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A white dwarf companion to the relativistic pulsar PSR J1141−6545*

J. Antoniadis,[1] † C. G. Bassa,[2] N. Wex,[1] M. Kramer[1] and R. Napiwotzki[3]
[1] *Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany*
[2] *Jodrell Bank Centre for Astrophysics, The University of Manchester, Alan Turing Building, M13 9PL Manchester, United Kingdom*
[3] *Centre of Astrophysics Research, University of Hertfordshire, College Lane, AL10 9AB Hatfield, United Kingdom*

ABSTRACT
Pulsars with compact companions in close eccentric orbits are unique laboratories for testing general relativity and alternative theories of gravity. Moreover, they are excellent targets for future gravitational wave experiments like LISA and they are also highly important for understanding the equation of state of super-dense matter and the evolution of massive binaries. Here we report on optical observations of the $1.02\,\mathrm{M}_\odot$ companion to the pulsar PSR J1141−6545. We detect an optical counterpart with apparent magnitudes $V = 25.08(11)$ and $R = 24.38(14)$, consistent with the timing position of the pulsar. We demonstrate that our results are in agreement with a white dwarf companion. However the latter is redder than expected and the inferred values are not consistent with the theoretical cooling tracks, preventing us from deriving the exact age. Our results confirm the importance of the PSR J1141−6545 system for gravitational experiments.

Key words: methods: photometry – binaries: close – pulsars: general – stars: neutron – white dwarfs – individual: PSR J1141−6545

1 INTRODUCTION

The value of relativistic binaries is highly recognised, as their study can provide insight into some of the holy grails of fundamental physics. Among them are tests of general relativity and alternative theories of gravity, the detection of gravitational waves, the study of the equation of state of super-dense matter and tests of evolutionary scenarios for heavy stars (for a complete review see Lorimer & Kramer 2004).

The sample of relativistic binaries discovered so far is dominated by double neutron stars, covering a wide range of orbital parameters. Another substantial fraction consists of white dwarf–neutron star binaries, most of them in almost perfectly circular orbits (e.g. review by van Kerkwijk et al. 2005). These systems are the result of the evolution of a massive primary which evolves fast, explodes as a supernova and becomes a neutron star (NS); and of a lighter secondary which evolves slower and eventually becomes a white dwarf (WD) (Driebe et al. 1998). During the final interaction phase, the NS is spun up to very short rotation periods and becomes a millisecond pulsar. Any eccentricity (primordial or resulting from the supernova kick) is dampened by tidal interaction before the secondary becomes a WD.

A significant exception to the preceding is the binary PSR B2303+46 (Stokes et al. 1985). In that system, the WD (van Kerkwijk & Kulkarni 1999) orbits the non-recycled pulsar in a highly eccentric orbit. Investigations into possible formation scenarios for this type of binary (Tauris & Sennels 2000; Davies et al. 2002; Church et al. 2006) have shown that they most likely originate from a binary system of massive stars with nearly equal mass. When the initially more massive star reaches the red giant phase, the secondary star accretes sufficient mass to surpass the Chandrasekhar limit, allowing it to eventually evolve into a NS. The primary star, however, loses sufficient mass to end up as a heavy WD. Hence, in the resulting system, the WD is expected to be older than the pulsar.

The only other promising candidate for this category is the PSR J1141−6545 binary system, initially discovered in a Parkes survey (Kaspi et al. 2000). PSR J1141−6545 is a 0.2 day binary in an eccentric orbit ($e \sim 0.17$, Bhat et al. 2008). The primary is a relatively young 394 ms pulsar (characteristic age ~ 1.4 Myrs), orbited by a compact object of unknown nature. Bhat et al. (2008) derived $M_\mathrm{c} = 1.02(1)\,\mathrm{M}_\odot$ for the mass of the companion by applying the relativistic DDGR orbital model (Damour & Deruelle 1986) to their timing measurements. The latter is consistent with

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† Member of the International Max Planck Research School (IMPRS) for Astronomy and Astrophysics at the Universities of Bonn and Cologne. e-mail: jantoniadis@mpifr-bonn.mpg.de

both a heavy WD and a light NS with the former case being more favoured by statistical evidence (Tauris & Sennels 2000). Jacoby et al. (2006) included the system in an optical survey but found no optical counterpart down to $R = 23.4$.

