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Discovery of millisecond pulsar companions in the globular cluster 47 Tucanae

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Abstract. We present near-ultraviolet and optical *Hubble Space Telescope* observations of the likely white dwarf companions to radio millisecond pulsars 47 Tuc Q, S, T, Y, and the previously identified white dwarf counterpart to 47 Tuc U. All five near-ultraviolet companions show colors that agree with the ones resulting from He-core white dwarf (He WD) cooling models for white dwarf masses $\sim 0.16 - 0.3\ M_{\odot}$. We find that the counterparts to 47 Tuc U and 47 Tuc T show Hα absorption, as is characteristic for white dwarfs with a H envelope, such as He WDs.

Key words. Binaries: general – Globular clusters: individual (47 Tucanae) – Pulsars: general - Pulsars: individual (PSR J0024–7204Q, PSR J0024–7204S, PSR J0024–7204T, PSR J0024–7203U, PSR J0024–7204Y)

1. Introduction

A millisecond pulsar (MSP) is a highly magnetized neutron star that has a spin period $\lesssim 20$ ms. According to the standard formation scenario for MSPs (Alpar et al. 1982), the neutron star has been spun up (until reaching periods of milliseconds) by accretion from a companion star.

Most MSPs in globular clusters (GCs) are found in binary systems. However, only ten

MSP companions have been firmly identified at optical wavelengths so far. The study of the companion gives important information about the binary, for instance about the spin-up process of the pulsar and (in GCs) the effects of dynamical stellar interactions on these binaries. In the standard formation scenario, the MSP is accompanied by a white dwarf (WD). Determining the properties of such WD companions by observations can help to understand the WD cooling process and constrain WD evolutionary models.

47 Tucanae (47 Tuc) is until now the globular cluster with the second highest number of MSPs identified. Of the 25 radio MSPs found, 15 are in a binary, but of those only two companions have been unambiguously identified in the optical. To understand possible differences between MSPs in the field and those in dense stellar environments, such as GCs, evidently we have to increase the sample with more identifications.

2. Data

We have used near-ultraviolet (NUV) and optical *Hubble Space Telescope* (HST) images of 47 Tuc from the programs GO 12950 (filters F300X and F390W) and GO 9281 (filters F435W, F625W and F658N), respectively. The data reduction was done using the Drizzlepac software provided by the Space Telescope Science Institute. Astrometric errors for the optical and NUV images are 0.064″ and 0.074″, respectively. Photometry was done by running the software package DAOPHOT on the stacked (by filter) images, which have a final pixel scale of 0.02″ pixel^{-1} for both NUV frames and 0.025″ pixel^{-1} for the three optical images. For the NUV images, independent photometry was done using the software package KS2 (Anderson et al. 2008). Both NUV photometric results are consistent. For more details about the observations, data reduction and analysis we refer to Rivera-Sandoval et al. (2015).

3. Results

Using the astrometrically calibrated NUV images we detected blue stars inside the 3σ error circles of the radio positions for the MSPs 47 Tuc Q, S, T, U, and Y (Figure 1). All five MSPs have spin periods below 8 ms, and orbital periods between 0.43 and 1.2 d (Freire et al., in prep.; Rivera-Sandoval et al. 2015). All companions were found with an offset smaller than 0.016″ from the radio positions.

Table 1. Mass, total age and bolometric luminosity for the MSP companions identified, as derived from the photometry of our NUV images and our He WD cooling models. A more complete table is given in Rivera-Sandoval et al. (2015).

MSP companion	M_{WD} ($M_\odot$)	Total age (Gyr)	log L ($L_\odot$)
Q_{UV}	0.175 – 0.20	6.2 – 0.7	-1.9 – -1.8
S_{UV}	0.20 – 0.25	0.8 – 0.2	-2.0 – -1.9
T_{UV}	0.20 – 0.30	0.8 – 0.12	-2.0 – -1.8
U_{UV}	0.16 – 0.175	2.1 – 1.6	-0.9 – -0.8
Y_{UV}	0.16 – 0.175	4.0 – 3.1	-1.6 – -1.5

In order to get more information about the MSP companions identified, we fitted He WD cooling tracks from Serenelli et al. (2002) to the obtained NUV photometric results (Figure 1). We found very good agreement between the models and observations. Derived values for masses, total ages (including proto-WD ages) and bolometric luminosities are given in Table 1.

