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DISCOVERY OF SHORT-PERIOD BINARY MILLISECOND PULSARS IN FOUR GLOBULAR CLUSTERS

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ABSTRACT

We report the discovery using the Parkes radio telescope of binary millisecond pulsars in four clusters for which no associated pulsars were previously known. The four pulsars have pulse periods lying between 3 and 6 ms. All are in circular orbits with low-mass companions and have orbital periods of a few days or less. One is in a 1.7-hour orbit with a companion of planetary mass. Another is eclipsed by a wind from its companion for 40% of the binary period despite being in a relatively wide orbit. These discoveries result from the use of improved technologies and prove that many millisecond pulsars remain to be found in globular clusters.

Subject headings: globular clusters: individual (NGC 6266, NGC 6397, NGC 6544, NGC 6752) — pulsars: general — binaries: close

1. INTRODUCTION

Globular clusters are a rich source of millisecond pulsars. Besides the evolution of primordial binary systems, exchange interactions in their core result in the formation of binary systems containing neutron stars. These systems subsequently evolve, spinning up the neutron star through mass accretion (Smarr & Blandford 1976; Bhattacharya & van den Heuvel 1991; Kulkarni & Anderson 1996). The millisecond pulsars formed in this way are among the most stable clocks in nature and are valuable for studies of the dynamics of clusters, the evolution of binaries embedded in them, and the interstellar medium (Phinney 1992; Hut et al. 1992; Bhattacharya & Verbunt 1991; Freire et al. 2000). However, they are difficult to find because the pulsed emission is weak and distorted by propagation through the interstellar medium, and the apparent pulse period may change rapidly because of binary motion. We have constructed a new high resolution filterbank system to improve the sensitivity to pulsars with high dispersion measure (DM) and we have implemented a new multi-dimensional code to search over a range of DMs and over a range of accelerations resulting from binary motion. Using these new capabilities, we have undertaken a search of globular clusters for millisecond pulsars. So far, we have discovered four millisecond pulsars in four clusters, none of which had previously known pulsars associated with them. All of these pulsars are members of short-period binary systems, and two of them have relatively high DM values. These detections bring the number of clusters containing known pulsars to 16.

2. OBSERVATIONS AND RESULTS

The new discoveries were made during a search of globular clusters using the Parkes 64-m radio telescope and the dual-polarization center beam of the multibeam receiver (Staveley-Smith et al. 1996) centered at 1374 MHz. With a system temperature of ~ 21 K and bandwidth of 256 MHz, this receiver has very high sensitivity. The effects of interstellar dispersion were removed by using a filterbank having 512×0.5-MHz contiguous frequency channels for each polarization. This new filterbank system has sufficient resolution to allow detection of millisecond pulsars with DMs of more than 200 cm^{-3} pc at frequencies around 1400 MHz. Signals from individual channels are detected, added in polarization pairs, high-pass filtered, integrated and 1-bit digitized every 125 μs, and then recorded on magnetic tape for off-line analysis. With an integration time of up to 2.3 hours per cluster, the nominal (8σ) sensitivity to a typical 3 ms pulsar with DM ~ 200 cm^{-3} pc is about 0.14 mJy, several times better than previous searches. The half-power width of the telescope beam at 1374 MHz is 14 arcmin, encompassing most or all of the mass of the target clusters.

Off-line processing is performed on a cluster of Alpha-500 CPUs at the Osservatorio Astronomico di Bologna or on the Cray T3E multiprocessor system of the CINECA Supercomputing Center, near Bologna, Italy. Each data stream is split into non-overlapping segments of 2100, 4200 or 8400 sec and these are separately processed. Data are first de-dispersed over a wide range of dispersion measures centered on the value expected for each cluster on the basis of a model of the Galactic electron layer (Taylor & Cordes 1993). Two different search algorithms were used at different phases of the search. Initially, the time domain data were interpolated to compensate for an acceleration and then transformed using a Fast Fourier Transform (FFT), with many trials to cover the expected acceleration range (cf. Camilo et al. 2000). Since this analysis involves many FFTs, it is relatively slow. Later analyses exploited the fact that even highly accelerated binaries have significant spectral power in a zero-acceleration FFT. Time-domain data were fast-folded at periods corresponding to spectral features above a threshold to form a series of 'sub-integration arrays' and these arrays were searched for the parabolic signatures of an accelerated periodicity. Parameters for final pulse profiles having a signal-to-noise ratio above 8 were output for visual examination.

