Mem. S.A.It. Vol. 87, 526

Memorie della

Optical companions to millisecond pulsars in globular clusters

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Abstract. According to the "canonical recycling scenario", millisecond pulsars (MSPs) form in binary systems containing a neutron star that is spun up through mass accretion from the evolving companion. Therefore, the final stage consists of a binary made of the MSP and the core of the deeply peeled star. In the last years, however, an increasing number of systems deviating from these expectations has been discovered, thus strongly indicating that our understanding of MSPs is far to be complete. Within the Cosmic-Lab project we identified 8 new companions to MSPs in Galactic globular clusters (GCs), more than doubling the number of previously known objects, and also reporting the first and unique detections of both a transitional-MSP and two Black-Widow companions in GCs. Moreover we performed a spectroscopic follow-up of the companion to PSRJ1740-5340A in NGC 6397, confirming that it is a deeply peeled star descending from a $\sim 0.8 M_{\odot}$ progenitor.

Key words. pulsars: individual (J0024-7204Q,S,T,Y, J1518+0204C, J1740-5340A, J1824-2452H,I, J1953+1846A) – globular clusters: general

1. Introduction

Millisecond Pulsars (MSPs) are fast rotating, highly magnetized neutron stars (NSs). Accordingly to the *"canonical recycling scenario"* they are thought to form in binary systems containing a slowly rotating NS that, during a phase of heavy mass accretion from an evolving companion, is spun up to millisecond spin period. The final stage consists of a binary made of the MSP and a deeply peeled or even an exhausted star (as a white dwarf; WD). However, in the last years systems deviating from such a scenario have been discovered, revealing that the formation and evolution mechanisms of MSPs are still unclear.

The identification of companions to MSPs in globular clusters (GCs) and the study of their nature is a fundamental step not only to investigate their formation and evolution, but also to quantify the occurrence of dynamical interactions, understand the effects of crowded stellar environments on the evolution of binaries, and determine the shape of the GC potential well (see Pallanca 2014a, and references therein). The study of these targets essentially consists of two steps: first, the photometric identification and characterization of the companion (see Ferraro et al. 2001, 2003a) and then, in the case of a bright object, a spectroscopic follow-up to constrain the orbital parameters of the system and its (likely anomalous) chemical composition (see Sabbi et al. 2003a,b; Ferraro et al. 2003b). Despite the paramount importance of identifying the companion stars to binary MSPs, before this project started, only 6 optical counterparts were known in GCs. Here, we report on the identification of 8 new companions and the spectroscopic follow up of a previously known companion.

2. Photometric and spectroscopic approach

Photometric study Starting from the information obtained from radio observations, the identification of optical companions to MSPs is based on three signatures: positional coincidence, location in the colour-magnitude diagram (CMD) and optical variability. *Positional coincidence:* to identify a MSP companion in a GC a necessary (but not sufficient) condition is the positional coincidence. The pulsar (PSR) position is accurately ($< 0.1''$) known from the radio observations. Therefore it is extremely important to have a good astrometric solution for the optical catalog in order to minimise the number of stars found within the positional error. *CMD position:* a data-set made of multi-band (to derive colors) and deep (to reach the faintest objects) observations, allows us to use the CMD as an important tool to identify and characterize MSP companions. In fact, since different kinds of companions (likely related also to different radio properties) are expected, the CMD position is a good indicator of the nature (degenerate or not) of the companion. In addition, from the CMD position, it is possible to estimate the companion mass through the comparison with theoretical stellar evolutionary models. Finally, if narrow band observations around the wavelength of the Hα transition are available, it is possible to photometrically constrain the presence of Hα excess, likely due to the presence of ionized material. *Variability:* beside the positional coincidence, the main signature of a companion is the presence of a magnitude modulation with a period in agreement with the PSR orbital motion (known from radio observations). Two main light curve shapes are commonly observed: - *"single-hill" shape*: characterized by one maximum (at the pulsar inferior conjunction) and one minimum (at the pulsar superior conjunction), typically associated to heating processes; - *"double-hill" shape*: characterized by two maxima (at quadratures) and two (asymmetrical) minima (at the conjunctions), typically associated to tidal distortions. The light curve is also very helpful to constrain some parameters of the system as the mass ratio, the Roche Lobe (RL) filling factor and the inclination angle. Note that, despite a weak degeneracy between the effects of different mass ratios and inclination angles, the amplitude of the light curve is mainly dependent on the inclination angle and hence this is the most suitable parameter to be constrained. Also a completely filled RL is often required to justify the observed light curve.

