A 20-cm Survey for Pulsars in Globular Clusters using the GBT and Arecibo

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Abstract. We have been conducting deep searches at $\sim$20 cm of >30 globular clusters (GCs) using the 305-m Arecibo telescope in Puerto Rico and the 100-m Green Bank telescope (GBT) in West Virginia. With roughly 80% of our search data analyzed, we have confirmed 13 new millisecond pulsars (MSPs), 12 of which are in binary systems, and at least three of which eclipse. We currently have timing solutions for five of these systems and basic orbital and spin parameters for six others.

1. Introduction

The number of known MSPs in GCs has increased significantly in the last few years due to a number of targeted surveys (see the review by Camilo & Rasio and the papers by Possenti and Jacoby in this volume) that have benefited from increased computational resources, new large-bandwidth pulsar backends (primarily at 20 cm), and improved search algorithms. Approximately half of the currently known $\sim$80 pulsars in 23 GCs[1] were found in the past four years. During the last three years we have been searching more than 30 GCs with the Arecibo and Green Bank telescopes. The high time and frequency resolution of these data, along with newly developed search algorithms (Ransom, Eikenberry, & Middleditch 2002, Ransom, Cordes, & Eikenberry 2003), makes us signifi-

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[1]http://www.naic.edu/$\sim$pfreire/GCpsr.html

cantly more sensitive than past surveys to sub-millisecond pulsations as well as to pulsars in ultra-compact binary systems. To date, we have confirmed 13 new MSPs in six GCs.

2.   Observations

2.1.   Arecibo

We observed all 22 GCs visible from Arecibo and within $50\,$kpc of the Sun using the L-Wide receiver ($1.1-1.7\,$GHz) and the Wideband Arecibo Pulsar Processors (WAPPs). The WAPPs are digital correlators with adjustable bandwidth, sampling time, and number of lags (Dowd, Hagen, & Sisk 2000). Our standard configuration for each WAPP uses $64\,\mu$s sampling (16-bit samples) and 256 lags across $100\,$MHz of bandwidth. The clusters were observed with a single WAPP for the full time they are visible by Arecibo, which can be up to $\sim2.75\,$hours.

We have been timing all our Arecibo discoveries on a roughly monthly basis with multiple WAPPs and have also searched this data for pulsars that may appear only occasionally when favorable scintillation causes them to brighten. Because of persistent and strong RFI from $\sim1220-1360\,$MHz, we have generally used three WAPPs centered at 1170, 1420, and $1520\,$MHz so that the data we obtain is relatively free of RFI and suitable for searching.

2.2.   Green Bank Telescope

In 2001 September and October, during some of the first scientific observations taken with the GBT, we observed 12 globular clusters for either $4\,$hrs (M2, M4, M75, M80, M92, and NGC 6342) or $8\,$hrs (M3, M13, M15, M30, M79, and Pal1) at L-band using one or two Berkeley-Caltech Pulsar Machines[2] (Backer et al. 1997). In general, the data consisted of $96\times1.4\,$MHz channels of 2 summed polarizations centered at $1375\,$MHz and 4-bit sampled every $50\,\mu$s. Large quantities of both persistent and transient broadband interference and the very strong Lynchburg airport radar with a period of approximately $12\,$s have made data analysis very difficult.

2.3.   Data Analysis

We have processed each observation using the `PRESTO` analysis package (Ransom 2001) using a computationally intensive multi-step procedure on a 52-node Linux cluster at McGill called "The Borg." We break each observation into small chunks of time ($\sim20\,$s) and examine each frequency channel in both the time and frequency domains in order to identify (and then mask out) strong interference. The observations are then de-dispersed, Fourier-transformed, pruned of known periodic interference, and then searched using both Fourier-domain acceleration searches and phase-modulation searches. We use acceleration searches on the

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[2]http://www.gb.nrao.edu/∼dbacker

observations as a whole and on various duration segments thereof. These acceleration searches are conducted on all clusters whether the dispersion measure is known towards it or not. Finally, we fold and examine by eye all candidates above $\sim 6\,\sigma$ that are not associated with known RFI sources. Additional details of the analysis procedure can be found in Ransom et al. (2004).

