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The PALFA Survey: Going to great depths to find radio pulsars

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Abstract. The on-going PALFA survey is searching the Galactic plane ($|b| < 5°$, $32° < l < 77°$ and $168° < l < 214°$) for radio pulsars at 1.4 GHz using ALFA, the 7-beam receiver installed at the Arecibo Observatory. By the end of August 2012, the PALFA survey has discovered 100 pulsars, including 17 millisecond pulsars (P < 30 ms). Many of these discoveries are among the pulsars with the largest DM/P ratios, proving that the PALFA survey is capable of probing the Galactic plane for millisecond pulsars to a much greater depth than any previous survey. This is due to the survey's high sensitivity, relatively high observing frequency, and its high time and frequency resolution. Recently the rate of discoveries has increased, due to a new more sensitive spectrometer, two updated complementary search pipelines, the development of online collaborative tools, and access to new computing resources. Looking forward, focus has shifted to the application of artificial intelligence systems to identify pulsar-like candidates, and the development of an improved full-resolution pipeline incorporating more sophisticated radio interference rejection. The new pipeline will be used in a complete second analysis of data already taken, and will be applied to future survey observations. An overview of recent developments, and highlights of exciting discoveries will be presented.

Keywords. Surveys, pulsars:general

1. Introduction

The PALFA survey is an on-going, large-scale, survey for radio pulsars tuned to find millisecond pulsars (MSPs). PALFA is similar to, but more sensitive than other on-going projects (e.g. HTRU-N/S, GBNCC, SPAN512, described by Ng *et al.*, Keith *et al.*, Lynch *et al.*, and Desvignes *et al.*, respectively, in these proceedings). MSPs are particularly useful for searches for the direct detection of nano-Hz gravitational waves using Pulsar Timing Arrays (e.g. van Haasteren *et al.* 2011), strong-field tests of relativistic theories of gravity (e.g. Kramer *et al.* 2006), studying the equation of state of ultra-dense matter (e.g. Demorest *et al.* 2010). Another main goal of the survey is to expand the known population of radio pulsars, to gain a better understanding of their overall numbers, the distribution of their properties, determine birth-rates, and estimate birth properties. The survey is sensitive to transient pulsars, such as nullers, rotating radio transients (RRATs), intermittent pulsars, and radio magnetars. Discoveries may also be young pulsars associated with high-energy emission, supernova remnants, or pulsar wind nebulae. PALFA has the potential for discovering even more exotic systems such as pulsar-black hole binaries, which could have profound ramifications for the understanding of gravitation (e.g. Wex and Kopeikin 1999).

The PALFA Survey makes use of the 7-beam L-band (1.4 GHz/21-cm) receiver installed on the Arecibo Observatory's William E. Gordon Telescope. Observing has focused on the plane of the Galaxy ($|b| < 5°$), in the two regions visible from Arecibo, due to its transit

Table 1. PALFA Survey observing system parameters.

	WAPP Spectrometers	Mock Spectrometers
Centre Frequency	1420/1440 MHz[a]	1375.432 MHz
Sample time	64 μs	65.476 μs
Bandwidth	100 MHz	322.617 MHz
Number of Channels	256	960

[a] The centre frequency of the WAPPs was increased in 2005 Nov. to reduce interference.

design, the "inner Galaxy" ($34° < l < 77°$) and the "anti-centre" ($168° < l < 214°$) regions.

The Wideband Arecibo Pulsar Processor (WAPP) spectrometers used by the PALFA survey since its beginning in 2004 were replaced with the more sensitive Mock spectrometer system in 2009. The Mock set-up allows for ALFA's full 320 MHz bandwidth to be recorded, more than tripling the bandwidth available compared to the older WAPP set-up. In 2009, before completely phasing out the WAPP spectrometers for use in the survey, both backends were run in parallel to ensure the quality of the data from the new system. The ALFA receiver's system temperature is ~24 K, and the gain is ~10.4 K/Jy for the central beam and ~ 8.2 K/Jy for the outer beams (Cordes *et al.* 2006). The survey's observing parameters, summarized in Table 1, are characterized by high time and frequency resolution. Integration times are 4.5 min for the inner Galactic region, and 2.25 min for the anti-centre region.

