

# New Millisecond Pulsars in Globular Clusters

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**Abstract.** A new search of globular clusters for millisecond pulsars is in progress at Parkes. In this paper we describe the motivation, the new hardware and software systems adopted, the survey plan and the preliminary results. So far, we have discovered ten new millisecond pulsars in four clusters for which no associated pulsars were previously known.

## INTRODUCTION

Exchange interactions in the core of globular clusters result in the formation of binary systems containing neutron stars. In these systems, the neutron star is eventually spun up through mass accretion from the evolving companion [1–3], resulting in the formation of millisecond pulsars. These objects are valuable for studies of the dynamics of clusters, the evolution of binaries, and the interstellar medium [4–7]. But searches for millisecond pulsars are difficult because they are usually rather weak and their signals are distorted by propagation through the interstellar medium, and because the apparent spin period may be affected by doppler-shift changes due to binary motion.

After several discoveries, made mainly in the early 1990s, no additional pulsars were found in globular clusters, leaving the question open why some clusters (e.g. 47 Tucanae or M15) had large numbers of detectable pulsars, whereas other apparently similar clusters have few or none.

When, a few years ago, a new multibeam 20-cm receiver was installed at Parkes, we decided to initiate a new search of globular clusters for millisecond pulsars. This receiver has a system temperature of  $\sim 21$  K and bandwidth of  $\sim 300$  MHz, resulting in an unprecedented sensitivity. In order to further improve our search capability, we have constructed at Jodrell Bank and Bologna a new high resolution filterbank system, made of  $512 \times 0.5$  MHz adjacent pass-band filters. This makes possible to remove the effects of dispersion in the interstellar medium more efficiently than previous searches, and allows the detection of millisecond pulsars with dispersion measures (DMs) of more than  $200 \text{ cm}^{-3}\text{pc}$ . The combination of this new equipment with the relatively high frequency of the multibeam receiver and its sensitivity level gives a unique opportunity to probe distant clusters. Also, because globular clusters are known to contain short-binary period millisecond pulsars, and because this class of objects is a very interesting one, we have implemented a new multi-dimensional code to search over a range of accelerations resulting from binary motion, in addition to the standard search over a range of DMs. So far, we have discovered 10 millisecond pulsars in four clusters, none of which had previously known pulsars associated with them. Five of these pulsars are members of short-period binary systems, and four of them have relatively high DM values.

## OBSERVATIONS AND RESULTS

We have selected about 60 clusters, on the basis of their central density and distance. Observations consist usually of a 2.3h integration on each target. The resulting nominal ( $8\sigma$ ) sensitivity to a typical 3 ms pulsar with  $\text{DM} \sim 200 \text{ cm}^{-3} \text{ pc}$  is about 0.14 mJy, several times better than previous searches. Sampling the 512 channels every  $125 \mu\text{s}$ , each observation produces a huge array, 32 Gsamples, or 4 Gbytes (packing the data at 1-bit/sample), and requires significant CPU resources for offline processing. In Bologna, we have implemented the new code on a local cluster of Alpha-500MHz CPUs and on the Cray-T3E 256-processor system at the CINECA Supercomputing Center.

In the off-line processing, each data stream is split into non-overlapping segments of 2100, 4200 or 8400 sec and these are separately processed. When the DM is not known precisely from the existence in a given cluster of a previously known pulsar, 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 [8], and then transformed using a Fast Fourier Transform (FFT). The analysis method exploits the fact that even relatively highly accelerated binaries might have significant spectral power in the FFT. Time-domain data are fast-folded at periods corresponding to a significant number of spectral features above a threshold to form

a series of ‘sub-integration arrays’ and these arrays are searched for the parabolic signatures of an accelerated periodicity. Parameters for final pulse profiles having significant signal-to-noise ratio are output for visual examination.

