycled MSPs ($P < 10$ ms) most often have He-core WD companions (Tauris 2011).

Studies of binary MSPs allow one to probe different astrophysical phenomena including formation and evolution of binary systems and accretion processes. The unique rotational stability makes them precise celestial clocks. This can be used to test the accuracy of gravitational theories and to search for gravitational waves with a 'pulsar timing array' (Kramer 2016; Manchester 2017).

Masses of both components in a binary system can be obtained through a high-precision radio timing by measuring the Shapiro delay (Shapiro 1964). However, this effect is most measurable if an orbit is highly inclined or a companion is massive. An alternative way to constrain masses and orbital parameters is optical observations (e.g., van Kerkwijk et al. 2005). In the case of a WD companion, its mass, spectral class, and temperature can be derived from comparison of photometric and/or spectroscopic data with predictions of WD cooling models. The derived WD mass together with the radio timing parameters then can be used to estimate the pulsar mass and in turn to constrain the equation of state of the superdense matter in NSs interiors (Lattimer & Prakash 2016). Optical observations also allow one to obtain the WD cooling age and, therefore, to constrain the binary system age independent of the pulsar characteristic age. This is important for studying the evolution of binary systems and pulsar spin evolution (e.g., Kiziltan & Thorsett 2010).

Binary MSP J0621+2514 (hereafter, J0621) was recently discovered in radio pulsation searches of *Fermi* unassociated sources with the Green Bank Telescope (Ray et al. 2012;

[1] http://www.atnf.csiro.au/people/pulsar/psrcat/ (Manchester et al. 2005).

Table 1. Parameters of the J0621 system obtained from Sanpa-arsa (2016). The distances $D_{\rm YMW}$ and $D_{\rm NE2001}$ are provided from the dispersion measure using the YMW16 (Yao, Manchester & Wang 2017) and NE2001 (Cordes & Lazio 2002) models for the distribution of free electrons in the Galaxy, respectively.

Right ascension (RA, J2000)	$06^{\rm h}21^{\rm m}10.^{\rm s}8542(1)$
Declination (Dec, J2000)	$+25°14'03.''83(3)$
Spin period P (ms)	2.7217879391872(4)
Period derivative $\dot{P}$ (10^{-21} s s^{-1})	24.83(3)
Orbital period P_b (d)	1.256356677(3)
Projected semi-major axis (lt-s)	1.276860(3)
Dispersion measure (DM, pc cm^{-3})	83.629(6)
Characteristic age τ_c(Gyr)	1.8
Surface magnetic field B (G)	2.6×10^8
Spin-down luminosity $\dot{E}$ (erg s^{-1})	4.71×10^{34}
Distance $D_{\rm YMW}$ (kpc)	1.64
Distance $D_{\rm NE2001}$ (kpc)	2.33

Sanpa-arsa 2016). This led to detection of γ-ray pulsations in the *Fermi* data. The pulsar parameters obtained from timing analysis are presented in Table 1. Sanpa-arsa (2016) suggested that the system contains a WD companion. Here we report a likely identification of the pulsar companion using the results of optical surveys.

2 The likely companion and its properties

We found a possible counterpart to J0621 using the Sloan Digital Sky Survey Data Release 14 (SDSS DR; Abolfathi et al. 2017) catalogue. The position of the point source SDSS J062110.86+251403.8 overlaps with J0621 at the 1σ significance. Its position and magnitudes in five filters are presented in Table 2 and the i'-band image of the pulsar field is shown in Figure 1. The source was also detected in three filters of the Panoramic Survey Telescope and Rapid Response System Survey (Pan-STARRS; Flewelling et al. 2016). The probability to detect an unrelated source at the pulsar position is $\sim 10^{-4}$ assuming the source magnitude r' of 18–23.

In Figure 2, we show $g' - r'$ vs. r' diagram for sources from the SDSS database located within 3 arcmin from the J0621 position. One can see that the presumed pulsar companion is shifted bluewards from the MS population indicating that it is likely to be a WD.

To obtain dereddened colours of the optical source, we estimated the interstellar reddening $E(B-V)$ utilising the dust model by Green et al. (2018) which is based on the MS stars photometry in the Pan-STARRS 1 and the 2MASS surveys. The reddening was then transformed to the extinction correction values using conversion coefficients provided by Schlafly & Finkbeiner (2011). For the DM distance $D_{\rm YMW} = 1.64$ kpc, we obtained the reddening value $E(B-V) = 0.25^{+0.02}_{-0.03}$ (see Table 1). This implies the dereddened colours $g'_0 - r'_0 = -0.12^{+0.14}_{-0.17}$, $r'_0 - i'_0 = -0.17^{+0.17}_{-0.18}$, and absolute magnitude $M_{r'} = 10.11^{+0.10}_{-0.11}$ (the errors include uncertainties on the reddening and magnitudes).