Spectroscopic study Because of the current instrumental limits, a spectroscopic follow-up can be performed only for bright companions. *Kinematical analysis:* the measure of the line of sight velocity of the companion is crucial to confirm the membership to the binary system and from the measure of the amplitude variation, once combined with the PSR radial velocity curve, it is possible to estimate the mass ratio independently of the inclination angle. *Chemical analysis:* the measure of the surface abundances of chemical elements is crucial, both to infer stellar parameters (as from Balmer lines in the case of WD companions), and to detect any anomaly (as C depletion and N enhancement, as expected in case of material partially processed by the CNO cycle in the case of a deeply peeled companion).

3. The studied companions

Companions to "canonicals": J0024-7204Q, J0024-7204S, J0024-7204T and J0024-7204Y in 47Tuc. We identified four new counterparts (to MSPs 47TucQ, S, T and Y) in 47 Tucanae. In the CMD, they are located in a region consistent with the cooling sequences of He-WDs with masses between 0.15 and $0.20 M_{\odot}$ (Cadelano et al. 2015). For each identified companion, mass, cooling age, temperature, and NS mass (as a function of the inclination angle) have been derived and discussed. See also Rivera-Sandoval et al. (2015) and Rivera-Sandoval's contribution in this Volume.

Companions to Redbacks (RBs): J1824-2452H and J1824-2452I in M28. The identified companion to the RB M28H is a RL-filled, bloated star, highly perturbed by the NS tidal field. Likely, it is a $0.2 M_{\odot}$, orbiting a $1.4 M_{\odot}$ MSP, in a plane with an orbital inclination of $\sim 60-70°$. The results obtained suggest that it is currently losing mass, and that the system is surrounded by large clouds of gas extending well beyond the RL, which probably is constantly replenished. Its location outside the cluster core suggests that the NS was recycled by another companion and that an exchange interaction occurred causing the ejection of the lightest star and kicking the newly-formed system away from the centre (Pallanca et al. 2010). The companion to the transitional-MSP (T-MSP) M28I showed a strong variability and underwent a significant increase of optical magnitude a few years before the recent X-ray outburst. In particular, during the quiescent state the companion is located along the MS, $\sim$ 3 magnitudes fainter than the turnoff (TO), while during the optical burst it is $\sim$ 2 magnitudes brighter and it is characterized by a bluer color, indicating a perturbed state. Moreover, the presence of strong Hα emission during the optical outburst phase suggests the presence of material accreting onto the NS (Pallanca et al. 2013).

Companions to Black Widows (BWs): J1518+0204C in M5 and J1953+1846A in M71. The companion to M5C is the first identification for a BW in a GC. It is a very faint and strongly variable star, located between the main sequence (MS) and the WD cooling sequences in the CMD. From its CMD position we constrained its effective temperature, luminosity and mass. Considering the largest permitted mass value (Mcom $\sim 0.2 M_{\odot}$) and the PSR mass function, it is possible to rule out very small inclination angles of the system. The magnitudes of this star have been measured in 14 out of 44 analyzed images around the PSR inferior conjunction, while it is under the detection limit at the PSR superior conjunction. A simple sinusoidal model suggests a flux variation due to irradiation, with an amplitude of the light curve larger than 3 mags (Pallanca et al. 2014b). The properties of the companion to M71A are in full agreement with those of the BW in M5. See Cadelano et al. (2015) and Cadelano's contribution in this Volume.

