Optical identification of the companion to PSR J1911–5958A, the pulsar binary in the outskirts of NGC 6752

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Abstract. We report on the identification of the optical counterpart of the binary millisecond pulsar PSR J1911–5958A, located in the outskirts of the globular cluster NGC 6752. At the position of the pulsar we find an object with \( V = 22.08, B - V = 0.38, U - B = -0.49 \). The object is blue with respect to the cluster main sequence by 0.8 magnitudes in each color. We argue that the object is the white dwarf companion of the pulsar. Comparison with white dwarf cooling models shows that this magnitude and color are consistent with a low-mass white dwarf at the distance of NGC 6752. If associated with NGC 6752, the white dwarf is relatively young, \( \lesssim 2 \) Gyr, which sets constraints on the formation of the binary and its ejection from the core of the globular cluster.

Key words. Pulsars: individual (PSR J1911–5958A) – globular clusters: individual (NGC 6752) – stars: neutron – stars: white dwarfs

1. Introduction

Recently, 5 millisecond pulsars have been discovered (D’Amico et al. 2002) towards the nearby galactic globular cluster NGC 6752. Three of them are located inside the 6′/7′ core radius (Lugger et al. 1995) while the other two are outside the 1′92 half-mass radius (Djorgovski 1993), at 2′/7′ and 6′/4′, respectively. The latter of these is a binary millisecond pulsar, PSR J1911–5958A (hereafter PSR A), and has a low-mass (\( \geq 0.19 M_\odot \)) companion (D’Amico et al. 2002). The pulsar period and period derivative suggest that it is a “canonical” recycled millisecond pulsar (see Phinney & Kulkarni 1994 for a review), and hence that the companion is likely a white dwarf.

The large separation of PSR A from the cluster center is puzzling. Colpi et al. (2002) have recently investigated possible scenarios, and found that both for the case of a primordial binary and for an exchange or scattering event with other cluster stars, it is very difficult to explain both the pulsar’s current position and its close circular binary orbit. Instead, they suggest that the binary may have been scattered to its current position by a binary composed of two 3–100\( M_\odot \) black holes.

One might learn more about the system’s origin (and verify cluster membership) if one can confirm that the companion is a white dwarf and measure its mass and age. Therefore, we searched for the optical counterpart in archival data. We report here on the results.

2. Observations and analysis

We searched the ESO and Hubble Space Telescope archives for images coincident with the pulsar position (\( \alpha_{2000} = 19^h 11^m 42^s 7562, \delta_{2000} = -59^\circ 58’ 26’’ 900’’; \) D’Amico et al. 2002). We found two images, taken with the Wide Field Imager (WFI) at the ESO 2.2 m telescope on La Silla. These observations, 4 minute \( B \) and \( V \)-band exposures, were taken during the night of May 13/14, 1999. The seeing was poor, \( \sim 1’’5 \) in \( V \). However, both images showed a faint object at the pulsar position (see below). This object was also present in two \( HST \) observations with the Wide Field Planetary Camera 2 (WFPC2; Holtzman et al. 1995). Both observations, U5F107 and U5F103 (GO-8256), were imaged in the same filters and had similar exposure times, 42 s in F555W (hereafter \( V_{555} \)), 220 s in F439W (\( B_{439} \)), 660 s in F336W (\( U_{336} \)) and 1800 s and 1693.5 s in F255W (\( nUV_{255} \)) for the first and second field, respectively. The position of the pulsar coincides with the WF3 chip for the U5F107 dataset, while it is on the WF4 chip on the other dataset.

2.1. Astrometry

The WFI detector has an array of 8 CCDs (2 rows of 4), each CCD having a field of view of 8′ × 16′, a total of 33′ × 34′.

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The position of the pulsar was coincident with chip 6 of the V-band image. We found that there was some distortion over the whole chip. To minimize its effect we only used the upper half of this chip for the astrometric calibration. Stars on this 8′ × 8′ sub-image were compared against entries in the USNO CCD Astrograph Catalog (UCAC; Zacharias et al. 2000). In total 68 UCAC stars coincided with this image and their centroids were measured. Of these 43 were not saturated and appeared stellar and unblended. One outlier, having a total residual of 0′.32 was rejected. The remaining stars were used to calculate an astrometric solution, fitting for zero-point position, scale and position angle. This solution has root-mean-square (rms) residuals of 0′.06 in both right ascension and declination. The statistical uncertainty in the astrometry is thus 0′.084 in each coordinate.

2.2. Photometry

We started with the pipeline calibrated HST/WFPC2 images, and used the HSTphot 1.1 (Dolphin 2000a) package for further reduction and photometry of the images. We followed the recommended procedures to mask bad pixels, defects, cosmic ray hits and hot pixels. Next we used the main task hstphot to find stars, measure positions, and determine calibrated photometry. The latter uses the aperture corrections, charge-transfer efficiency corrections and zero-points of Dolphin (2000b).