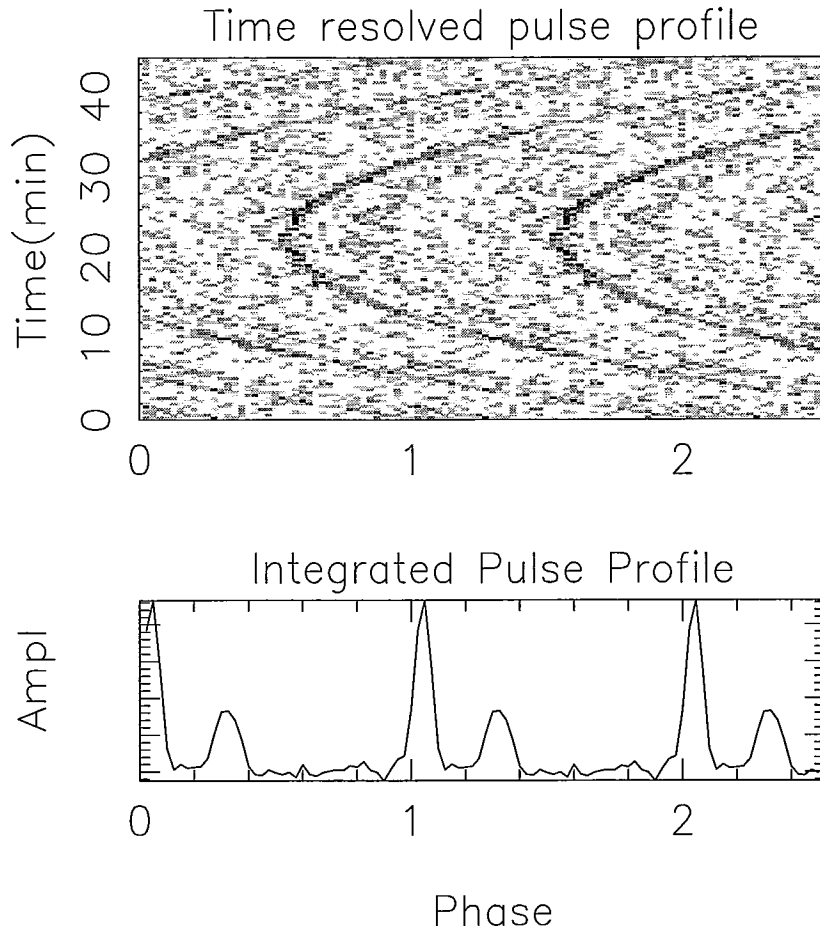
When a pulsar is detected and confirmed in a cluster, we usually reprocess the data. The raw data are de-dispersed at the single DM value of the newly discovered pulsar; then the resulting time series is interpolated to compensate for an acceleration and transformed using a FFT, with many trials to cover a large acceleration range. Since this analysis involves many FFTs, it is relatively slow, and has been rarely used when a DM value (or a narrow DM range) was not available.

## Millisecond pulsars in NGC 6752

NGC 6752 is believed to have a collapsed core and was already known to possess a large proportion of binary systems and dim X-ray sources. In this cluster, we have first discovered a 3.26 ms pulsars in a 21 h orbital period binary system, PSR J1910–59A [9](see Fig 1). This pulsar has a relatively low DM,  $34 \text{ cm}^{-3}\text{pc}$  and scintillates markedly, similar to the pulsars in 47 Tucanae, so it is seen rarely. As has been already experienced on 47 Tucanae [10], amplification due to scintillation might occasionally help in the detection of additional rather weak millisecond pulsars in the same cluster. And in fact, devoting a large amount of observing time to this cluster, we have already found four additional previously unseen millisecond pulsars (Table 1).

## An eclipsing millisecond pulsar in NGC 6397

NGC 6397 is a prime candidate for globular cluster searches. It is close and has a very dense and probably collapsed core and it contains at least four X-ray sources, but there was no known pulsar associated with NGC 6397 prior to this search. In this cluster we have found PSR J1740–53, a millisecond pulsar with a spin period of 3.65ms and an orbital period of 1.35 days [9]. This pulsar is eclipsed for more than 40 % of the orbital phase. Similar eclipses are observed in other binary pulsars [11,12]. But these systems are close binary systems (with orbital periods of a few hours) and have relatively light companions (minimum mass  $< 0.1 M_{\odot}$ ). In contrast, J1740-53 is in a rather wide binary system, with an orbital period of 1.35 days, and has a heavier companion ( $> 0.18 M_{\odot}$ ). It seems unlikely that a wind of sufficient density could be driven off a degenerate companion, and hence produce the observed eclipses. Therefore, follow-up observations of this pulsar will be useful to probe the eclipse mechanism in millisecond pulsars.



