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The Timing of Globular Cluster Pulsars at Parkes

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Abstract The Parkes Globular Cluster survey at 1.4 GHz has found so far twelve recycled pulsars in six globular clusters. Timing of these sources as well as follow-up observations at other electro-magnetic bands are providing a wealth of interesting results, which are summarized here.

Key words: pulsar — binary system — globular cluster

1 INTRODUCTION

Recycled pulsars result from the transfer of matter and angular momentum from a mass-donor companion to an old neutron star in a binary system (e.g. Alpar et al. 1982). Most of them are extremely stable clocks, allowing for accurate measurements of their rotational parameters, position and apparent motion in the sky. Coupled with the very compact nature of the underlying neutron star, this fact makes a pulsar to be a magnificent test mass for probing gravitational effects. In fact, recycled pulsars discovered in globular clusters (GCs) have proven to be valuable tools for investigating: *(i)* the potential well of a globular cluster (e.g. Camilo et al. 2000); *(ii)* the dynamical interactions in a globular cluster core (e.g. Phinney & Sigurdsson 1991); *(iii)* the gas content in a globular cluster (e.g. Freire et al. 2001); *(iv)* the neutron star retention in a globular cluster (e.g. Kulkarni et al. 1991); *(v)* the binary evolution in a very dense stellar environment (e.g. D'Amico et al. 2001; Freire et al. 2004); *(vi)* the equation of state for the nuclear matter (e.g. Edwards, van Straten & Bailes 2001; Hessels et al. 2006b). Most of the aforementioned investigations have been the results of extended programs of follow-up timing observations of the millisecond pulsars (MSPs) hosted in a given globular cluster. In particular, if semi-regularly performed for at least 4–5 yrs, these observations (besides refining the values of the basic parameters of a source, i.e. spin rate, position, and, if applicable, orbital period, projected semi-major axis etc) usually allows to attain very high precision in the estimation of further relevant parameters, such as proper motions, higher order spin derivatives or also binary parameters like periastron advance, orbital period derivative and so on.

Of course before being timed a recycled pulsar must be discovered and pulsars in GCs are indeed elusive sources. Their large distances make their flux density typically very small and their signals strongly distorted

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Table 1 Parameters of the Recycled Pulsars Discovered in the PKSGC Survey

Cluster Name	Pulsar Name	$P_{\rm spin}$ ms	DM cm^{-3} pc	$P_{\rm orb}$ days	$a_p \sin i$ lt-s	$M_{\rm c,min}$ $M_\odot$	Offset $R_{\rm core}$
NGC 6266	J1701−3006A	5.24	115.0	3.80	3.48	0.20	2.0
	J1701−3006B	3.59	113.4	0.14	0.25	0.12	0.15
	J1701−3006C	3.80	114.6	0.21	0.19	0.07	1.0
NGC 6397	J1740−5340	3.65	71.8	1.35	1.65	0.19	11
NGC 6441	J1750−3703	111.6	233.2	17.3	24.4	0.58	2.0
NGC 6522	J1803−3002	7.10	193.4	single			4.4
NGC 6544	J1807−2459	3.06	134.0	0.071	1.65	0.009	1.2
NGC 6752	J1911−5958A	3.27	33.7	0.84	1.21	0.19	73
	J1910−5959B	8.36	33.3	single			0.8
	J1911−6000C	5.28	33.2	single			30
	J1910−5959D	9.03	33.3	single			0.6
	J1910−5959E	4.57	33.3	single			0.5

by propagation through the dispersive interstellar medium. In addition, they frequently are members of close binary systems, causing large changes in the observed spin period and sometimes periodic eclipsing of the radio signal. Six years ago we undertook a new search for MSPs in GCs (the Parkes Globular Cluster survey: PKSGC) exploiting the low system temperature (~ 21 K) and the large bandwidth (~ 300 MHz) of the new 20-cm receiver installed at the 64 m Parkes radiotelescope. We have built at Jodrell Bank and Bologna a new high resolution filterbank, made of 512×0.5 MHz adjacent pass-band filters, giving the unprecedented opportunity to probe distant clusters. Also we have implemented a new multi-dimensional code to search over a wide range of accelerations resulting from binary motion, in addition to the standard search over a range of DMs (see Possenti et al. 2003 for a detailed description of data acquisition and processing).