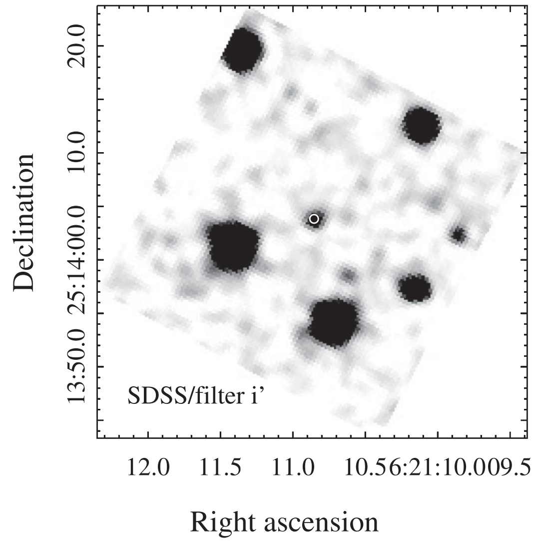

Figure 1. SDSS i'-band image of the J0621 field. The white circle shows 5σ pulsar position uncertainty that accounts for the optical astrometric referencing and radio timing position uncertainties from Table 1.

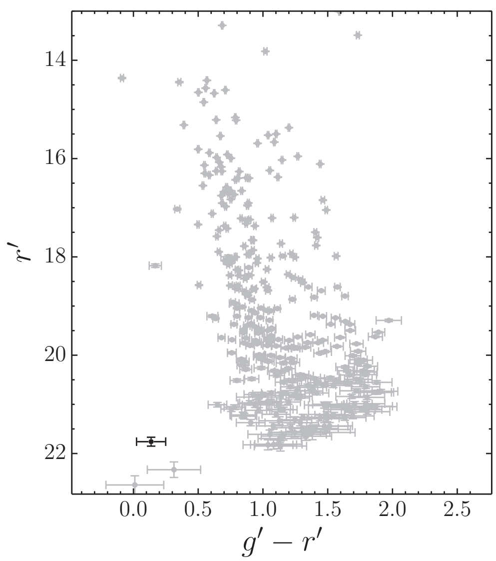

Figure 2. Colour–magnitude diagram for sources from the SDSS database located within 3 arcmin of the J0621 position. The likely pulsar companion is shown in black.

We compared these values with various WD cooling tracks to check whether the optical source can be indeed a WD. The colour–magnitude and colour–colour diagrams are shown in Figures 3 and 4 where the model predictions for different classes of WDs from Panei et al. (2007), Holberg & Bergeron (2006), Tremblay, Bergeron, & Gianninas (2011), Kowalski & Saumon (2006), and Bergeron et al. (2011)[2] are presented.

[2] http://www.astro.umontreal.ca/~bergeron/CoolingModels

doi:10.1017/pasa.2018.21

Table 2. Magnitudes of the J0621 optical counterpart candidate SDSS J062110.86+251403.8 obtained from SDSS catalogue.

RA[a]	Dec[a]	u'	g'	r'	i'	z'
$06^{h}21^{m}10.^{s}861(4)$	$+25°14'03.''808(55)$	22.97(37)	21.90(7)	21.76(9)	21.78(13)	21.23(32)

[a] Position uncertainties include centroiding and calibration errors and calculated as described in Theissen, West, & Dhital (2016).

