The Helium White Dwarf orbiting the Millisecond Pulsar in the halo of the Globular Cluster NGC6752

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ABSTRACT

We have used deep high-resolution multiband images taken at the ESO Very Large Telescope to identify the optical binary companion to the millisecond pulsar (PSR J1911–5958A) located in the halo of the Galactic Globular Cluster NGC6752. The object turns out to be a blue star whose position in the Color Magnitude Diagram is consistent with the cooling sequence of a low mass \((M \sim 0.17−0.20M_\odot)\), low metallicity Helium white dwarf (He-WD) at the cluster distance. This is the second He-WD which has been found to orbit a millisecond pulsar in GGCs. Curiously both objects have been found to lie on the same mass He-WD cooling sequence. The anomalous position of PSR J1911–5958A with respect to the globular cluster center (\(\sim 6\)‘) suggested that this system has recently (\(\lesssim 1\) Gyr) been ejected from the cluster core as the result of a strong dynamical interaction. The data presented here allows to constrain the cooling age of the companion within a fairly narrow range (\(\sim 1.2 − 2.8\) Gyr), therefore suggesting that such dynamical encounter must have acted on an already recycled millisecond pulsar.

Subject headings: Globular clusters: individual (NGC6752); stars: evolution – pulsars: individual (PSR J1911–5958A) – binaries: close.

1Based on observations collected by using the Very Large Telescope, at the European Southern Observatory, Cerro Paranal, Chile, within the observing programme 71.D-0232.
1. Introduction

PSR J1911−5958A has been discovered on 1999 October 17 during a search for Millisecond Pulsar (MSPs) in Galactic Globular Clusters (GGCs) in progress at the Parkes Radiotelescope (D’Amico et al. 2001). It is a binary millisecond pulsar with a spin period of 3.26 ms, an orbital period of 0.84 days and very low eccentricity (e < 10^{-5}). Precise celestial coordinates \( (RA = 19^h 11^m 42.756, DEC = -59^\circ 58' 26''.91) \) have been recently obtained for this source from pulsar timing observations (D’Amico et al. 2002). This position is far away (\( \sim 6' \)) from the cluster optical center: indeed PSR J1911−5958A is the more off-centered pulsar among the sample of 44 MSPs whose position in the respective cluster is known, and it suggests that this object might be the result of strong interactions occurred in the cluster core.

Colpi et al. (2002) explored a number of possibilities for the peculiar location of PSR J1911−5958A: a careful analysis led to discard the hypothesis of a primordial binary (born either in the halo or in the core of the cluster) and to reject also the possibility of a 3-body scattering or exchange event off core stars. Hence they conjectured that a more massive target (\( ? \), either a binary or a single intermediate-mass black hole, see also [colpi03a,colpi03b] could have provided the necessary thrust to propel PSR J1911−5958A into its current halo orbit at an acceptable event rate.

Moreover, beside PSR J1911−5958A, NGC6752 hosts also the second most displaced MSP ever seen in a globular (PSR J1911−6000C) and at least two (out the three) MSPs located in the cluster center (\(?\), PSR-B and PSR-E, see Figure 2 in) [ferraro03 experience strong acceleration, implying an unusually high central mass to light ratio \( (M/L \gtrsim 6) \) (D’Amico et al. 2002; Ferraro et al. 2003). Ferraro et al. (2003) showed that NGC6752 is a dynamically evolved cluster probably undergoing a post-core-collapse bounce and investigated scenarios for simultaneously explaining both the anomalous acceleration of PSR-B and PSR-E and the ejection of PSR J1911−5958A and PSR J1911−6000C, concluding that the existence of a binary black hole of intermediate mass (Colpi et al. 2002) could be a viable possibility.

Optical detection of the companion to a millisecond pulsar in a globular cluster proved particularly helpful in assessing the origin and the evolution of the binary, besides supporting its cluster membership (\( ? \), see, e.g.,) [edmonds01,ferraro01a,edmonds02. In fact, unlike the systems in the galactic field, the age, metallicity, extinction, distance and hence intrinsic luminosity and radius can be estimated from the parent cluster parameters. Hence, we undertook a systematic program (Ferraro et al. 2001a,b) devoted to the optical identification of MSPs companion in GGCs; as a part of this project in this Letter we present the identification of the optical counterpart to the PSR J1911-5958A companion.
2. Observations and data analysis

The photometric data presented here consist of a set of high resolution images obtained by using the camera FORS1 mounted at the ANTU Unit Telescope 1 (UT1) of the Very Large Telescope (VLT) at ESO on Cerro Paranal (Chile) on three nights in March, April and May 2003. All the observations have been performed in the High Resolution (HR) mode of FORS1. In this configuration the plate-scale is $0'1/pixel$ and the FORS1 $2048 \times 2048$ pixel$^2$ array has a global field of view of $3'4 \times 3'4$. The data comprise eight $220 \text{s}$ V-band exposures, five $360 \text{s}$ B-band exposures and three $1500 \text{s}$ U-band exposures, roughly centered on the PSR J1911$-$5958A (hereafter MSP-A) nominal position. All the observations were performed in service mode under good seeing conditions (FWHM $= 0'5 - 0'7$).