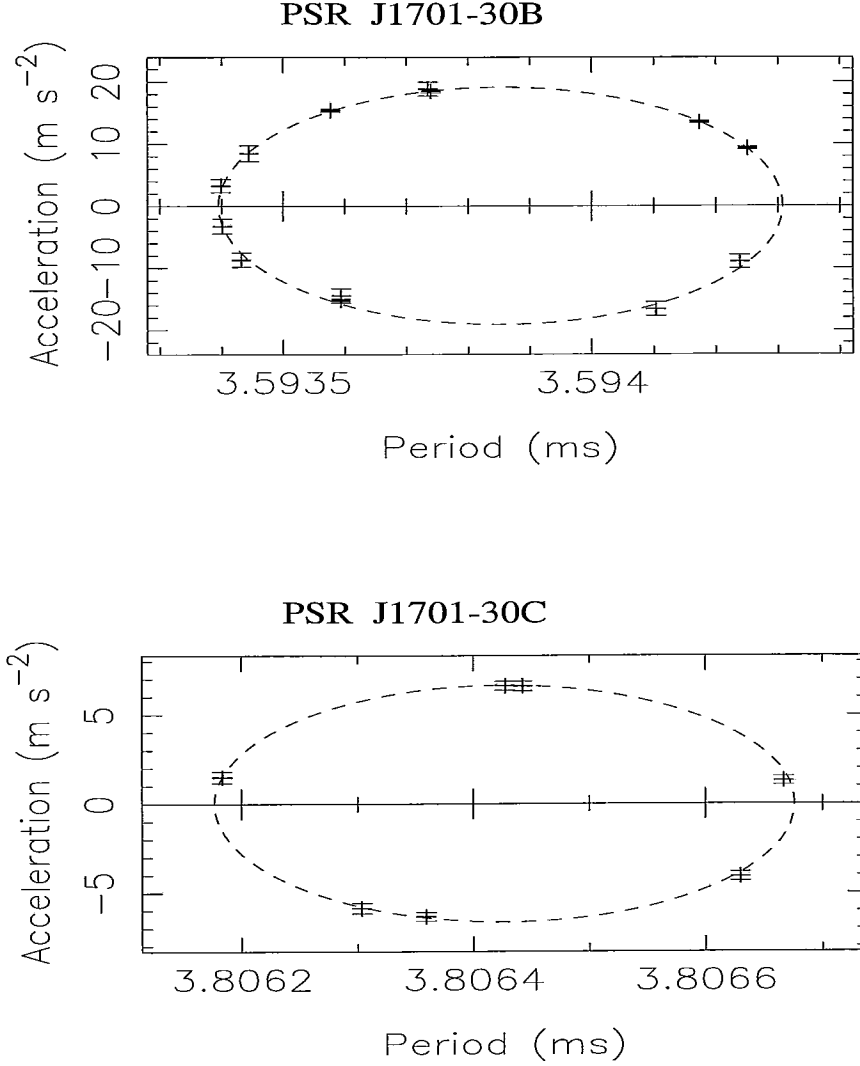
**FIGURE 1.** Integrated (bottom panel) and time-resolved (top panel) pulse profile for PSR J1910-58A in NGC6752. The curvature in the top panel show that the apparent period varies during the observation due to the pulsar's orbital motion

### Millisecond pulsars in NGC 6266

We have discovered three millisecond binary pulsars in NGC 6266, another relatively dense cluster. The first one, PSR J1701-30A [9], has a spin period of 5.24 ms, an orbital period, 3.8 days, and the mass function indicates a minimum companion mass of  $0.19 M_{\odot}$ . This system is similar to several low-mass binary pulsars, associated with globular clusters or in the Galactic field. But the two other systems found, PSR J1701-30B and PSR J1701-30C, belong to the class of short-binaries. They have spin periods of 3.6 ms and 3.8 ms and orbital periods of 3.8h and 5.2h (Fig. 2).

### An ultra-short binary in NGC 6544

This cluster is also one of the closest, and most concentrated globular clusters known. The pulsar discovered, PSR J1807-24 [9,13], has a spin period of 3.06 ms and it is binary, with an extremely short orbital period, 1.7 hours, the second



**FIGURE 2.** Observed accelerations plotted against barycentric period for PSR J1701–30B and PSR J1701–30C in NGC 6266. Dashed ellipses represent best fits circular orbits given in Table 1

shortest known. Even more interestingly, the projected semi-major axis of the orbit is only 12 light-ms. The corresponding minimum companion mass is only  $0.0089 M_{\odot}$  or about 10 Jupiter masses.

## CONCLUSIONS

In Table 1 we report the preliminary parameters of the new millisecond pulsars discovered so far in four globular clusters. It is too early to draw new conclusions on the pulsar content of globular cluster, as there are many clusters in our sample that need to be searched. The present experiment raises an interesting issue from the observational point of view: besides sensitivity and powerful search algorithms,

**TABLE 1.** Parameters of the millisecond pulsars discovered

Cluster	Pulsar	Period (ms)	DM ( $\text{cm}^{-3}$ pc)	Orbital period (days)	Mass function ( $M_{\odot}$ )
NGC6266	J1701–30A	5.2415660(4)	114.4(3)	3.805(1)	0.0031
	J1701–30B	3.59386(2)	114.4(3)	0.159(3)	0.0009
	J1701–30C	3.80643(2)	114.4(3)	0.221(5)	0.0002
NGC6397	J1740–53	3.650328896926(9)	71.8(2)	1.35405971(2)	0.0027
NGC6544	J1807–24	3.0594487974(3)	134.0(4)	0.071092(1)	$3.85 \times 10^{-7}$
NGC6752	J1910–59A	3.266186212(3)	34(1)	0.83711(1)	0.0029
	J1910–59B	8.35779(1)	34(1)	-	-
	J1910–59C	5.27732(2)	34(1)	-	-
	J1910–59D	9.03528(2)	34(1)	-	-
	J1910–59E	4.57177(2)	34(1)	-	-

a key strategy in a search for millisecond pulsars in globular clusters is to devote a large amount of observing time to each target. In fact, quite often these objects have properties such that they can be seen very rarely only: scintillation in low DM clusters, abnormally long eclipses, and unfavourable orbital phases in the case of ultra-short binaries might easily prevent the detection during a single observation. But the hidden systems are very often the very interesting ones.

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