Figure 1 shows time-resolved and average pulse profiles for the four new pulsars. The time-resolved diagrams shown in the top panels of the figure are the sub-integration arrays used in the fast folding. Parameters for the four pulsars and the associated globular clusters are given in Table 1. For PSR J1807–24, these result from a coherent phase fit using the timing pro-

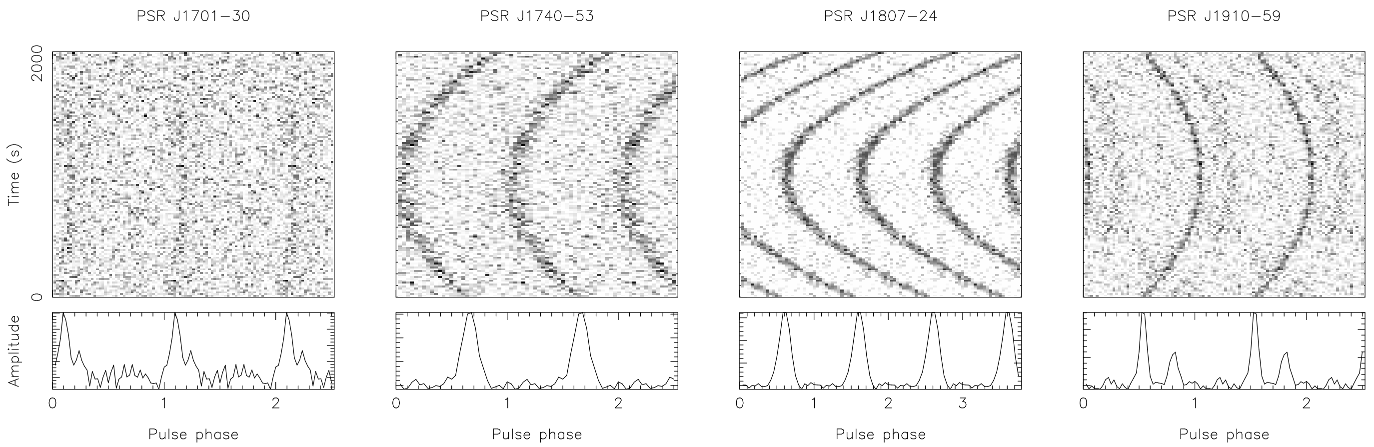

Fig. 1.— Time-resolved (upper panels) and integrated (lower panels) pulse profiles for the four new binary millisecond pulsars over a 2100-sec observation. Each horizontal line in the upper panels represents the mean pulse profile for 16 seconds of data folded with the mean period value indicated by the spectral analysis. A pulsar with a stationary period would form a straight trace in this diagram. The integrated pulse profile for PSR J1910−59 has two widely separated components. PSR J1701−30 may have significant emission in the interpulse region.

gram TEMPO[1]. Parameters for PSRs J1701–30 and J1740–53 are derived by fitting observed periods obtained from short observations (typically 30 min) with a binary model. For PSR J1910–59, the values are obtained by fitting to the period and acceleration values measured at various epochs (see §2.4). Uncertainties are given in parentheses and refer to the last quoted digit. Except for PSR J1910–59, the quoted epoch is the time of ascending node of the binary motion. The mass function, $f(M_p) = M_c^3 \sin^3 i/(M_p+M_c)^2$, where M_p and M_c are the pulsar and companion masses, is computed from the observed binary parameters. A minimum mass for the companion may be derived from this by assuming an edge-on orbit, i.e., $i = 90°$, and a pulsar mass $M_p = 1.35$ M$_\odot$. Flux densities are approximate only and are estimated from the system sensitivity and observed signal-to-noise ratio. PSR J1740–53 is eclipsed for part of its orbit, and the quoted flux density refers to epochs away from eclipse. PSR J1910–59 scintillates markedly and the quoted flux density is an estimated mean value including the non-detections. Cluster parameters are from the compilation of Harris (1996)[2]. The telescope beam was centered on the nominal cluster position. z is the perpendicular distance from the Galactic plane, and DM sin $|b|$, where b is the Galactic latitude, is the 'z- component' of dispersion measure.

The four pulsars have pulse periods lying between 3 and 6 ms and all are in circular orbits with relatively low-mass companions. Two of them (PSRs J1701–30 and J1807–24) have relatively high DM and would not be detectable without the use of the new filterbank system. The orbital periods range from 3.8 days down to only 1.7 hours for PSR J1807–24. Three of them (PSRs J1740–53, J1807–24 and J1910–59) show significant acceleration over a relatively short time scale. While PSRs J1740–53 and J1807–24 are relatively strong, PSR J1910–59 is rather weak and would not be easily detectable using conventional 'non-accelerated' search codes.