A sub-image of $800 \times 800$ pixels centered on the nominal position of the MSP-A has been extracted from the original frames and carefully analyzed. All the reductions have been carried out using ROMAFOT (Buonanno et al. 1983), a package specifically developed to perform accurate photometry in crowded fields, allowing for a visual inspection of the quality of the PSF-fitting procedure. In order to optimize the search for faint objects a median-combined image in each band has been obtained and the search procedure has been performed on the deepest combined image. Then the masks with the star positions have been adapted to each image and the PSF-fitting procedure performed on each individual frame separately. The resulting instrumental magnitudes have been transformed to a common photometric system and then averaged. Thus, a final catalogue with the coordinates and the average instrumental magnitude in each filter has been compiled for all the stars identified in the considered sub-image. Photometric calibration of the instrumental magnitudes (in the B and U band) was obtained using four photometric standard stars (Landolt 1992) secured under photometric conditions. Since no accurate calibration of the V filter was possible with the data secured in service, we calibrated the V magnitude by using $\sim 200$ stars in common with the $B,V$ catalog recently published by Ferraro et al. (2003). The stars in common between the two catalogs permitted also an independent check of the calibration obtained in the B band, displaying agreement within a few hundredths of magnitude.

The stars identified in the considered sub-image have been reported to an absolute astrometric system by using the 200 stars in common with the Ferraro et al. (2003) catalog (already astrometized). The details of the procedure adopted to derive the astrometric solution are described in other papers (Ferraro et al. 2001b, 2003). In short, the new astrometric Guide Star Catalog (GSCII) was used to search for astrometric standard stars lying in the considered field of view (FoV). At the end of the procedure, the rms residuals were of the order of $\sim 0'3$ both in RA and Dec and we assume this value as representative of the astrometric accuracy.
3. Results

Figure 1 shows the $U, U - V$ and $B, B - V$ Color Magnitude Diagram (CMD) for the stars (large filled circles) identified in the $80'' \times 80''$ FORS1 sub-image considered here. Most of the stars trace a clean and well defined main sequence (MS) spanning almost 8 mags in the $U$ band reaching $U \sim 26$. Only a few sparse objects, showing a blue excess, are visible on the left side of the MS. The most extreme blue objects in the CMDs are CO white dwarfs (WDs): once the MS is matched, they nicely overlaps the position of a CO-WDs population (shown as small empty circles in Fig. 1) observed in this cluster by Renzini et al. (1996) and Ferraro97. In particular, the colors and the luminosities of the three CO-WDs found here and of the previously observed population agree with the theoretical cooling sequence for $0.5M_\odot$ hydrogen rich WDs (Wood 1995) (drawn as heavy dashed line in Fig. 1).

On the basis of the accurate astrometric positions obtained from the photometric catalog, we identified a blue object (hereafter COM J1911−5958A) lying at only 0''1 from the nominal position of PSR J1911−5958A. Finding chart (in the $B$-band filter) for COM J1911−5958A is shown in Fig. 2. Only a few objects ($\sim 10$) are lying in the region of the CMD to the left of the MS: considering the FoV of the sub-image, there is a very small probability ($\lesssim 5 \times 10^{-5}$) of detecting one of the blue objects just by chance in a circular aperture of radius $\sim 0.3''$ (corresponding to the uncertainty in the relative radio-optical astrometry) centered on the pulsar position.

The position of COM J1911−5958A is marked as a large empty square in the CMDs in Fig. 1, whereas absolute coordinates and magnitudes are listed in Table 1. Taking into account the expected variability of this object and the global uncertainty in the calibration of the photometric zero-point, we conservatively adopted an overall uncertainty in the reported magnitudes of 0.15 mag. While we were writing this Letter a not yet refereed paper by Bassa et al. appeared on the web (astro-ph/0307340) also presenting the optical identification of this object. Though the identification is consistent with that presented here, it can be considered, at most, a preliminary detection since the object is nearly at the detection limit in the exposures utilized in that paper. The deep VLT observations presented here allow us to measure the object with a quite high S/N ratio (70−120) and to derive the photometric properties of the star with much higher accuracy.

