Recent Globular Cluster Searches with Arecibo and the Green Bank Telescope

S. M. Ransom$^{1,2}$, J. W. T. Hessels$^1$, I. H. Stairs$^3$, V. M. Kaspi$^1$, D. C. Backer$^4$, L. J. Greenhill$^5$, & D. R. Lorimer$^6$

$^1$McGill University Physics Dept., 3600 University St., Montreal, QC H3A 2T8, Canada

$^2$Center for Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139

$^3$Department of Physics and Astronomy, University of British Columbia, 6224 Agricultural Road, Vancouver, BC V6T 1Z1, Canada

$^4$Dept. of Astronomy and Radio Astronomy Laboratory, University of California at Berkeley, 601 Campbell Hall 3411, Berkeley, CA 94720

$^5$Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138

$^6$University of Manchester, Jodrell Bank Observatory, Macclesfield, Cheshire SK11 9DL, UK

Abstract. We report the discovery of seven new millisecond pulsars during 20 cm searches of 19 globular clusters using the recently upgraded Arecibo Telescope and the new Green Bank Telescope (GBT). Five of the pulsars are in compact binaries, three of which are eclipsing. One of the systems is in an eccentric orbit which is almost certainly highly relativistic. Additional searches and timing observations are underway.

1. Introduction

In the past few years several groups have reported the discovery of 27 new millisecond pulsars (MSPs; 21 of which are in binary systems) in 8 globular clusters (Camilo et al., 2000; Possenti et al., 2001; Ransom, 2001; Jacoby et al., 2002), including an amazing 11 new binary MSPs in 47 Tucanae alone (e.g. Lorimer et al., these proceedings). The timing and multi-wavelength follow-up of these systems has already resulted in a wealth of science on the pulsar companions, the globular clusters, and the pulsars themselves (e.g. Freire et al., 2001; Heinke et al. and Possenti et al., these proceedings).

A significant fraction of the success of these searches can be attributed to improvements in instrumentation and computational capability. At Parkes — where most of these new pulsars have been found — the addition of a wide-bandwidth, low-temperature 20 cm receiver has revitalized cluster pulsar searching. Earlier searches were conducted almost exclusively at either 400 or 600 MHz.
where significant dispersion smearing, pulse scattering, and high galactic background temperatures greatly reduce the system sensitivity. Searching at 20 cm mitigates these issues and in general improves sensitivities even though the pulsars themselves are often fainter at the higher frequency. Additionally, the extensive (but computationally expensive) use of acceleration searches on clusters with known dispersion measures (DMs) has greatly improved sensitivities to pulsars in compact binaries (e.g. Johnston & Kulkarni, 1991).

With the availability of post-upgrade Arecibo and the GBT, a dedicated 104-processor computer cluster at McGill, and new binary pulsar search algorithms (Ransom, Eikenberry, & Middleditch, 2002; Ransom, Cordes, & Eikenberry, 2002), we decided to search several of the most promising northern globular clusters at 20 cm.

2. Observations and Data Analysis

In 2001 June at Arecibo, we observed two full tracks (typically 1.5–2.5 hrs) on each of 10 clusters (M3, M5, M13, M15, M53, M71, NGC4147, NGC6426, NGC6760, and Pal2) using the Wideband Arecibo Pulsar Processor (WAPP)\(^1\). Typical observing parameters included 64 µs sampling of 256 16 bit lags of 2 summed polarizations over a bandwidth of 100 MHz and centered at 1475 MHz. With a data rate of \(~\sim 7.6\) MB/s, we accumulated \(~\sim 1.5\) TB of search data. An additional \(~\sim 1.5\) TB of search data were taken in 2002 July on 12 other globular clusters and are currently being processed.

In 2001 September and October at the GBT, we observed 12 clusters for either 4 hrs (M2, M4, M75, M80, M92, and NGC6342) or 8 hrs (M3, M13, M15, M30, M79, and Pal1) using one or two Berkeley-Caltech Pulsar Machines\(^2\) (Backer et al., 1997). Observations were made using 96 × 1.4 MHz channels of 2 summed polarizations centered at 1375 MHz and 4 bit sampled every 50 µs. We took a total of \(~\sim 0.5\) TB of data. Significant 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 a challenge. Approximately one quarter of these data remain to be fully analyzed.

We searched the data in several stages. After attempting to remove significant interference via time and frequency domain methods, we de-dispersed the data over suitable ranges of DMs based either on the average DM of the cluster for those with known pulsars or \(~\sim 50–200\)% of the predicted DM according to Taylor & Cordes (1993). We performed Fourier-domain acceleration searches and phase-modulation (i.e. sideband) searches on the full observations and then additional acceleration searches on overlapping short intervals of \(~\sim 15\) and \(~\sim 40\) min duration. To date, we have discovered seven new MSPs (see Table 1) and have several other good candidates awaiting confirmation.