This paper reports on optical observations of the companion star in the PSR J1141−6545 binary system. Our main scientific rationale for this study is that in the case of a positive WD confirmation, the system would be of great importance for gravitational tests. In particular, because of its gravitational asymmetry, PSR J1141−6545 would be one of the most constraining systems known for general relativity in the strong field regime as it is expected to emit strong dipolar gravitational radiation in a wide range of scalar-tensor theories (Will 1993; Esposito-Farese 2005; Bhat et al. 2008).

The structure of the text is as follows: in Section 2 we describe the observations and the data reduction process while in Section 3 we present our results. Finally, in Section 4 we discuss our findings and comment on their astrophysical consequences and their importance in gravitational tests.

2 OBSERVATIONS AND DATA REDUCTION

We have obtained optical images in the V-band and R-band filters, of the field containing PSR J1141−6545 using the FORS1 instrument mounted at the UT2 of the Very Large Telescope (VLT). Both filters resemble the standard Johnson-Cousin filters but have slightly higher sensitivity in the red, sharper cut offs and higher throughput. The observations were conducted in service mode during the night of 6th of April 2008. The conditions were photometric and the average seeing of the night was $0.''7$. The total exposure time was 600 seconds in V and 1500 seconds in R. In order to minimize potential problems with cosmic rays and guiding errors and avoid saturation of bright stars, the exposures were split in three sub-exposures of 200 seconds in the V-band and three sub-exposures of 500 seconds in the R-band. For the data reduction we used the FORS1 pipeline provided by ESO. Each image was first bias corrected and flat-fielded using twilight flats. Bad pixels and cosmic ray hits in all frames were replaced by a median over their neighbourghs. The resulting frames were then sky-subtracted, registered and combined in one averaged frame for each filter.

2.1 Photometry

We performed point-spread function (PSF) photometry on the average frame of each filter using DAOPHOT II (Stetson 1987) inside the Munich Image Data Analysis System (MIDAS). The PSF was determined following a slightly modified version of the recipe in Stetson (1987). First, we selected 100 bright, unsaturated stars ($\leqslant 40000$ ADUs) located within $1'$ distance from our target. Then we fitted their PSFs with a Moffat function and through an iterative process we rejected fits with root mean square (rms) residuals greater than 1 per cent. The stars in the vicinity of the PSF template stars were then removed with the SUBTRACT routine of DAOPHOT II and the PSF was determined again on the subtracted image, improving the rms of the fit by a factor of $\sim$2. Finally, the instrumental magnitudes of all stars within the same distance were extracted.

For the photometric calibration we first found the offset between PSF and aperture magnitudes of six isolated bright stars in both our science images. This offset was used to transform the extracted PSF magnitudes to aperture ones. Zero-points and colour terms were determined by analysing two archival images of NGC 2437 (one in each band), obtained during the 5th of April 2008. The latter contains more than 80 Stetson photometric standards (Stetson 2000). Of those, we used only 30 depicted on the same area of the CCD as our target. We determined their instrumental magnitudes using the same aperture, inner and outer sky radii as in our science images. We fitted for zero-points and colour terms using the average extinction coefficients provided by ESO (0.120(3) and 0.065(4) per airmass for V and R respectively) and used them to transform our measurements to the standard Johnson-Cousin system. The rms residual of the fit was 0.02 mag in V and 0.04 mag in R.

2.2 Astrometry

For the astrometric calibration we selected 58 astrometric standards from the USNO CCD Astrograph Catalogue (UCAC3, Zacharias et al. 2010) that coincided with the $7' \times 4'$ averaged V image. Because of the 200 sec exposure times, only 13 of them were not saturated or blended and appeared stellar. The centroids of these stars were measured and an astrometric solution, fitting for zero-point position, scale and position angle, was computed. Two outliers were iteratively removed, and the final solution, using 11 stars, had root-mean-square residuals of $0.''056$ in right ascension and $0.''058$ in declination, which is typical for the UCAC3 catalogue.