The location of COM J1911−5958A in the CMDs ($\sim 1.5$ mag bluer than the MS in the diagram) excludes it is a CO-WD whilst it resembles $U_{opt}$, the companion to PSR J0024−7203U in 47 Tuc (Edmonds et al. 2001), which was suggested (Edmonds et al. 2001) to be a low mass Helium core WD (He-WD) from the comparison with theoretical models by Serenelli et al. (2001). However, the He-WD tracks used by Edmonds et al. (2001) were
computed for progenitors with high (solar) metallicity ($Z = 0.02$).

Here we have applied the same procedure taking advantage of a new set of tracks specifically computed (Serenelli et al. 2002) for globular cluster applications, i.e. assuming progenitors with low metallicities. In particular, we used the cooling tracks at $Z = 0.001$, which are the closest to the cluster metallicity ($[Fe/H] = -1.43 \pm 0.04$) as recently derived by Gratton et al. (2003). The cooling sequences for two He-WD masses ($0.172$ and $0.197 M_\odot$, respectively) are over-plotted in Fig. 1 (light dashed lines). The models have been drawn by adopting a distance modulus $(m - M)_0 = 13.13$ (?, from the homogeneous distance scale for 61 GGCs derived by) ferraro99 and a reddening $E(B - V) = 0.04$ (Harris 1996; Gratton et al. 2003). Note that the distance modulus adopted here is consistent both with the estimate obtained from the WD cooling sequence ($(m - M)_0 = 13.05 \pm 0.1$) by Renzini et al. (1996) and with the most recent determination ($(m - M)_0 = 13.12 \pm 0.08$) derived from MS fitting by Gratton et al. (2003).

Inspection of Fig. 1 reveals that luminosity and color of COM J1911$-$5958A well agree with its being a He-WD of mass in the range $0.17 - 0.20 M_\odot$. In particular, from the $Z = 0.001$ models of masses $0.172M_\odot$ and $0.197M_\odot$ by Serenelli et al. (2002), we derive the following estimates for the properties of COM J1911$-$5958A: a temperature in the interval $T_{\text{eff}} = 10,000 - 12,000$ K, a gravity $\log g = 6.12 - 6.38$, a luminosity $L = 0.03 - 0.04 L_\odot$, a radius $R = 3 - 4 \times 10^9$ cm and a cooling age in the range $1.2 - 2.8$ Gyr.

4. Discussion

We have identified the optical companion to the millisecond pulsar PSR J1911$-$5958A located at 3.3 half mass radii from the center of the globular cluster NGC6752. $U$, $B$ and $V$ magnitudes (and related colors) of the optical source are compatible with its being a Helium white dwarf hosted in the globular’s halo.

From the pulsar mass-function (?, 0.0026887 $M_\odot$) damico02, it results a minimum companion mass (corresponding to a system seen edge-on, i.e. with orbital inclination $i = 90^\circ$) $M_{\text{COM}} = 0.185 M_\odot$ for a pulsar mass of $1.35 M_\odot$ (Thorsett & Chakrabarty 1999). Given the upper limit ($M_{\text{COM}} \lesssim 0.2 M_\odot$) of the range of masses of COM J1911$-$5958A inferred from the cooling tracks of Serenelli et al. (2002), we can constrain the inclination $i$ to be larger than $\geq 70^\circ$. Adopting a larger value for the pulsar mass would result in a even larger lower limit for the orbital plane inclination.

Dynamical friction can rapidly drive back to the cluster core a object of total mass of order 1.6 $M_\odot$ moving on a highly eccentric orbit in the cluster potential. In particular,
ejection of PSR J1911−5958A from the core to the outskirts of NGC6752 (implying a radial orbit) cannot be occurred more than $\tau_{df} = 0.7 - 1$ Gyr ago (Colpi et al. 2002). The cooling age of COM J1911−5958A is longer than $\tau_{df}$, implying that any dynamical event responsible for the ejection probably acted on an already recycled millisecond pulsar. Hence, the optical identification of COM J1911−5958A tends to exclude (i) the scenarios in which the recycling process occurred after (or was triggered by) the dynamical encounter which propelled the pulsar in the cluster halo (but see the discussion in Sigurdsson, 2003) and (ii) any kinds of interactions imparting a significant eccentricity to the binary pulsar (having excluded a recent mass transfer phase, the circularization of the system at the present level, $e \lesssim 10^{-5}$, would require a time much longer than $\tau_{df}$). In particular, among the proposed black hole hypotheses (Colpi et al. 2003a,b) a binary black hole of mass in the range 10-200 $M_\odot$ seems the most plausible candidate.