\(^1\)http://www.naic.edu/~wapp
\(^2\)http://www.gb.nrao.edu/~dbacker
Table 1: Newly Discovered MSPs

| Pulsar      | Telescope            | $P_{\text{psr}}$ (ms) | DM (pc cm$^{-3}$) | $P_{\text{orbit}}$ (hr) | $a_1 \sin(i)/c$ (lt-s) | Min $M_2^a$ (M$_\odot$) |
|-------------|----------------------|------------------------|-------------------|-------------------------|-------------------------|--------------------------|
| M30A        | GBT                  | 11.0                   | 25.1              | 4.18                    | 0.23                    | 0.10                     |
| M30B        | GBT                  | 13.0                   | 25.1              | $\gtrsim$ 15            | Unk.                    | $\sim$ 0.35              |
| M13C        | GBT & Arecibo        | 3.72                   | 30.1              |                         |                         |                          |
| M13D        | Arecibo              | 3.12                   | 30.6              | 14.2                    | 0.92                    | 0.18                     |
| M5C         | Arecibo              | 2.48                   | 29.3              | 2.08                    | 0.057                   | 0.038                    |
| M71A        | Arecibo              | 4.89                   | 117               | 4.24                    | 0.078                   | 0.032                    |
| M3A         | Arecibo              | 2.54                   | 26.5              | Unk.                    | Unk.                    | Unk.                     |

$^a$ Assuming a pulsar mass ($M_1$) of 1.4 M$_\odot$.

3. The Pulsars

3.1. The Isolated MSP M13C

M13C is a fairly typical isolated pulsar in M13 which was discovered simultaneously in Arecibo and GBT observations. Interstellar scintillation causes significant changes (factors of 2–10) in the measured flux density of M13C (and the three other known pulsars in the cluster) over timescales of several hours.

3.2. Three Eclipsing MSPs

M30A, M5C, and M71A are all in very compact circular systems and eclipse for $\sim$20% of their orbital period at 20 cm. M30A and M5C show evidence of time delays at both eclipse ingress and egress (presumably due to dispersive delays as the pulses pass through the ionized wind of the companion star), while M71A seems to simply slowly fade and reappear at the eclipse ingress and egress.

M30A differs in several respects from the other two eclipsing MSPs. It has a much longer pulse period (11 ms as opposed to 2.5 ms and 4.9 ms for M5C and M71A respectively), it displays large changes in flux density due to interstellar scintillation, and it likely has a significantly more massive companion than the other two eclipsing MSPs. Archival HST imaging and recent Chandra data may allow us to identify and characterize the companion star (e.g. Edmonds et al., 2001). Optical and/or X-ray follow-up on the nature of the companions to M5C and M71A may also be possible once timing positions are available.

3.3. Other Binaries

M3A has only recently been discovered and confirmed in Arecibo data taken this past summer and hence the orbital solution is currently unknown. However, the large accelerations measured in the searches imply that it is most likely in a compact binary. Since M3A scintillates significantly, we anticipate discovering more MSPs in this cluster.

M13D is in a longer period binary ($\sim$14 hrs) with a near circular orbit ($e \sim 0.0006$) around a more massive companion ($\gtrsim 0.18$ M$_\odot$). A several year
timing baseline should allow us to measure the rate of change of the angle of periastron, $\dot{\omega}$, and hence determine the total mass of the system.

M30B is perhaps the most intriguing of the new MSPs. It was discovered during the initial observation of M30 at the same DM as M30A. The measured significances were $\sim 30 \sigma$ and $\sim 10 \sigma$ from the two BCPMs, which had different center frequencies, total bandwidths, and interference conditions. But in the more than 20 GBT observations of M30 taken since then, we have not seen it again. In the $\sim 7$ hrs in which it was visible, however, we measure four significant frequency derivatives of the pulsar due to the orbital motion. Using these derivatives and the technique described by Joshi & Rasio (1997), we determine that the orbit must have $e > 0.35$, an orbital period of $\sim 1$–10 days, and a companion mass $\gtrsim 0.35 M_\odot$, making it a highly relativistic system with the potential to accurately measure the component masses and test gravitational theories.

4. Future Prospects

We are timing each of the new MSPs mentioned above and analyzing the remaining search data from Arecibo and the GBT. In the near future, better pulsar backends at Arecibo (4 WAPPs covering 400 MHz of bandwidth) and the GBT (the $\sim 600$ MHz bandwidth “Spigot” card) and a much improved 20 cm receiver at Arecibo will improve our timing precision and allow us to find fainter pulsars in the timing data. Observations at other promising frequencies (i.e. 375 MHz at the GMRT and 800 MHz at the GBT) may uncover even more pulsars in these clusters. Finally, analysis of optical and X-ray observations will help to maximize the science output from these remarkable systems.

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