We selected 65 GCs in the framework of the PKSGC survey, with the characteristics of being located in the southern sky, of not having an already known associated pulsar and of having a favourable (i.e. high) ratio between the core density and the square of their distance (both these values derived from optical observation). In Table 1 we list the parameters for the 12 new MSPs which we have discovered so far in six clusters of the aforementioned list. Full precision parameters and related uncertainties are reported in the following papers: D'Amico et al. 2001, D'Amico et al. 2001b, D'Amico et al. 2002, Possenti et al. 2003. These discoveries increased by 25% to the total number (now 24) of globular clusters hosting a known millisecond pulsar. Taking advantage of the availability at the Cagliari Observatory of *Mangusta* (a new large cluster of 60 CPUs), we have completed the regular processing of the collected data at 1.4 GHz, while simultaneously undertaking a re-processing of all the observations, applying a fully coherent search for ultra "accelerated" pulsars. Further data collected at 3.0 GHz are also under analysis.

2 MOST RECENT RESULTS FROM TIMING

2.1 The Peculiar Ejected Pulsars in NGC 6752: Proper Motion and Radial Velocity Determination

The globular cluster NGC 6752 is known to host 5 millisecond pulsars (D'Amico et al. 2001, 2002), which showed, since their discovery, peculiar features. PSR J1910−5959B and PSR J1910−5959E (hereafter PSR B and E) reside in the central region of the GC and show large negative $\dot{P}$ values, which are interpreted as an effect of the GC gravitational potential well. The resulting central mass to light ratio (M/L) is much larger (Ferraro et al. 2003b) than that reported in literature and at least *twice* as large as the typical value $M/L \sim 2-3$ observed in the sample of the core collapsed clusters. Even more unexpected is the position of the pulsars PSR J1911−5958A (hereafter PSR A) and PSR J1911−6000C (PSR C). The first holds the record of being the farthest MSP ($\approx$ 3.3 half mass radii) ever observed from the centre of a globular; PSR-C, an isolated pulsar, ranks second in the list. Their very offset positions naturally rose the question of their being really associated with the globular cluster.

After 5 years of regular timing observations, we have finally derived (Corongiu at el. 2006) the amplitude μ and the position angle PA (with respect to the north) of the proper motions of these two pulsars: $\mu_{\rm A} = 4.9 \pm 0.3$ mas yr^{-1} and PA$_{\rm A} = 219 \pm 3$ deg for PSR A; $\mu_{\rm C} = 6.8 \pm 2.2$ mas yr^{-1} and PA$_{\rm C} = 225 \pm 20$ deg for PSR C (uncertainties are at 2σ). As shown in Figure 1, they appear nicely in agreement with each other within current uncertainties (some years more will be necessary for determining the proper motions of the 3 fainter pulsars close to the cluster center). This fact and the proximity of the two objects in the plane of the sky allowed us to estimate that the joint probability $\mathcal{P}$ for the positional and kinematic characteristics of PSR A and PSR C to be due to chance (i.e. due to two Galactic field pulsars unrelated to NGC 6752) is $\mathcal{P} < 10^{-5}$. With this result in publication, the association of the binary PSR A with NGC 6752 has been strengthened furthermore by the measurement (Cocozza et al. 2006) of the radial velocity $V_{\rm PSRA}$ of the center of mass of the binary system. This was possible thanks to spectroscopic observations performed on 2004 of the pulsar companion, identified back in 2003 as a Helium white dwarf (Bassa et al. 2003; Ferraro et al. 2003c). It turns out to be $V_{\rm PSRA} = -28.1 \pm 4.9$ (1σ uncertainties), fully in agreement[1] with the radial velocity of NCG 6752, $V_{\rm NGC6752} = -27.9 \pm 0.8$ (Harris 1996, catalog revision 2003).

With the issue of PSR A's and C's cluster membership settled, we are left with the question: is there any relation between their peculiar positions in NGC 6752 and the high mass to light ratio in the innermost region of the cluster? In fact the strong gravitational pull experienced by PSR B and PSR E could be explained with $\sim 1\,000\ M_\odot$ of low luminosity unseen matter (Ferraro et al. 2003b) enclosed within the central 0.08 pc of the cluster. Given the observed shape of the cluster density profile, it could be most probably due to: *(a)* a very high concentration of white dwarfs or neutron stars; *(b)* a central (single or binary) intermediate mass black hole. On the other hand, *(b)* appears a viable hypothesis to account for the unprecedented positions of PSR A and PSR C. Their locations contrast that expected on the basis of mass segregation and call for the occurrence of recent dynamical events that propelled the pulsars from the core to the cluster outskirts. These ejections are much more probable if the scattering target is significantly more massive than the propelled system and that strongly favors a scenario involving black-hole(s). In particular it has been shown that a double black-hole of intermediate mass ($\sim 100\ M_\odot$) could explain the location of the ejected pulsars (Colpi, Possenti & Gualandris 2002; Colpi, Mapelli & Possenti 2003), satisfy the requirements of the star density profile (Ferraro et al. 2003b) and properly fit the dynamical evolution of the cluster (Sigurdsson 2002).