All four of the associated clusters are relatively nearby, have high central luminosity densities $L_0 \sim 10^5$ L$_\odot$ pc^{-3}, and concentrated cores. NGC 6397 and NGC 6544 lie within the top four places of a list of globular clusters (Harris 1996) ordered by either distance from the Sun or central luminosity density.

[1]http://pulsar.princeton.edu/tempo

[2]see update at http://physun.mcmaster.ca/Globular.html

2.1. *PSR J1701–30 in NGC 6266*

PSR J1701–30 has the longest pulse period of the four pulsars, 5.24 ms. The orbital period, 3.8 days, is also the longest of the four, and the mass function gives a minimum companion mass of 0.19 M$_\odot$. The parameters in Table 1 are derived from a fit to 17 independent measurements of the apparent pulse period between 1999 December and 2000 July. This system is typical of many low-mass binary pulsars, either associated with globular clusters or in the Galactic disk (Camilo et al. 2000). Its companion is probably a low-mass helium white dwarf. The host cluster, NGC 6266, is listed in the catalogue as having a collapsed core, although this is not certain (Djorgovski 1993).

2.2. *PSR J1740–53 in NGC 6397*

NGC 6397 is a prime candidate for globular cluster pulsar searches (e.g., Edmonds et al. 1999). As mentioned above, it is close and has a very dense and probably collapsed core (King, Sosin, & Cool 1995). Between 2000 July 20 and July 28, PSR J1740–53 was observed on 26 occasions but only detected on about half of these. The observed variations in apparent pulsar period over the July observing session allowed determination of the orbital parameters listed in Table 1. When the observed signal strength was plotted against orbital phase (Fig. 2), it became clear that the pulsar was not seen at orbital phases between about 0.05 and 0.45. These non-detections are centered on orbital phase 0.25 when the pulsar is most distant from the Earth and hence most likely to be eclipsed by a wind emanating from the companion. Similar eclipses have been seen in other binary systems, for example, PSR B1957+20 (Fruchter et al. 1990), PSR B1744–24A in the cluster Terzan 5 (Lyne et al. 1990; Nice & Thorsett 1992) and PSR J2051–0827 (Stappers et al. 1996). All of these are very close binary systems with orbital periods of just a few hours and very light companions (minimum mass < 0.1 M$_\odot$). Creation of the eclipsing wind by ablation of the companion by energetic particles from the pulsar is a viable mechanism in these cases (Rasio, Shapiro, & Teukolsky 1991; Thompson et al. 1994).

TABLE 1
OBSERVED AND DERIVED PARAMETERS FOR FOUR MILLISECOND PULSARS AND THEIR ASSOCIATED CLUSTERS

Pulsar	PSR J1701–30	PSR J1740–53	PSR J1807–24	PSR J1910–59
Period (ms)	5.2415660(4)	3.6503298(3)	3.0594487974(3)	3.266182(3)
Epoch (MJD)	51698.415(2)	51615.658(4)	51734.97510(1)	51745.0
DM (cm^{-3} pc)	114.4(3)	71.8(2)	134.0(4)	34(1)
Orbital period (days)	3.805(1)	1.3541(1)	0.071092(1)	0.865(5)
a sin$i$ (light-s)	3.48(1)	1.66(2)	0.01220(3)	1.27(4)
Mass function ($M_\odot$)	0.0031	0.0027	3.85×10^{-7}	0.0029
Minimum companion Mass ($M_\odot$)	0.19	0.18	0.009	0.19
Flux density (mJy)	0.2	1.0	1.3	0.2
Luminosity (mJy kpc^2)	10	5	8	3
DM sin $\|b\|$ (cm^{-3} pc)	14.7	14.8	4.9	14.4
Cluster	NGC 6266	NGC 6397	NGC 6544	NGC 6752
R. A. (J2000)	$17^{h}01^{m}12^{s}.6$	$17^{h}40^{m}41^{s}.3$	$18^{h}07^{m}20^{s}.6$	$19^{h}10^{m}51^{s}.8$
Dec. (J2000)	$-30^\circ06'44''$	$-53^\circ40'25''$	$-24^\circ59'51''$	$-59^\circ58'55''$
Galactic longitude	353.6	338.2	5.8	336.5
Galactic latitude	+7.3	–11.9	–2.2	–25.6
Distance (kpc)	6.7	2.2	2.5	3.9
z (kpc)	+0.85	–0.45	–0.10	–1.7
Log(L_0)($L_\odot$ pc^{-3})	5.15	5.69	5.78	4.92
r_{core} (arcmin)	0.18	0.05	0.05	0.17
r_{tidal} (arcmin)	9	16	2.1	55