The low number of astrometric standards used makes the astrometric solution sensitive to random noise, and hence we computed another solution using stars from the 2MASS catalogue. Of the 360 stars from this catalogue that coincided with the V image, 245 were not saturated and appeared stellar and unblended. The iterative scheme removed outliers and converged on a solution using 210 stars with rms residuals of $0.''14$ and $0.''13$. This solution is consistent with the UCAC3 astrometric solution to within the uncertainties and we are confident in using the UCAC3 solution for the astrometric calibration.

3 RESULTS

A faint star is present on the timing position of the pulsar (Manchester et al. 2010) in both the averaged V and R images (Fig. 1). The optical position is $\alpha_{2000} = 11^{\mathrm{h}}41^{\mathrm{m}}07.^{\mathrm{s}}00(2)$ and $\delta_{2000} = -65^{\circ}45'19.''01(10)$, where the uncertainty is the quadratic sum of the positional uncertainty of the star (approximately $0.''08$ in both coordinates) and the uncertainty in the astrometric calibration. This position is offset from the timing position by $\Delta\alpha = -0.''08 \pm 0.''11$ in right ascension and $\Delta\delta = 0.''10 \pm 0.''12$ in declination. Hence, the timing and the optical positions agree within errors. The images have an average stellar density of 239 stars per square arcminute, which translates to only a 0.9 per cent probability of a chance coincidence within the 95 per cent confidence error circle, which has a radius of $0.''20$. The star has $V = 25.08(12)$ and $R = 24.38(14)$ and at $V - R = 0.70(18)$,

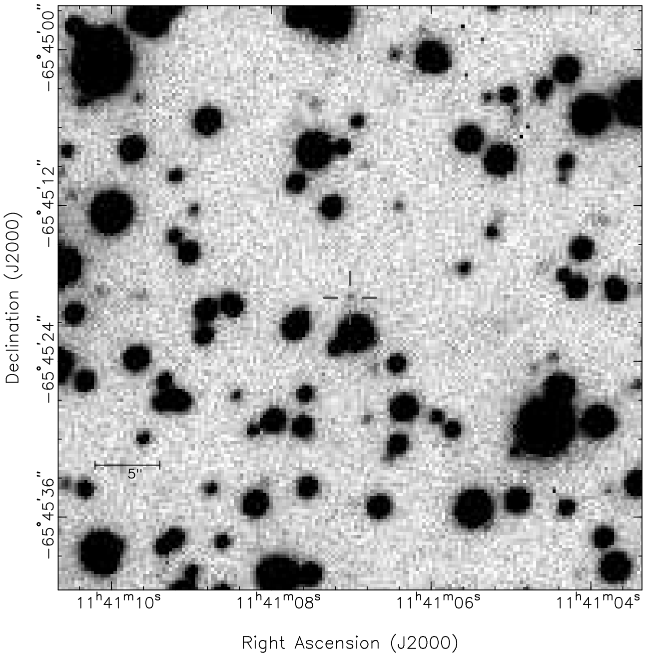

Figure 1. A $45'' \times 45''$ subsection of the averaged V-band image. The timing position of PSR J1141−6545 is denoted by $1''$ tickmarks.

it is significantly bluer than the bulk of the stars in the field, which have $V - R = 1.27(30)$ for $24 < V < 26$. Any MS or post-MS star would be brighter and/or redder given the distance ($\geqslant 3.7$ kpc, Section 3), hence we are confident that the star inside the error circle is the white dwarf companion to PSR J1141−6545 (Fig. 2).