2.3. The counterpart to PSR J1911−5958A

The UCAC catalog is on the ICRS at the 20 mas level (Assafin et al. 2003). Including this uncertainty in the uncertainty of the astrometric tie, we obtain 95% confidence radii for the WFI and HST/WFPC2 frames of 0′.211 and 0′.235, respectively. Within these radii there is a single object, see Fig. 1. The HST/WFPC2 positions and magnitudes are tabulated in Table 1.

The photometric measurements of the object in the two datasets are consistent for all filters except nUV. The object is 0.7 magnitudes brighter in the first dataset than in the second. However, we compared the magnitudes of 240 stars that overlapped between the two datasets and found that, on average, stars in the first dataset were brighter by 0.34 magnitudes in nUV, which removes the observed discrepancy. We have not, however, found an explanation for this large offset between the two datasets.

The magnitudes in the HST flight system filters (U, B, and V) were transformed to the Johnson-Cousins UBV (Vega) system using the transformations by Holtzman et al. (1995). The resulting average magnitudes for the object in...
Table 1. Positional and photometric data.

| Dataset | Date (UT) | R.A. (J2000) | Decl. (J2000) | nUV$_{255}$ | U$_{336}$ | B$_{439}$ | V$_{555}$ |
|---------|-----------|--------------|--------------|-------------|-----------|-----------|-----------|
| U5F107  | March 2, 2000 @ 10:29 | 19$^h$11$^m$42.756 | -59$^\circ$58′26.87′ | 20.74 ± 0.23 | 21.49 ± 0.15 | 22.40 ± 0.21 | 22.10 ± 0.17 |
| U5F103  | March 3, 2000 @ 13:54 | 19$^h$11$^m$42.757 | -59$^\circ$58′26.83′ | 21.44 ± 0.24 | 21.78 ± 0.14 | 22.49 ± 0.17 | 22.09 ± 0.14 |

The object is blue by about 0.8 magnitudes. The minimum mass for the companion is constrained by the pulsar mass function. For a pulsar mass of 1.35 M$_\odot$ (Thorsett & Chakrabarty 1999) this minimum mass is 0.185 M$_\odot$. The lower limit increases for heavier pulsars, roughly by 0.004 M$_\odot$ for every 0.05 M$_\odot$ step in the pulsar mass. Assuming a random probability distribution for the inclination of the binary, we find that there is 90% probability that the companion mass is less than 0.5 M$_\odot$. Given this range of masses and the fact that PSR A is a recycled millisecond pulsar, it is likely that the companion is a Helium-core white dwarf.

To verify whether our observations are compatible with a Helium-core white dwarf at the distance of the cluster, we compare our magnitudes with the predictions from the white dwarf cooling tracks of Serenelli et al. (2002). We use their tracks for $Z = 0.001$, as this metallicity provides the best match to the metallicity of NGC 6752 ([Fe/H] = −1.43 ± 0.04; Gratton et al. 2003). We also assume a V-band distance modulus ($m - M_V$) = 13.24 ± 0.08 and reddening $E_{B-V} = 0.040$, as recently determined by Gratton et al. (2003), and use the relative extinction coefficients listed by Schlegel et al. (1998).

Figure 2 shows the cooling tracks for Helium-core white dwarfs with $Z = 0.001$ for masses in the range of 0.183 to 0.336 M$_\odot$. It appears that the magnitude and colors of the companion to PSR A are compatible with the two lowest-mass tracks, 0.183 and 0.197 M$_\odot$. Note that the 0.183 M$_\odot$ model is below the minimum mass inferred from the pulsar mass function.

We have fitted the observed absolute $UBV$ magnitudes against the predictions from the $Z = 0.001$ Helium-core white dwarf models. A $\chi^2$ statistic was computed for each entry in the model from the difference between the observed and modelled absolute magnitudes. Table 2 shows, for each model with a given mass, the properties of the white dwarf at the $\chi^2$ minimum. Both Fig. 2 and Table 2 show that the lowest mass models, 0.197 to 0.244 M$_\odot$, are preferred. At these masses the white dwarf is rather hot, with $T_{\text{eff}} \approx 11 000 – 16 000$ K.

Given these high temperatures, the counterpart is relatively young, < 2 Gyr (see both Fig. 2 and Table 2). The precise value strongly depends on the mass, since white dwarfs with lower masses have relatively thick hydrogen envelopes, where residual hydrogen shell burning keeps the white dwarf hot. From the values listed in Table 2 one sees a jump in the cooling age between the 0.197 and 0.230 M$_\odot$ models. This reflects a dichotomy in the thickness of the hydrogen layer, where, above a certain critical mass, the thickness has been reduced by shell flashes early in the evolution (Althaus et al. 2001). As the shell burning is through the CNO cycle, the critical mass depends on the metallicity: ~ 0.18 M$_\odot$ for solar metallicity, ~ 0.22 M$_\odot$ for $Z = 0.001$ and ~ 0.26 M$_\odot$ for $Z = 0.0002$ (Althaus et al. 2001; Serenelli et al. 2002).