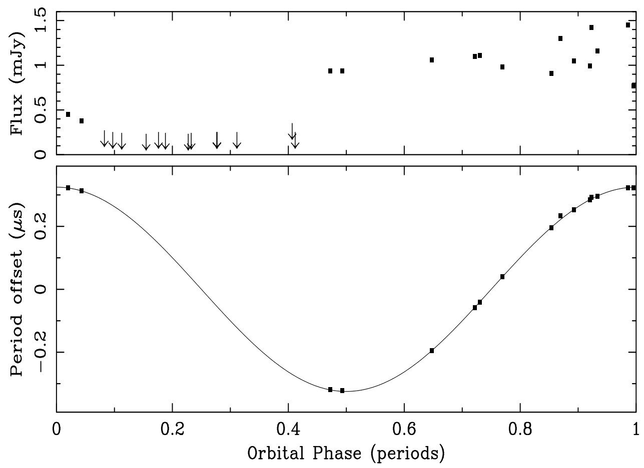

Fig. 2.— Observed offsets in the apparent pulse period of PSR J1740–53 in NGC 6397 (corrected to the solar-system barycenter) from the mean value of 3.650330 ms, and observed flux values through the orbital period. Each point corresponds to an observation of 2100 sec duration. The arrows in the upper plot indicate upper limits from observations where the pulsar was not detected.

In contrast, PSR J1740–53 is in a rather wide binary orbit of period 1.35 days. Assuming a typical surface dipole magnetic field of 5×10^8 G for the pulsar, the resulting energy loss rate $\dot{E}_{35}\sim0.5$ (where $\dot{E}_{35}$ is the spin-down luminosity in units of 10^{35} erg s^{-1}) implies a pulsar wind energy density impinging on the companion significantly less than that estimated for other close eclipsing systems. It seems unlikely that a wind of sufficient density could be driven off a degenerate companion, because the optical depth at 1.4 GHz for free-free absorption τ_{ff} scales as the 7^{th} power of the orbital separation (Rasio, Shapiro, & Teukolsky 1991).

Another possibility is that the orbital inclination is rather small, $\sim20^\circ$, and the companion is a normal star of mass comparable to the turn-off mass of the cluster, ~0.8 $M_\odot$. Although such a star (of radius $\gtrsim0.8R_\odot$) is well inside its Roche Lobe ($R_{RL}=2.2R_\odot$), it presents a much larger cross-section and has a more loosely bound atmosphere than a lighter degenerate companion, favoring the release of a wind sufficiently dense to produce the eclipse (Podsiadlowski 1991). In this case, for low wind temperatures, $T\sim10^4$ K, free-free absorption alone could be a viable eclipse mechanism with $\tau_{ff}\sim2\times10^3\,T_4^{-3/2}v_8^{-6}(f\,\dot{E}_{35})^2$, where T_4 and v_8 are the temperature and the wind terminal velocity in units of 10^4 K and 10^8 cm s^{-1} and f represents the efficiency of conversion of the pulsar spin-down energy in an outflow of matter from the companion. For hotter winds ($T\gtrsim10^5$ K) other absorption processes may need to be invoked (Thompson et al. 1994).

2.3. *PSR J1807–24 in NGC 6544*

NGC 6544 is also one of the closest, densest and most concentrated globular clusters known. A radio continuum source of flux density 1.2 mJy was discovered at its center by Fruchter & Goss (2000), but up to now, pulsar searches have been unsuccessful. PSR J1807–24 is the strongest of the four pulsars with a mean flux density at 1374 MHz of 1.3 mJy. This is very similar to the flux density of the radio continuum source and it is almost certain that most or all of the radio flux from this source is from the pulsar. We have assumed the continuum source position, R.A.(J2000) $=18^{h}07^{m}20^{s}.24$, Dec.(J2000) $=-24^\circ59'25''.3$, when deriving the pulsar spin and orbital parameters given in Table 1. This position is about 26 arcsec from the nominal cluster center.