The surprises in the study of the pulsars in NGC 6752 are far from finished. For instance, it must be still understood the discrepancy between the proper motions of PSR A and PSR C and that (measured in the optical band) of the whole cluster (Corongiu et al. 2006): see Figure 1. In addition, according to the analysis of Cocozza et al. (2006), the light curve from the companion to PSR A would result different with respect to those of all the other pulsar companions detected so far: a result at variance with that obtained by Bassa et al. (2006).

2.2 The Predominance of Binaries in NGC 6266: a Pre-Core Collapse Signature?

The Parkes Globular Cluster Search discovered 3 recycled pulsars in the globular cluster NGC 6266 (D'Amico et al. 2001; Possenti et al. 2003). The inferred luminosities of the MSPs A, B and C ($\sim 10-20$ mJy kpc^2 at 1 400 MHz: Possenti et al. 2003) place them in the brightest end of the luminosity function of the MSPs in GC, entailing the possible existence of many slightly dimmer MSPs in NGC 6266. In fact three more fainter sources have been subsequently detected by Jacoby et al. (2002), exploiting the higher sensitivity of the Green Bank Telescope. Even more interesting, a *Chandra* pointing revealed the presence in the inner part of the globular of few tens of X-ray sources (Pooley et al. 2003), whose colours suggest that NGC 6266 should harbour tens of MSPs.

At variance with the other GCs in which at least five pulsars have been discovered (Ter5, 47Tuc, M28, M15, M5, M13, NGC6440, NGC 6752, and NGC6624), all the 6 known millisecond pulsars in NGC 6266 are bound in binaries. The absence of known isolated pulsars cannot be explained invoking a selection effect since, for a given spin period and flux density, an isolated MSP is easier to detect than a binary MSP. Unfortunately, the observational biases affecting the fraction $\mathcal{F}_{\rm is}$ of isolated pulsars discovered in a given cluster (with respect to the total observed MSP population) are difficult to quantify precisely. Considering all the other clusters, $\mathcal{F}_{\rm is} \geq 2/5$. If this ratio applies to NGC 6266, the probability of having the first six detected pulsars be all binary is $\leq 5\%$. If this absence of isolated pulsars in NGC 6266 is not a statistical fluctuation, it must relate to the mechanisms of formation of these objects and their interplay with the dynamical state of the cluster. In this respect, it has been recently shown (Beccari et al. 2006) that the star density profile of NGC6266 is well reproduced by a standard King model with an extended core ($\sim 19''$) and

[1] See Bassa et al. (2006) for a different interpretation of the same spectroscopic data.

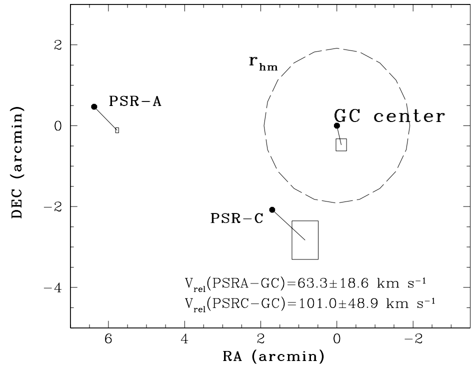

Fig. 1 Comparison among the expected drifts (assuming uniform motion) after 10^4 years for NGC 6752 as a whole, PSR A, and PSR C. Each drift is represented by a line drawn from the position of the pulsars and of the cluster center and a box whose amplitude represents the uncertainties (at 2σ) on the determination of the proper motion. The units on both right ascension and declination axes are arcmin. The dashed circle represents the portion of the cluster enclosed within the half-mass radius. Proper motion uncertainties for the pulsars are from Corongiu et al. (2006), while the uncertainties for the optical proper motion of the cluster are from Dinescu et al. (1999).

a modest value of the concentration parameter ($c = 1.5$), indicating that the cluster has not-yet experienced core collapse. Hence, detailed numerical simulations would be helpful in investigating if trapping of almost all the neutron stars in close binary systems can really occur during the phase immediately preceding the core collapse of a globular. An alternate possibility is that all the known millisecond pulsars have been created in a "burst" very recently: thus, they have not had enough time to ablate their companions away or to experience a dynamical interaction leading to the ionization of the binary.