Heinke et al. (2005) found associations between the MSPs in 47 Tuc with X-ray sources detected in the cluster using the *Chandra X-ray Observatory*. We found that the offsets between our detected counterparts and the center of the X-ray error circles are between 0.05″ and 0.25″ for Q_{UV}, T_{UV}, U_{UV}, and Y_{UV} (counterparts to 47 Tuc Q, T, U and Y, respectively); while for S_{UV}, the offset is 0.34″ (the largest among the five counterparts). The most likely reason for this large offset is that 47 Tuc S and the nearby isolated MSP 47 Tuc F are detected as a single, confused X-ray source (W77), with a position in between the radio positions of 47 Tuc S and F. According to Bogdanov et al. (2006), all the binary MSPs here discussed have X-ray luminosities $L_X = 2.9 - 8.9 \times 10^{30}$ erg s^{-1} in the 0.1–10 keV band.

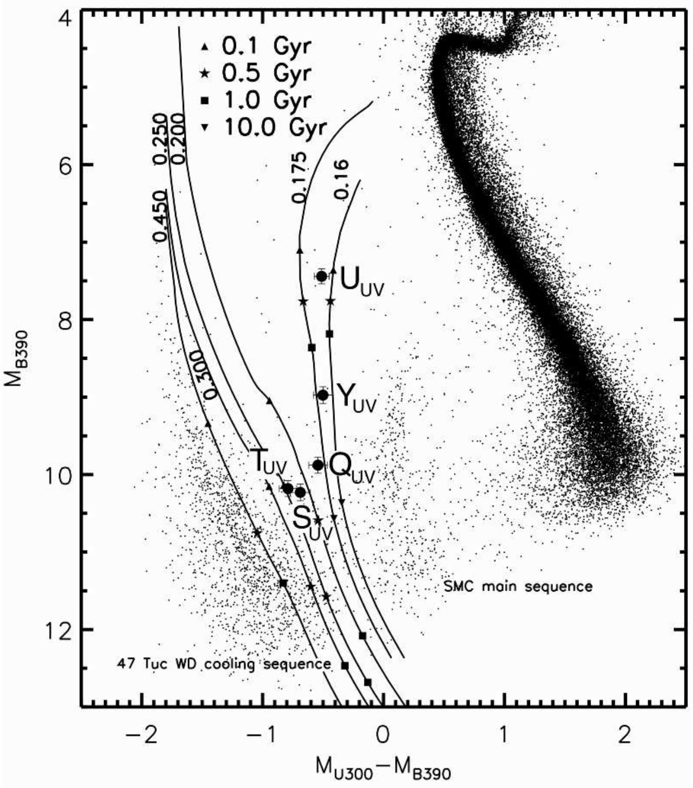

Fig. 1. NUV CMD obtained with DAOPHOT photometry. The MSP companions are marked with circles and the respective letters of the pulsars. The absolute magnitudes were calculated using a distance to 47 Tuc of 4.69 kpc (Woodley et al. 2012) and reddening $E(B-V) = 0.04$ (Salaris et al. 2002). The different lines correspond to He WD cooling models as in Serenelli et al. (2002) computed for an initial metallicity of $Z = 0.003$, as is appropriate for 47 Tuc. The numbers at the top of each line correspond to the mass of the He WD in units of solar mass. A coloured CMD is shown in Rivera-Sandoval et al. (2015)

3.1. NUV results

In the NUV colour magnitude diagram (CMD) of 47 Tuc, the object Q_{UV} is located between the Small Magellanic Cloud (SMC) main sequence and the WD cooling sequence of the cluster. From the He WD cooling models, we found that this object could be the oldest among the five MSP companions identified.