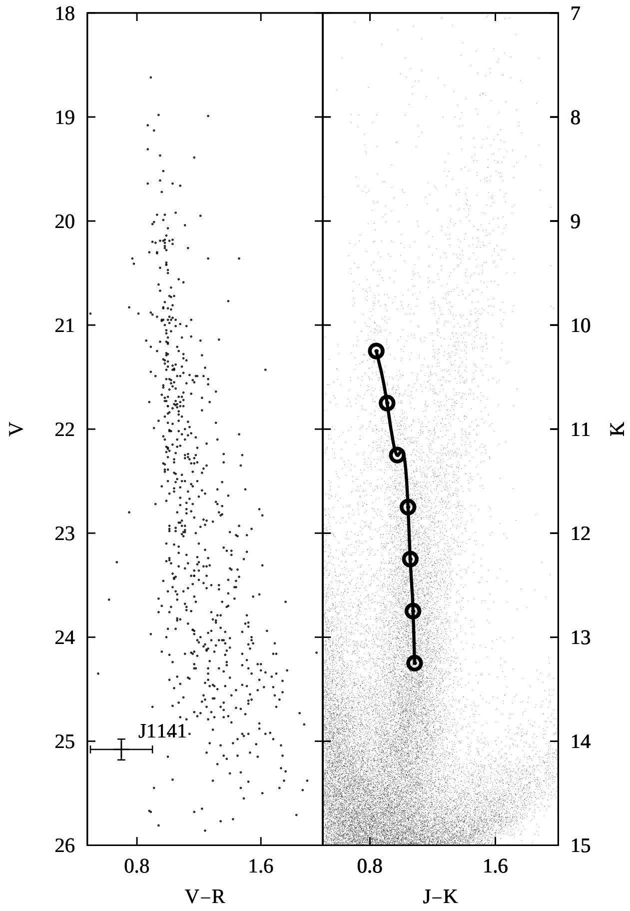

Figure 2. Left: The extracted V magnitudes of all objects in our data, plotted against their $V - R$ colours. The counterpart of PSR J1141−6545 is placed among the faintest and bluest objects. **Right**: Colour−Magnitude diagram of 2MASS sources, located within $20'$ distance from PSR J1141−6545. The circles indicate the calculated position of red clump stars. The line is a $3^{\rm rd}$ order spline connecting all circles.

3.1 Distance and reddening

The intrinsic color and brightess of the WD and hence its cooling age and temperature, can be inferred from our measurements under the condition of an accurate distance and reddening estimate. Unfortunately, as for most pulsars, the distance to the PSR J1141−6545 system is not well known.

An estimate can be made from the observed dispersion measure (DM) and a model of the free electron distribution in the Galaxy. Using the NE2001 Galactic free electron model (Cordes & Lazio 2002), we find $d = 2.4$ kpc for the observed DM $= 116.08\,{\rm cm}^{-3}$pc (Manchester et al. 2010) towards PSR J1141−6545. Traditionally the uncertainty on DM derived distances is quoted at 20 per cent, however, a comparison with pulsar parallaxes indicate that the uncertainties may be as large as 60 per cent (Deller et al. 2009). Ord et al. (2002) placed a lower bound on the distance by measuring the H I absorption spectrum of the pulsar. They concluded that the binary must be located beyond the tangent point predicted by the Galactic rotation model of Fich et al. (1989) to be at 3.7 kpc.

The interstellar extinction towards PSR J1141−6545 was traced using the red clump stars method described in Durant & van Kerkwijk (2006). We used a sample of 44168 stars from the 2MASS catalogue, situated within $20'$ distance from PSR J1141−6545 (right panel of Fig. 2). We then split the sample in seven 0.5 mag−wide stripes, ranging from $K = 10$ to $K = 13.5$ and traced the $J - K$ location of the helium−core giants by fitting their distribution with a power law plus a Gaussian, as in Durant & van Kerkwijk (2006) (right panel of Figure 2). We used $K_0 = -1.65$ for the intrinsic luminosity, $(J - K)_0 = 0.65$ for the intrinsic colour (infered from low-extinction 2MASS fields, van Kerkwijk personal communication) and $A_K = 0.112 A_V$ (Schlegel et al. 1998). The extinction was found to range from $A_V = 0.65$ to $A_V = 2.64$ for distances of $1.1 - 4.5$ kpc. For the 3.7 kpc distance of Ord et al. (2002), we deduce $A_V = 2.47$. Our values are larger than the ones derived by the model of Marshall et al. (2006) (e.g. $A_V = 2.52$ for 3.7 kpc), most likely due to the different resolution of our method, but consistent with the values derived by Drimmel et al. (2003) (e.g. $A_V = 2.05$ for 3.7 kpc).

3.2 Age and Temperature

The thermodynamics of WDs are simple in nature, making the cooling rates and ages easy to calculate. Several models exist for a wide variety of masses and compositions (e.g.