3. Results

With $\sim 80\%$ of our data analyzed to our satisfaction, we have discovered and confirmed at least 13 new MSPs, 12 of which are in binary systems. In addition, we have at least 2 additional binary MSP candidates which we believe are real, but have not (as of yet) confirmed. The new systems include the first pulsars discovered in four clusters: M3, M30, M71, and NGC 6749, as well as three new pulsars each in the GCs M5 and M13. In this section we briefly discuss the interesting properties of the new systems, organized by cluster. All cluster properties come from the GC catalog of Harris (1996)[3].

Table 1.   Newly Discovered Millisecond Pulsars in Globular Clusters

Pulsar	Telescope	P_{psr} (ms)	DM (pc/cm^3)	P_{orb} (hr)	x^a (lt-s)	Min M_2^b (M$_\odot$)
M3A	Arecibo	2.545	26.5	Unk.	Unk.	Unk.
M3B	Arecibo	2.390	26.2	34.0	1.9	0.20
M3C^f	GBT	2.166	26.5	Unk.	Unk.	Unk.
M3D	Arecibo	5.443	26.3	>50 days	Unk.	Unk.
M5C^{c,e}	Arecibo	2.484	29.3	2.08	0.057	0.038
M5D	Arecibo	2.988	29.3	29.3	1.6	0.19
M5E	Arecibo	3.182	29.3	26.3	1.2	0.14
M13C^{c,d}	GBT+AO	3.722	30.1	–	–	–
M13D^c	Arecibo	3.118	30.6	14.2	0.92	0.18
M13E$^{e?}$	Arecibo	2.487	30.3	5.12	0.17	0.061
M30A^{c,e}	GBT	11.02	25.1	4.18	0.23	0.10
M30B	GBT	12.99	25.1	>15	Unk.	$\sim$0.35
M71A^{c,e}	Arecibo	4.889	117	4.24	0.078	0.032
NGC6749A	Arecibo	3.193	194	$\sim$day	Unk.	Unk.
NGC6749B^f	Arecibo	4.968	192	Unk.	Unk.	Unk.

^{a} $x \equiv a_1 \sin(i)/c$. ^{b} Assuming a pulsar mass (M_1) of $1.4\,\mathrm{M_\odot}$.
^{c} Pulsar has a timing solution. ^{d} Isolated. ^{e} Eclipsing. ^{f} To be confirmed.

3.1. M3

M3 is a relatively normal cluster at a distance of $\sim$10.4 kpc. We have confirmed three new MSPs in M3: the 2.54-ms binary M3A, the 2.39-ms binary M3B, and the long period binary M3D, with a spin period of 5.44 ms. These are the

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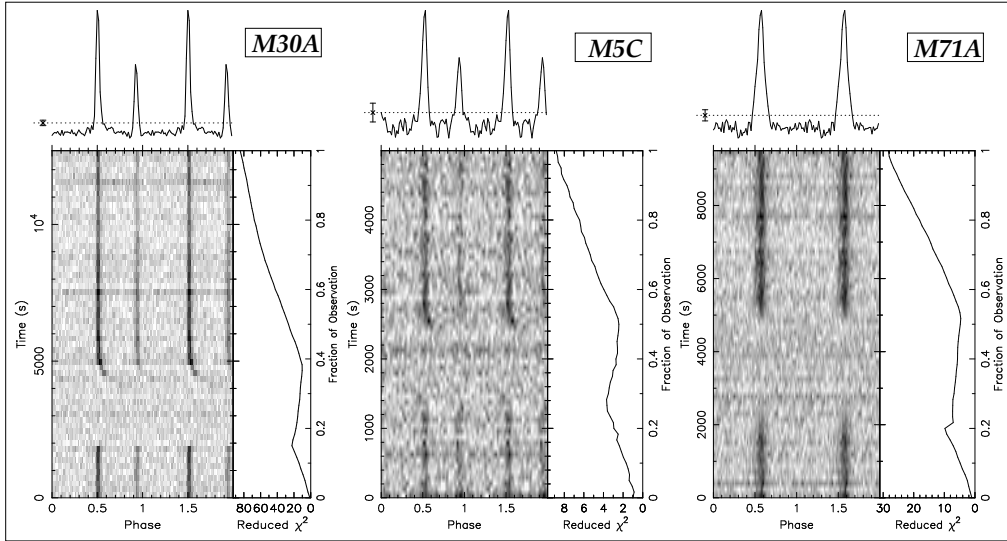[3]http://www.physics.mcmaster.ca/resources/globular.html