2.3 The Eccentric Pulsar in NGC 6441: a Heavy White Dwarf or a Neutron Star Companion?

In NGC 6441 (Possenti et al. 2001) a mildly recycled radiopulsar has been found: PSR J1750−3703 (three further recycled radiopulsars have been subsequently discovered in this cluster from observations performed at the Green Bank Telescope, Ransom et al. 2006a). PSR J1750−3703 orbits a companion whose minimum mass is $0.58\ M_\odot$. This fact and the large orbital eccentricity ($e = 0.71$) favor two interpretations for the nature of the system: *(a)* a pulsar orbiting a star (a heavy white dwarf or a main sequence star) acquired during an exchange interaction in the cluster core; *(b)* a double neutron star binary. The available data span of timing observations has already allowed us to get a determination of the periastron advance (and hence on the total mass) of the system. However, the resulting limits on the total mass of the binary $2.03\ M_\odot < M_{\rm TOT} < 2.27\ M_\odot$ (2σ) do not allow us to safely discriminate between the two aforementioned hypotheses.

2.4 PSR J1740−5340 in NGC 6397: Archetype of the Class of High-Mass Black-Widow Pulsars

The recyled pulsar (PSR J1740−5340) harboured in NGC 6397 displays unique features: it is a member of a binary with a relatively large orbital period of 1.35 days, but nevertheless it undergoes eclipses for about 40% of the orbit at 1.4 GHz (D'Amico et al. 2001b) and sometimes shows striking irregularities in the radio pulsation even at the inferior conjunction, i.e. when the pulsar is at the closest distance from us. Light curves (Ferraro et al. 2001; Orosz & van Kerkwijk 2003; Kaluzny et al. 2003) and spectroscopic observations (Ferraro et al. 2003) of the optically identified companion (Ferraro et al. 2001) suggest that it must have a mass in the interval 0.22–0.32 $M_\odot$ and completely (or almost completely) fill its Roche lobe. These facts, combined with radio measurements, indicate that the companion may be either *(i)* the remnant of the star that spun up the pulsar (Ferraro et al. 2001) and is now experiencing the so-called *radio-ejection* phase (Burderi, D'Antona & Burgay 2002), *(ii)* a star which exchanged its position in the binary with that of the star which originally spun-up the pulsar (Grindlay et al. 2002), *(iii)* a sub-subgiant resulting from a binary-binary encounter in the cluster core (Orosz & van Kerkwijk 2003) or *(iv)* a combination of the cases (i) and (ii) (King, Davies & Beer 2003). The latter hypothesis seems favoured by the recent discovery of similar systems in other clusters (e.g. Ter 5, Ransom et al. 2005). In this case, PSR J1740$-$5340 would be the archetype of a new class of binary pulsars, which we name *high mass black-widow* pulsars, in which the mass loss is driven by the nuclear evolution of the companion (King, Davies & Beer 2003), rather than by the mechanism of ablation. The latter is believed to hold in the case of the ordinary *black-widow* pulsars, orbiting low mass almost completely swelled companion stars.

In all cases, PSR J1740$-$5340 appears the best available target for studying how the pulsar energetic flux interacts with the plasma released by the companion: the complex structure of the H_α emission line (Sabbi et al. 2003) could be a confirmation that the *radio-ejection* mechanism is indeed at work in this system; the presence of He-lines in absorption may be ascribed to a hot barbecue-like strip on the companion surface heated by a highly anisotropic pulsar flux (Sabbi et al. 2003); the enhanced Litium abundance can result from nuclear reactions triggered by accelerated particles flowing from the pulsar (Sabbi et al. 2003b). The evidence for an enhanced Litium abundance and for the presence of He-lines in absorption are particularly intriguing, since the refined value of the spin-down power of PSR J1740$-$5340 ($\dot{E} \sim 3.3 \times 10^{34}$ erg s^{-1}) should not be high enough for producing strong effects of irradiation on the companion surface facing the pulsar (Orosz & van Kerkwijk 2003).

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