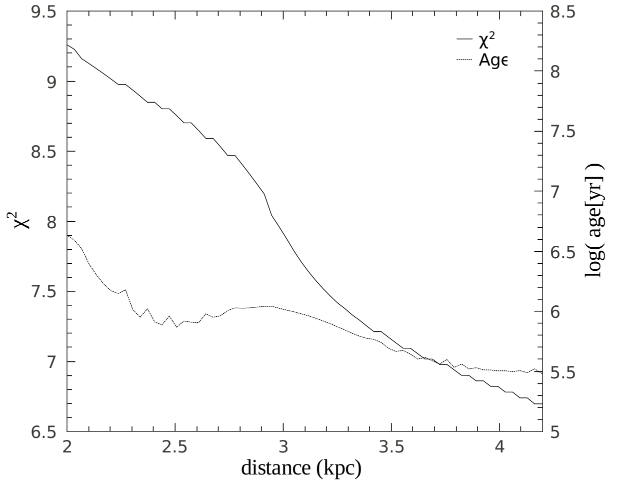

Figure 3. χ^2 index (Eq. 1, left axis) and best-fit age (right axis) as a function of distance. The goodness of the fit continually increases with distance. The best solution is found at 4.2 kpc where the V magnitude of the WD becomes equal to the brightest value provided by the model.

Holberg et al. 2008; Bergeron et al. 1995). In the high mass domain, the colours and temperatures derived by these models are in good agreement, independently of the chemical composition, especially for ages smaller than 8 Gyrs. Once the mass and absolute magnitudes are known, one can correlate them with a theoretical cooling track and derive the age. In the case of the PSR J1141−6545 binary, this calculation is complicated by the uncertain distance estimate and by the fact that the measured $V-R$ color is redder than expected. In order to find the age of the WD we used the O/Ne-core 1.06 $\mathrm{M}_\odot$ cooling track of Holberg et al. (2008) and searched for the best solution in the $\{d, A_V, T_{\mathrm{WD}}\}$ parameter space by minimising the quantity:

$$\chi^2 = \frac{[V_0(d, A_V) - V_{\mathrm{WD}}(T)]^2}{\sigma_V^2} + \frac{[R_0(d, A_R) - R_{\mathrm{WD}}(T)]^2}{\sigma_R^2} \quad (1)$$

with V_0 and R_0 the absolute magnitudes for a given distance and reddening; V_{WD} and R_{WD} the predicted magnitudes for a given age T; and $\sigma_{\mathrm{V,R}}$ the photometric uncertainties. We varied the distance between 2 and 4.2 kpc with a 0.1 step size. For each distance, A_V was derived from our reddening calculations. Finally, the extinction was convered using $A_R = 0.819 A_V$ (Schlegel et al. 1998). Unfortunately, our method yielded no compelling solution (Fig. 3), not only for the most reliable 1.06 $\mathrm{M}_\odot$ track but for other Holberg et al. (2008) and Bergeron et al. (1995) tracks of similar masses as well. In each case the minimum χ^2 was constrained by the minimum age provided by the particular model. The impact of the results on formation scenarios of PSR J1141−6545 is discussed in the next section.

4 CONCLUSIONS AND DISCUSSION

The results of this paper, for the first time, provide indisputable evidence for the gravitational asymmetry of the PSR J1141−6545 binary system, i.e. its composition of a strongly self-gravitating body, the pulsar ($E^{\mathrm{grav}}/mc^2 \sim 0.2$), and a weakly self-gravitating body, the white dwarf ($E^{\mathrm{grav}}/mc^2 \sim 10^{-4}$). This is of utmost importance for testing alternative theories of gravity with this system, in particular tests of gravitational dipolar radiation. In fact, the direct observation of the white dwarf companion to PSR J1141−6545 substantiates limits on alternative gravity theories derived in the past, like in (Esposito-Farese 2005; Bhat et al. 2008). Before the optical detection of the companion to PSR J1141−6545, its WD nature was inferred from the mass measurement, which is based on general relativity, and Monte-Carlo simulations of interacting binaries. These arguments are clearly less compeling than the evidence provided here, and become debatable when testing alternative theories of gravity, in particular when performing generic tests like in the double pulsar (Kramer & Wex 2009) and the PSR J1012+5307 system (Lazaridis et al. 2009).