S_{UV} is the faintest He WD among the five reported in this work (Figure 1). For this object we have derived a mass between 0.20 and 0.25 $M_{\odot}$ and a total age up to 0.8 Gyr, including its time spent as proto-WD. In a previous work, Edmonds et al. (2003) detected the companion of 47 Tuc T in the *U* filter. However, due to the presence of a star at only 0.07″ from the WD, this object was not properly identified in optical wavelengths, prohibiting a color measurement. Using NUV images, we unambiguously identified this object and found it in the NUV CMD in a position very close to that of S_{UV}. The counterpart for 47 Tuc U was discovered by Edmonds et al. (2001), who concluded that it is likely a He WD. In the NUV CMD this object is found as the brightest of the five MSP companions reported (Figure 1, Table 2). The nature of Y_{UV} as MSP companion was confirmed in Rivera-Sandoval et al. (2015), where the timing position for 47 Tuc Y was published

Table 2. Astrometric and DAOPHOT photometric results for the MSP counterparts. The numbers in parenthesis correspond to DAOPHOT errors. Errors in the absolute astrometry are 0.074″. A more complete table is given in Rivera-Sandoval et al. (2015).

MSP companion	R. A. (J2000)	Decl. (J2000)	U_{300}	B_{390}	B_{435}	R_{625}	Hα
Q_{UV}	$00^h\ 24^m\ 16.493^s$	–72° 04′ 25.15″	22.95(3)	23.41(4)	23.84(6)	23.6(1)	22.93(8)
S_{UV}	$00^h\ 24^m\ 03.976^s$	–72° 04′ 42.34″	23.16(3)	23.77(5)	23.47(5)	–	–
T_{UV}	$00^h\ 24^m\ 08.551^s$	–72° 04′ 38.92″	23.04(2)	23.72(3)	23.9(1)	23.5(2)	23.4(1)
U_{UV}	$00^h\ 24^m\ 09.836^s$	–72° 03′ 59.69″	20.545(9)	20.98(1)	20.860(5)	20.82(1)	20.84(1)
Y_{UV}	$00^h\ 24^m\ 01.402^s$	–72° 04′ 41.84″	22.09(2)	22.51(5)	22.36(5)	–	–

for the first time. Using NUV images, we confirmed the blue color of Y_{UV}, as suggested previously by Edmonds et al. (2003). From the He WD cooling tracks we estimated that this object, together with Q_{UV}, are possibly the oldest He WD companions among the five discussed in this work.

3.2. Optical results

Because of the stellar crowdedness in 47 Tuc, the identification of the MSP companions at optical wavelengths (particularly in the filters F658N or Hα and F625W or R_{625}) is very difficult. For this reason, optical photometry could be derived only for Q_{UV}, T_{UV} and U_{UV} (Table 2). For the last two objects, we found Hα-R_{625} colors that indicate the presence of a broad Hα absorption line in the optical spectrum, as expected for a WD with a hydrogen envelope. For Q_{UV} there is not evident absorption; however, the optical photometry has considerable errors and might be affected by the presence of bright stars nearby.

3.3. Conclusions

We found that the five MSP companions have NUV colors that are consistent with those of He WDs, as expected from the MSP standard formation scenario. From the fitting of He WD cooling tracks to the NUV magnitudes, we determined the masses, ages and luminosities for all the counterparts. Using the values of the derived parameters for the five He WD companions in this work, together with the formulae given by Paczyński (2002) (assuming a neutron star mass of 1.35 $M_\odot$), we calculated and compared the Roche lobe and WD radii for each companion. We found that the five WDs fit well within their Roche lobe. This indicates that there is no ongoing accretion on the neutron star that could contribute to the X-ray luminosities observed. Also, as we can see from Table 1, we found that the estimated ages of the five WDs (taking into account their proto-WD age) are not larger than 6 Gyr. This value is considerable lower than the age of 47 Tuc (9.9 ± 0.7 Gyr; Hansen et al., 2013). This result could mean that the dynamical interactions during the later evolution of the cluster play a more important role in the origin of MSPs than primordial formation.

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