Figure 1.   Profiles of the three eclipsing MSPs found in the survey. Two cycles are shown for clarity. The grey-scale shows the pulses as a function of time during the observation. In each case the eclipse is clearly visible and for M30A and M5C an eclipse delay is also visible at eclipse egress.

first pulsars discovered in this cluster, and we currently have one good, but still unconfirmed, candidate, M3C (2.16 ms). None of these pulsars have an average flux density large enough to be consistently detectable with Arecibo and were all discovered during favorable periods of scintillation. We have sufficiently many detections of M3B for an orbital solution, and are nearing an orbital solution for M3D (assuming that its orbit is circular). We have detected M3A only three times, making it currently impossible to unambiguously determine its orbit. We note that even though we have not identified M3A in most of the observations, it is likely that intense blind folding searches near its nominal pulse period will uncover additional detections. The M3 pulsars will be presented in Hessels et al., in preparation.

3.2.   M5

M5 is a fairly normal cluster at a distance of ~ 7.5 kpc. Anderson et al. (1997) previously reported the discovery and timing of two pulsars in the cluster: the isolated 5.5-ms pulsar M5A and the 7.9-ms binary pulsar M5B. Our observations quickly uncovered an eclipsing 2.48-ms "Black-Widow" pulsar M5C in a compact 2.1 hr orbit (see Fig. 1). M5C exhibits pulse arrival delays at eclipse ingress and egress by $\gtrsim 0.1$ ms, significantly larger than most of the other Black-Widow pulsars. We have also identified M5C in an archival *Chandra* X-ray image. Recently, we have uncovered two additional MSPs in the cluster: M5D and M5E both seem to be "normal" binary MSPs with $\sim 0.2\, M_\odot$ companions in circular ~ 1 day orbits. Both pulsars are extremely faint at 20 cm, though, so timing solutions for the pulsars may be very difficult to obtain. More details will soon be available in Stairs et al., in preparation.

3.3. M13

M13 is a low mass and low density cluster at a distance of ~7.7 kpc. Anderson (1992) reported the discovery of the isolated 10.4-ms pulsar M13A and the 3.5-ms binary M13B and argued that their presence in such a low density cluster required additional formation mechanisms besides two-body tidal encounters. Our observations have uncovered 3 additional MSPs: the isolated 3.72-ms M13C, the "normal" binary MSP 3.12-ms M13D, and the possibly eclipsing 2.49-ms M13E. M13E seems to lie in or near the "gap" splitting the Black-Widow type binaries and the more massive Ter5A-like systems (see the contribution by P. Freire in this volume). Timing measurements of pulsars M13A−D show them all to be old ($\tau_c > 2 \times 10^9$ yr) with very low surface magnetic fields (B $< 7 \times 10^8$ G). Calculations similar to those in Phinney (1992) show that the measured spin-up of M13D constrains the mass-to-light ratio in the core of the cluster to be > 2 $M_\odot/L_\odot$ (Ransom et al., in prep.).

3.4. M30

M30 is a core-collapsed cluster at a distance of ~8 kpc. Using the GBT, we discovered two MSPs in the cluster, one of which (PSR J2140-2310A) now has a full timing solution. M30A is an eclipsing 11-ms MSP in a 4.2 hr orbit where the pulsed emission is eclipsed ~20% of the time (see Fig. 1). Arrival time delays of duration up to 1−2 ms are visible during eclipse ingress and egress when scintillation (which is very strong towards the cluster) is favorable. M30A has likely been detected in X-rays by *Chandra* and possibly in the optical by *HST*. M30B (PSR J2140-23B) is a 13-ms pulsar that we have only seen once (but at very high significance in two pulsar back-ends) presumably due to scintillation. The pulsar is in a very eccentric orbit ($e > 0.5$) with an orbital period of 1−10 days and a companion of minimum mass 0.35 $M_\odot$. Future detections will allow the measurement of $\dot{\omega}$ (and hence the total system mass) and probably relativistic γ which will provide the masses of both companions. More details on these two pulsars are available in Ransom et al. 2004.