Concerning the cooling age of the WD, our results are discrepant with the cooling tracks of regular WDs. Therefore, we could neither confirm nor reject the proposed formation scenarios for PSR J1141−6545. In particular, as demonstrated in figure 4, if the distance to the system is 3.7 kpc or higher (Ord et al. 2002) then the WD is brighter than expected and the best-fit solution to the cooling curve is found at an age smaller ($< 10^5$ yrs) than the characteristic age of the pulsar. On the other hand, if the 2.4 kpc DM distance is closer to the real one, then our results remain consistent with a WD older than the pulsar ($\sim 10^8$ yrs). In both cases, the colour is redder than expected but still consistent with the cooling track within 2σ. If the excessive reddening is true and not the result of an unidentified systematic error, then it can not be explained by interstellar extinction. Hence its source is most likely intrinsic to the system and possibly the consequence of an interaction between the WD and the super-nova, which polluted the atmosphere of the WD and changed its spectral fingerprint. It is worth mentioning that after performing the same kind of analysis (Section 3) on the prototype eccentric WD-NS binary PSR B2303+46 using the B, V and R colours reported by van Kerkwijk & Kulkarni (1999), we found that it shows similar deviations from the expected cooling track. The red color of these systems could also be explained by the presence of a cold disk around the WD which causes an excessive brightness towards the red part of the spectrum. However this scenario is less favoured because such a disk would be highly unstable given the high eccentricity of the binaries. Moreover the disk would produce orbit-correlated timing residuals that are not yet reported. Future multi-band photometric observations would be able to provide further insight into the formation history of both binaries.

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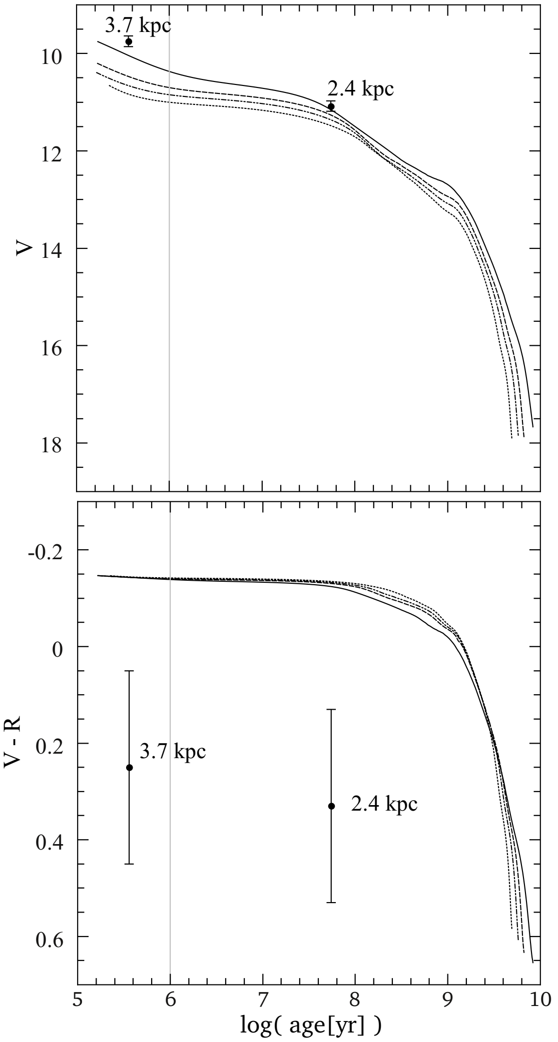

Figure 4. Cooling track of a $M = 1.06\,\mathrm{M}_\odot$ O/Ne WD (solid line) based on the work of Holberg et al. (2008) as reflected in its $(V-R)_0$ colour (lower panel) and brightness (upper panel). Further WD model sequences are overplotted for comparison (masses: $1.16, 1.20, 1.24\,\mathrm{M}_\odot$; dashed, dashed-dotted and dotted line respectively). The color and brightness of PSR J1141−6545 is also plotted against age, for the distance of 3.7 kpc (Ord et al. 2002) and the 2.4 kpc DM distance. The error-bars in both panels represent the 1σ uncertainties derived from monte-carlo simulations of photometric and calibration errors propagation. The grey vertical line shows the characteristic age of the pulsar.

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