Timing observations of the pulsar were conducted using the 76-m Lovell Telescope at Jodrell Bank Observatory at a central frequency of 1396 MHz. A coherent fit to a total of 99 pulse times of arrival over a 7-day period starting on 2000 July 7 gave timing residuals with an rms of 94 μs. The resulting parameters are given in Table 1 which shows that the orbital period is extremely short, 1.7 hours, the second shortest known. Even more interestingly, the projected semi-major axis of the orbit is tiny, only 12 light-ms. The corresponding minimum companion mass is only 0.009 $M_\odot$ or about 10 Jupiter masses. Apart from the planetary system around PSR B1257+12 (Wolszczan & Frail 1992; Wolszczan 1994), this is the least massive pulsar companion known. There is no evidence for any eclipse of PSR J1807–24 or significant dispersive delay, unlike many other pulsars with low-mass companions which are eclipsed by a wind from the companion during part of the orbit. This is somewhat surprising as the pulsar and companion are only about 500,000 km apart and ablation by the pulsar radiation might be expected to be strong. One possibility is that the system has a small inclination angle so that it is more face-on. In this event the companion mass would be somewhat larger than the minimum value and hence the system may be similar to eclipsing systems such as PSR B1957+20. Alternatively, the companion may in fact be very light and of a different structure or composition to those of the eclipsing systems, for example, a low-mass brown dwarf or massive planet. This pulsar was independently discovered by Ransom et al. (2000).

2.4. *PSR J1910–59 in NGC 6752*

NGC 6752 is believed to have a collapsed core although it is less centrally concentrated than NGC 6397 (Ferraro et al. 1997). The cluster also has a large proportion of binary systems in its core (Ramachandran & Bhattacharya 1997). PSR J1910–59 was discovered in 4 consecutive data sets of length 2100 sec, recorded at Parkes on 1999 October 17, showing a significant acceleration (~ -2.2 m s^{-2}) on each data set. The pulsar has a relatively low DM, 34 cm^{-3}pc, and it is therefore not surprising that it scintillates strongly, similar to the pulsars in 47 Tucanae (Camilo et al. 2000). Because of this and its low mean flux density (Table 1), it is difficult to detect, with only seven successful observations so far out of 20. These are insufficient to allow determination of the binary parameters by fitting to apparent periods. However, the orbital parameters have been obtained by using the method recently described by Freire, Kramer, & Lyne (2000). This primarily involves fitting an ellipse to observed values of period and acceleration at different epochs. The orbital period is about 21 hours and the minimum companion mass is 0.19 $M_{\odot}$. Apart from the shorter orbital period, this system is very similar to that in NGC 6266 and is typical of binary systems with a low-mass helium white dwarf companion.

3. IMPLICATION FOR THE GALACTIC ELECTRON DISTRIBUTION

Because of their known distances, pulsars in globular clusters provide an important constraint on the distribution of free electrons in the interstellar medium. In particular, most are at relatively large z-distances and hence they place an important constraint, in fact essentially the only constraint, on the 'vertical' extent of the Galactic electron layer. Table 1 lists the parameter DM sin $|b|$, the 'vertical' component of the dispersion measure. The three pulsars at larger z-distances have remarkably similar values of this parameter. These values are consistent with those of other clusters at similar z-distances (Bhattacharya & Verbunt 1991) and indicate a scale height for the electron layer of between 500 and 1000 pc in directions toward the Galactic Center. The remaining cluster, NGC 6544, lies within the electron layer and has a value for DM sin $|b|$ consistent with values for other pulsars with similar independently measured z-distances.

4. CONCLUSIONS

We have discovered short-period binary millisecond pulsars in four globular clusters which contained no previously known pulsars. These detections break the long hiatus in such discoveries and will help in the current understanding of millisecond pulsars in globular clusters. In fact, the four clusters presented here are very close and dense, and the absence of millisecond pulsars in their core was rather intriguing. The new discoveries result from the use of enhanced receiving systems having low system noise, wide bandwidths and good frequency resolution, combined with the use of high-speed data acquisition systems and improved search algorithms operating on powerful computing systems. They demonstrate that many millisecond pulsars, especially those in short-period binary systems, remain to be discovered in the globular clusters of our Galaxy. Such systems provide important constraints on the formation and evolution of binary systems in clusters and are significant in investigations of cluster dynamics. At present, it is not at all obvious why some clusters (e.g., 47 Tucanae) have large numbers of detectable pulsars, whereas other apparently similar clusters (e.g., NGC 6544) have few or none.

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