3.5. M71

M71 is another low mass and low density cluster; however, it is relatively nearby at ~4 kpc. We discovered the first (and so far only) pulsar in this cluster in our initial observation of it with Arecibo. The pulsar is almost certainly a cluster member given its location ~0.6 core radii from the cluster center and a DM (~117 pc cm^{-3}) that is reasonably close to the prediction of the NE2001 Galactic electron model (~86 pc cm^{-3}; Cordes & Lazio 2002). M71A is yet another Black-Widow-like eclipsing binary (see Fig. 1) with $P_{psr} = 4.89$ ms and a minimum companion mass of $M_{c,\min} = 0.03\,M_\odot$. Due to the relatively high DM, the pulsar does not scintillate at 20 cm, nor are delays in the pulse arrival times visible at eclipse ingress or egress. Its proximity and the low density of the cluster (i.e., less source crowding) make M71A a good target for both optical and X-ray observations. More details will soon be available in Stairs et al., in preparation.
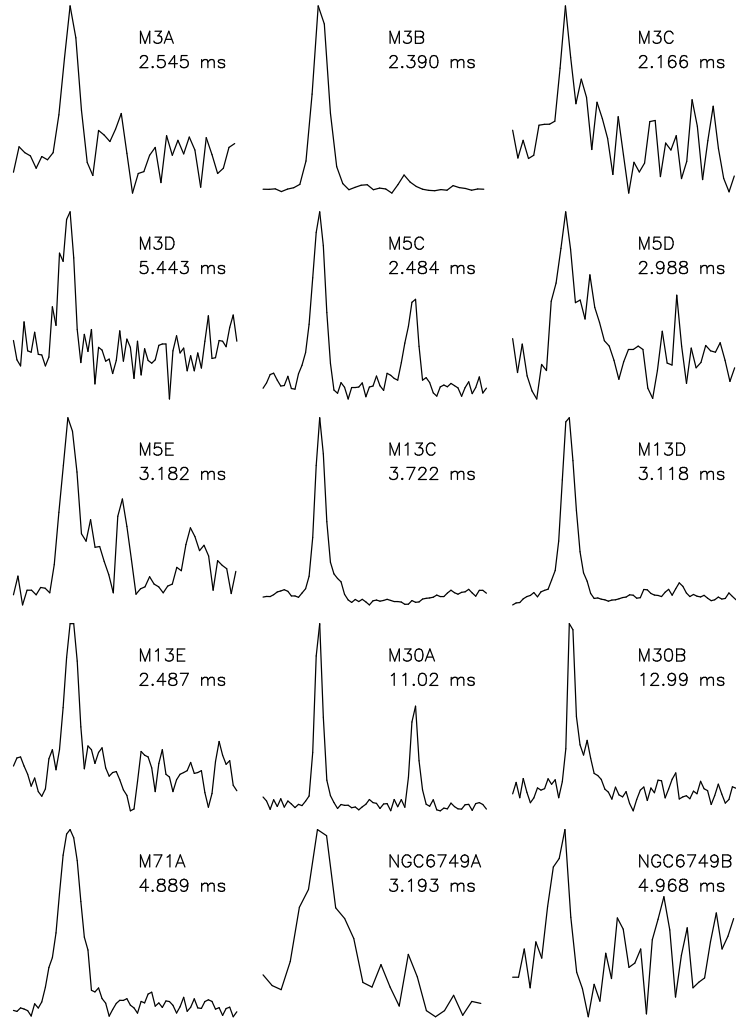
Figure 2.   Pulse profiles for 13 new MSPs and 2 candidates (M3C and NGC 6747B).

3.6.   NGC 6749

NGC 6749, which is at $\sim$7.9 kpc, has the lowest concentration ($c = log(\mathrm{r}_t/\mathrm{r}_c)$) and the second lowest central luminosity density of any GC with known pulsars. We have confirmed one new MSP in NGC 6749, the 3.19-ms binary NGC 6749A. This is the first pulsar in this cluster, although we have a good but unconfirmed candidate for NGC 6749B (4.97 ms). Timing observations are planned with Arecibo and will allow us to solve the orbit of NGC 6749A, hopefully confirm NGC 6749B, and potentially uncover additional pulsars.

4.   Conclusion

Our on-going 20-cm survey of clusters using the GBT and Arecibo has been very successful, resulting in the discovery of 13 new MSPs. These detections have benefitted greatly from the upgraded Arecibo telescope, the WAPP pulsar backends, and perhaps most importantly, a prodigious amount of available computing power. The vast majority of these systems would not have been discovered without both computationally expensive acceleration searches and repeated observations of the clusters. We anticipate determining timing solutions for the majority of the systems — or at least reliable orbital parameters — within the next year. We also believe that future multi-wavelength campaigns will uncover many more pulsars in these clusters.

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