Since the first discovery of an optical counterpart to a binary MSP companion in GGC (?, $U_{opt}$, the companion to PSR J0024−7203U in 47 Tuc;)]edmonds01, the zoo of the optical MSP counterparts in GGCs is rapidly increasing: a surprisingly bright object (COM J1740−5340, either a subgiant or a heated MS) has been discovered (Ferraro et al. 2001b) in NGC6397, and a very faint source (W29, the companion to PSR J0024−7204W) has been found by Edmonds et al. (2002) in 47 Tuc. Moreover, an additional potential MSP companion (W34 in 47 Tuc) has been recently discussed by Edmonds et al. (2003). Fig. 3 shows a comparison of the photometric properties of the available optical identifications of MSP companions hosted in GGCs. The MS stars of NGC6752, the models of CO-WD and two He-WD cooling sequences by Serenelli et al. (2002) are also plotted in Fig. 3 as reference. Two among the five sources seem really peculiar: i.e., the bright object in NGC6397 (which is as luminous as the turn off stars and shows quite red colours) and the faint W29 in 47 Tuc, which is also too red to be a He-WD (Edmonds et al. 2002). Bassa et al. (2003) suggested a similarity between the photometric properties of COM J1911−5958A and W29 in 47 Tuc. As can be seen from Figure 3, COM J1911−5958A is significantly brighter and bluer than W29 and it turns out to be more similar to $U_{opt}$. Indeed, $U_{opt}$ and COM J1911−5958A are found to lie nearly on the same mass He-WD cooling sequence and W34 in 47 Tuc curiously shares the same photometric properties of COM J1911−5958A . Indeed, if confirmed as a MSP companion, W34 would be the third He-WD companion orbiting a MSP in GGCs roughly located on the same-mass cooling sequence. If further supported by additional cases, this evidence could confirm that a low mass $\sim 0.15 - 0.2 M_\odot$ He-WD orbiting a MSP is the favoured system generated by the recycling process of MSPs not only in the Galactic field (Hansen & Phinney 1998) but also in GGCs (Rasio et al. 2000).

COM J1911−5958A is relatively bright and will allow detailed follow-up observations: both optical time series photometry and spectroscopy of this object are planned at the ESO
VLT, in order to determine the parameters of the He-WD companion, the mass ratio of the two components of the binary and eventually the mass of the neutron star.

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Fig. 1.— \((U, U - V)\) and \((B, B - V)\) CMDs for the stars identified in a region of \(80'' \times 80''\) centered at the nominal position of the PSR J1911−5958A. The optical counterpart to the pulsar companion (COM J1911−5958A) is marked with a large empty square. The heavy dashed line is the CO-WD cooling sequence from Wood (1995); the two light dashed lines are the cooling tracks for He WD masses 0.197 and 0.172 \(M_\odot\) (the lowest mass model is the reddest one) from Serenelli et al. (2002). The small triangles along the two tracks labels different ages (1, 2 and 3 Gyr, respectively). The CO-WD population observed in this cluster by Renzini et al. (1996) and Ferraro et al. (1997, 2003b, in preparation) is also plotted as small open circles in the left panel.
Fig. 2.— Finding chart for COM J1911−5958A showing the median-combined B-band image. The region covers 15″×15″, also plotted is the 1σ error circle (0′.3) for the absolute astrometric positioning of the optical image. North is up and East is to the left.
Fig. 3.— Optical companions to MSP detected in GGCs in the \((M_U, (U-V)_0)\) absolute plane: COM J1911−5958A is plotted as in Figure 1, while the other objects with a \textit{large empty square}. As in Figure 1, we present the cooling tracks for He-WD from Serenelli et al. (2002) and the CO-WD cooling sequence from Wood (1995). Main sequence stars of NGC6752 are also plotted \textit{(small open circles)} as reference. Note that \(U_{\text{opt}}\) and COM J1911−5958A appear to lie along the same He-WD cooling sequence. Also W34 in 47 Tuc (if confirmed to be a MSP companion) shares the same photometric properties of COM J1911−5958A. In order to place in the plot the 3 objects belonging to 47 Tuc, the distance modulus \(((m-M)_0 = 13.27)\) and the reddening \((E(B-V) = 0.055)\) of this cluster have been adopted according to Zoccali et al. (2001); the approximate position of COM J1740−5340 (companion to PSR J1740−5340 in NGC6397) in the absolute plane has been obtained by shifting the CMD of Figure 1 of Ferraro et al. (2001b) to match the main sequence of NGC6752.
Table 1. Photometric data and position for COM J1911−5958A

<table>
<thead>
<tr>
<th></th>
<th>$V$</th>
<th>$B$</th>
<th>$U$</th>
<th>$\alpha_{J2000}$</th>
<th>$\delta_{J2000}$</th>
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<td>22.13</td>
<td>22.06</td>
<td>19h 11m 42s743</td>
<td>−59° 58' 26&quot;85</td>
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