3. Ramifications

The minimum mass for the companion is constrained by the pulsar mass function. For a pulsar mass of 1.35 M$_\odot$ (Thorsett & Chakrabarty 1999) this minimum mass is 0.185 M$_\odot$. The
the mass range of interest here, their results are similar. Their 
0.195 M\(_\odot\) model has a cooling age of 1.2 Gyr, comparable to 
the age of the Serenelli 0.197 M\(_\odot\) model. For higher masses the 
cooling age decreases. The 0.300 M\(_\odot\) model by Driebe et al. 
(1998) has a cooling age of 0.2 Gyr, down to 25 Myr for the 
heaviest model, with a mass of 0.414 M\(_\odot\).

Finally, we note the similarity between the position in the 
color-magnitude diagram of the companion of PSR A and the 
white dwarf, as well as a much more precise cooling age. The 
radius would allow one to confirm the association of the binary 
with NGC 6752. If the association is confirmed, the more accurate 
distance to NGC 6752 provides additional constraints on 
the radius and thus the mass of the white dwarf. Combining the 
white dwarf mass with a radial-velocity orbit of the white dwarf 
(and thus a mass ratio), would give the mass of the pulsar.

4. Discussion and conclusions

We have detected the optical companion to the binary millisecond 
pulsar PSR J1911–5958A, which is located 6.4 from the 
center of NGC 6752. The companion is blue with respect to the 
cluster main sequence by 0.8 magnitudes in \(B-V\) and comparison 
of its colors and magnitude with white dwarf models 
shows that it is consistent with a Helium-core white dwarf at 
the distance of NGC 6752.

Irrespective of the cooling models we use, we find that the 
white dwarf is at most 2 Gyr old. This age is similar to the 
\(\geq 0.7\) Gyr the binary can be expected to stay in the outskirts if 
it is currently on a highly eccentric orbit in the cluster (Colpi et al. 
2002), which suggests that the white dwarf formed during, 
or shortly after, an encounter that also ejected the binary from 
the core, in an exchange interaction involving a binary with 
another star or binary. In the scenarios in which the binary was 
formed in the periphery, or scattered by a binary black hole, the 
incidence of the two time scales has to be due to chance.

One would expect the characteristic age of the pulsar to 
be similar to the cooling age of the white dwarf, as the pul-
sar starts to spin down after the cessation of mass transfer, 
while the white dwarf starts to cool. This seems not to be 
the case for PSR A, for the characteristic age of the pulsar is 
P/(2P) \(\sim 17\) Gyr (D’Amico et al. 2002). It may be instead that 
the assumption underlying the characteristic age is wrong, 
and that the period at which the pulsar started spinning is similar to 
the current one.

Compared to other white dwarf companions to millisecond 
pulsars, the companion to PSR J1911–5958A is bright, 
\(V \approx 22\), which opens the possibility to determine detailed physical 
parameters (e.g., Van Kerkwijk et al. 1998, Callanan et al. 
1998). For instance, one could measure the white dwarf tem-
perature and surface gravity through spectroscopy. By compar-
ison with models, this would lead to a mass and radius of the 
white dwarf, as well as a much more precise cooling age. The 
radius would allow one to confirm the association of the binary 
with NGC 6752. If the association is confirmed, the more accurate 
distance to NGC 6752 provides additional constraints on the 
radius and thus the mass of the white dwarf. Combining the 
white dwarf mass with a radial-velocity orbit of the white dwarf 
(and thus a mass ratio), would give the mass of the pulsar.

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Table 2. Fitting results for Helium–core white dwarf models 
with a metallicity of \(Z = 0.001\). The observed absolute \(UBV\) 
magnitudes were fitted against the modelled values. The dered-
ddened, observed values \(U - B\), \(B - V\) and \(MV\) are given in the 
second row.

| Mass \((M_{\odot})\) | \(T_{\text{eff}}\) \((k\text{K})\) | \(\tau_{\text{c}}\) \((\text{Gyr})\) | \(U - B\) \(\text{mag}\) | \(B - V\) \(\text{mag}\) | \(MV\) \(\text{mag}\) | \(\chi^2\) |
|---|---|---|---|---|---|---|
| 0.183 | 10.6 | 2.30 | -0.31 | 0.08 | 8.92 | 0.9 |
| 0.197 | 11.7 | 1.36 | -0.37 | 0.03 | 8.98 | 1.1 |
| 0.230 | 14.7 | 0.37 | -0.59 | -0.06 | 9.14 | 3.4 |
| 0.244 | 15.6 | 0.27 | -0.64 | -0.08 | 9.18 | 4.2 |
| 0.300 | 19.1 | 0.07 | -0.80 | -0.13 | 9.29 | 8.1 |
| 0.336 | 20.3 | 0.05 | -0.85 | -0.14 | 9.33 | 9.5 |
| 0.380 | 21.6 | 0.05 | -0.89 | -0.16 | 9.34 | 10.6 |
| 0.390 | 22.1 | 0.04 | -0.91 | -0.16 | 9.34 | 11.1 |
| 0.422 | 23.8 | 0.03 | -0.95 | -0.18 | 9.39 | 12.9 |
| 0.449 | 24.7 | 0.06 | -0.98 | -0.19 | 9.40 | 13.7 |