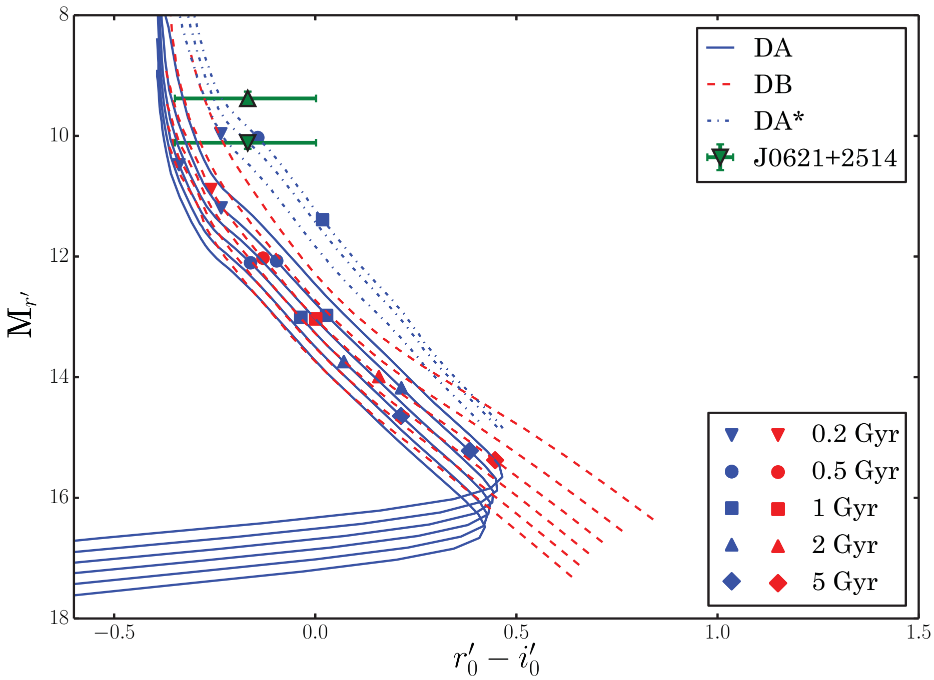

Figure 3. Colour–magnitude diagram with various WD cooling tracks. Dash-dotted blue lines show tracks for He-core WDs with hydrogen atmospheres and masses 0.1869, 0.2026, and 0.2495 $M_\odot$ (labelled as DA*; Panei et al. 2007), solid blue lines—for WDs with hydrogen atmospheres and masses 0.3–0.8 $M_\odot$ (labelled as DA; the step is 0.1 $M_\odot$; Holberg & Bergeron 2006; Kowalski & Saumon 2006; Tremblay et al. 2011), red dashed lines—for WDs with helium atmospheres and masses 0.2–0.7 $M_\odot$ (labelled as DB; the step is 0.1 $M_\odot$; Bergeron et al. 2011). WD masses increase from upper to lower curves. Cooling ages are indicated by different symbols. The location of the J0621 companion is marked by the green triangles (the upper one is for the distance $D_{\rm NE2001} = 2.33$ kpc and the lower one—for $D_{\rm YMW} = 1.64$ kpc).

According to these diagrams, the optical source most likely belongs to a class of He-core WDs with a mass of $\lesssim 0.5 M_\odot$. This is a rather young (the cooling age of ~0.2–0.5 Gyr) and hot (the effective temperature of $\approx 10\,000 \pm 2\,000$ K) WD. For the distance $D_{\rm NE2001}$=2.3 kpc, these estimates remain the same due to large colour uncertainties (see Figure 3; $M_{r'} = 9.38^{+0.10}_{-0.11}$).

3 DISCUSSION AND CONCLUSIONS

We identified the likely optical counterpart for the binary MSP J0621. The source is different by its colours from the MS stars (see Figure 2) which supports its association with the pulsar. Comparing its absolute magnitudes and colours with WD cooling tracks, we found that the companion most likely belongs to the class of the He-core WDs with the temperature $T \approx 10\,000 \pm 2\,000$ K. The estimated companion mass M_c is less than 0.5˜$M_\odot$. We compared the J0621 period P, the orbital period P_b, and the companion mass M_c with parameters of other known binary MSPs (see, e.g., Manchester 2017). This system lies in the M_c–P and M_c–P_b planes among others with similar parameters.

From evolutionary tracks, we obtain the WD cooling age of ~0.2–0.5 Gyr. The latter is much shorter than the pulsar characteristic age of 1.8 Gyr. The situation is similar to PSRs J1012+5307, J1909−3744, and J1738+0333 and their WD companions, which also have large discrepancies between two ages (see, e.g., van Kerkwijk et al. 2005, and references therein). Two explanations of that have been suggested. At first, a pulsar age may be overestimated. If its initial period is similar to the current one, then its real age can be compatible with a short cooling age. J0621 is a rather energetic pulsar