Spectroscopic follow-up of the RB J1740-5340A in NGC 6397 We measured the abundances of C and N in the companion to the RB 6397A, finding that they are incompatible with the values expected on the surface of a MS star. By comparing these abundances with the chemical gradients predicted by theoretical stellar models, we were able to put new constraints on the nature of this object. In particular, this seems to be a star peeled down to an interior layer where the CN-cycle approximately reached the equilibrium. The envelope of the star has been completely removed and, assuming an initial mass of $\sim 0.8 M_{\odot}$, we estimated that it lost $\sim 75\%$ of its initial mass during the interaction with the PSR. The C and N abundances also allowed us to identify a mass range for the MSP companion: only the portion of the stellar model between 0.17 and $0.28 M_{\odot}$ is in agreement with both the observed C and N abundances. This confirms previous mass estimates, demonstrating that the analysis of the C and N surface abundances provides a powerful diagnostic of the companion mass which is totally independent of other, commonly used methods (Mucciarelli et al. 2013).

4. Conclusions

All the discussed objects well fit in the context of MSP classification. In fact the companions to RBs are low mass ($\sim 0.2 M_{\odot}$) stars located close to the MS, a few magnitudes fainter than the TO. The companions to BWs are very low mass objects located in the middle between WDs and MS stars and they appear to be heated by the PSR flux. Instead, as expected, all the companions to canonicals MSPs are He-WDs (see figure 1 for the position in the CMD). In order to clarify the evolutionary history of binary low mass MSPs we tried to sketch a possible scenario (see Figure 9.2

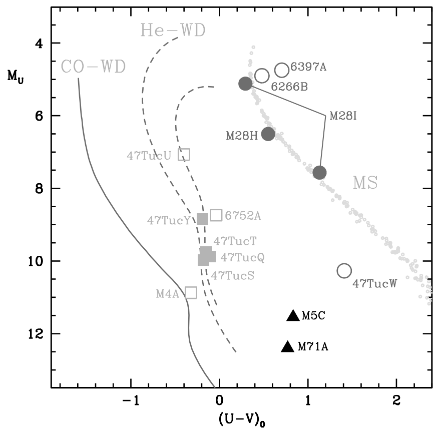

Fig. 1. CMD location of all the known companions to MSPs in GCs. Filled symbols mark the new identifications discussed here. Circles, triangles and squares identify the companions to RBs, BWs and canonicals, respectively. For clarity also the main locus of MS stars and the WD cooling sequences are reported.

in Pallanca 2014a). We tentatively assumed the observed properties of different classes as representative of different evolutionary paths. In particular, from the low-mass X-ray binary (LMXB) phase, MSPs can evolve through a RB phase, during which the MSP is active in the radio band and the companion is bloated (thus producing the typical "double-hill" light curve) and likely it is losing material causing radio eclipses (as in the case of M28H). However, as observed for M28I, there are a few T-MSPs swinging between a radio dominated phase and a X-ray dominated phase, during which the NS is accreting material. The final stage is characterized by what remains of the companion: likely the He-core. On the other hand, MSPs can evolve through BW systems, in which the companions are ablated and probably are semi-degenerate stars, like brown dwarfs surrounded of lost material that produces the long lasting observed radio eclipses (as M5C and M71A). Moreover given the relative faintness of these objects, the illumination by the PSR flux is responsible of the "single-hill" light curve. These systems likely evolve in binaries containing a MSP and a very low mass object (a brown dwarf). If the companions have been completely ablated, they could also evolve in isolated MSPs. Of course in GCs the scenario is even more complex because exchange interactions could happen. In this case, the MSP can acquire a new (more massive) companion, while the original light companion is ejected. Therefore a crucial step forward in our knowledge of MSP formation would be the definition of a diagnostic able to discriminate between the original companion of the NS and a star acquired because of an exchange interaction. A possible clue could be obtained from the location in the GC and the three-dimensional motion in the cluster. In fact, in the case of an exchange interaction, the binary system could be expelled out of the core. For example, M28H is suggested to be the product of a recent exchange interaction because it is located out of the core and, in absence of perturbations, it would have already sunk in the innermost region under the effect of mass segregation. Also the timescales of each phase are unknown. Hence catching a large sample of systems in these peculiar phases and determining their relative frequency would be crucial.

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