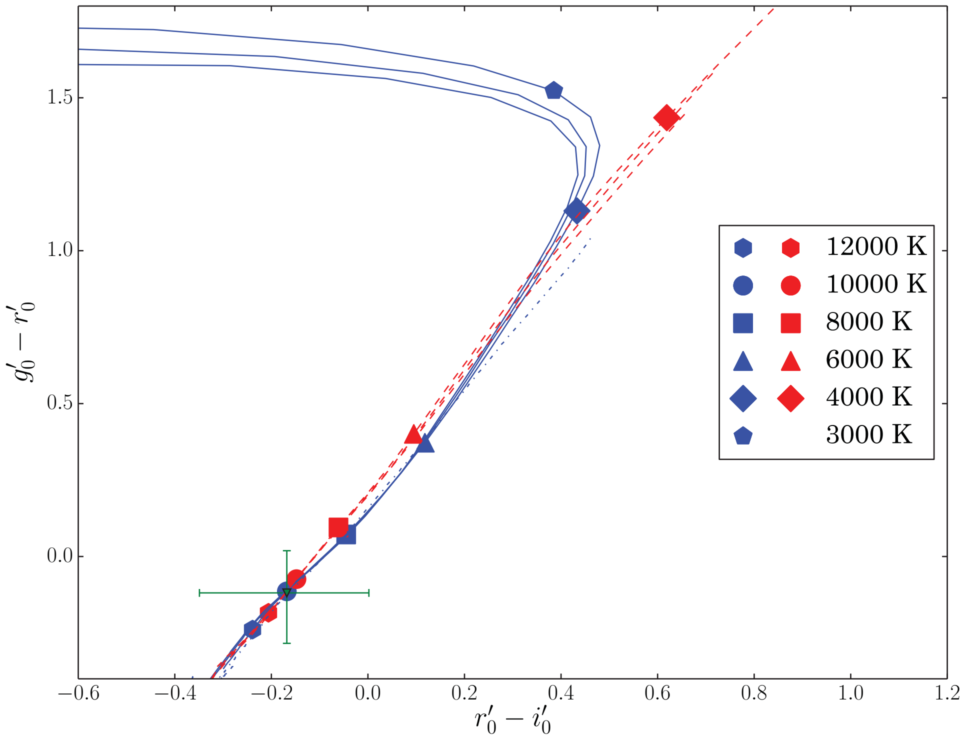

Figure 4. Colour–colour diagram with various WD cooling tracks. The model predictions demonstrated in Figure 3 are labelled by the same symbols and colours. WD temperatures are indicated by different symbols. The location of the J0621 companion is marked by the green cross.

and we cannot exclude that it is young. Second, a WD cooling age may be underestimated. WDs can stay hot for a long time due to residual hydrogen burning in the thick hydrogen envelopes. The latter takes place for the extremely low-mass (ELM; $M_{\rm WD} \lesssim 0.2$˜M$_\odot$; Panei et al. 2007; van Kerkwijk et al. 2005) sources. Comparison between cooling tracks of ELM WDs with thin and thick hydrogen envelopes was recently provided by Calcaferro, Althaus & Córsico (2018, see their Table 1). For example, a WD with $M_{\rm WD} = 0.15$˜M$_\odot$ and thin envelope cools down to an effective temperature of 9 400 K in 0.03 Gyr in contrast with the 2 Gyr required by the thick envelope sequence. The latter case is in agreement with our results for the J0621+WD system. The alternative explanation of the WD high temperature is the low metallicity of its progenitor (Serenelli et al. 2002). CNO flashes in such stars are less intensive than in stars with solar metallicity and, therefore, even very old WDs remain relatively hot and bright.

At the estimated temperature and mass, spectra of WDs with hydrogen envelopes are characterised by a large number of Balmer lines. Spectroscopic observations may reveal such lines in the spectrum of J0621's putative companion and allow one to better constrain its temperature, surface gravity, mass, and chemical composition. Radial velocity measurements would confirm the source relation to the pulsar and provide the mass ratio and, therefore, the pulsar mass. For a 22-mag source, this is feasible with 8–10-m class ground-based telescopes.

ACKNOWLEDGEMENTS

The authors thank the referee Scott Ransom for the useful comments which helped to improve the quality of the paper. AYuK and SVZ acknowledge PAPIIT grant IN-100617 for resources provided towards this research. Funding for the Sloan Digital Sky Survey IV has been provided by the Alfred P. Sloan Foundation, the U.S. Department of Energy Office of Science, and the Participating Institutions. SDSS-IV acknowledges support and resources from the Center for High-Performance Computing at the University of Utah. The SDSS web site is www.sdss.org. The Pan-STARRS1 Surveys (PS1) and the PS1 public science archive have been made possible through contributions by the Institute for Astronomy, the University of Hawaii, the Pan-STARRS Project Office, the Max-Planck Society and its participating institutes, the Max Planck Institute for Astronomy, Heidelberg and the Max Planck Institute for Extraterrestrial Physics, Garching, The Johns Hopkins University, Durham University, the University of Edinburgh, the Queen's University Belfast, the Harvard-Smithsonian Center for Astrophysics, the Las Cumbres Observatory Global Telescope Network Incorporated, the National Central University of Taiwan, the Space Telescope Science Institute, the National Aeronautics and Space Administration under Grant No. NNX08AR22G issued through the Planetary Science Division of the NASA Science Mission Directorate, the National Science Foundation Grant No. AST-1238877, the University of Maryland, Eotvos

Lorand University (ELTE), the Los Alamos National Laboratory, and the Gordon and Betty Moore Foundation.

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