The high resolution employed by the PALFA survey allows for the dispersive smearing caused by free electrons in the interstellar medium along the line-of-sight to be almost completely removed for pulsars at any depth into the Galactic plane using incoherent dedispersion techniques. Scattering due to multi-path propagation still limits the depth to which the fastest spinning pulsars can be detected within the Arecibo-visible sky (see Figure 1, left).

The large collecting area and hence high gain of the Arecibo Observatory make the PALFA survey the most sensitive large-scale survey of the Galactic plane to date. The high sensitivity of the survey enables integration times far shorter than would be possible when using smaller telescopes, and reduces the total data volume of the survey. It is important to note that shorter observations are more computationally efficient to search, especially for pulsars in binary systems.

2. Processing

Processing of PALFA survey data is currently done with two complementary pipelines. One is based on the PRESTO suite of pulsar search code†. The other pipeline makes use of the BOINC-based‡ Einstein@Home distributed global volunteer computing platform¶.

Before data are distributed to processing sites the data are converted to 4-bits-per-sample PSRFITS format, and archived at Cornell University's Center for Advanced Computing. All data are tracked by a database at Cornell. Data are automatically downloaded from the archive by processing sites.

† http://www.cv.nrao.edu/~sransom/presto/
‡ http://boinc.berkeley.edu/index.php
¶ http://einstein.phys.uwm.edu/

2.1. *PRESTO*

The PRESTO pipeline first searches for, and removes, bright un-dispersed narrow-band impulsive, and periodic, radio frequency interference (RFI) signals in the data.

The pipeline then dedisperses the data with an assumed dispersion measure (DM) value, removing the corresponding frequency-dependent delay. Since the DM of unknown pulsars are not known *a priori*, 4188 (1140) dedispersed time series, each with a different trial DM value ranging from 0 to ∼1000 pc cm^{-3}, are generated when searching Mock (WAPP) observations. Each resulting time series is then searched in the time domain for bright individual pulses, and in the Fourier domain for periodic signals.

Each dedispersed time series is searched for single pulses. To increase sensitivity to pulses of width larger than the observation's sampling time a series of boxcar matched filters of different widths are convolved with the data. A summary plot of all significant candidate pulses identified at all trial DMs is produced, and inspected.

In order to increase sensitivity to pulsars in binary systems a series of trial Fourier-domain templates, each corresponding to a constant acceleration, are used when searching the Fourier Transform of the dedispersed time series (see Ransom *et al.* 2002, for more details). Given the length of PALFA observations, and the number and range of trial acceleration values, the PRESTO pipeline maintains sensitivity to pulsars in binary orbits with periods as small as ∼1 hour.

The PRESTO pipeline then identifies the most likely pulsar candidates from the list of periodicity signals identified. For each periodicity candidates the raw data are folded using its period and DM, and a diagnostic plot is produced. Also, a series of scoring heuristics are computed for each folded candidates. These are later used as input to Artificial Intelligence (AI) systems trained to identify pulsar-like candidates, and ignore RFI-like and noise-like signals that were folded by the pipeline. All periodic signals identified are summarized in overview diagnostic plots.

The PRESTO pipeline is run on computing resources at the University of British Columbia, and on the Guillimin supercomputer† managed by McGill University. Combined, 3000-6000 observations can be reduced per month, depending on contention for resources on Guillimin.

2.2. *Einstein@Home*

Prior to distributing data to volunteers' computers, the Einstein@Home-based pipeline identifies, and masks narrow-band impulsive RFI in the time-domain. The pipeline also identifies periodic RFI, which is replaced by random noise. The pipeline then generates 3808 (628) dedispersed time series for Mock (WAPP) data, each with a different trial DM, up to ∼1000 pc cm^{-3}. These dedispersed time series that are transferred to volunteers' computers to be analyzed.

Sensitivity to binary pulsars is improved by using 6662 circular orbital templates to demodulate the time series in the time domain. This technique is capable of detecting isolated pulsars (e.g. Knispel *et al.* 2010), and still maintains sensitivity to pulsars in binaries with orbital periods as short as ∼11 min. The Fourier transform of each demodulated time series is searched for periodic signals. The top 100 signals are returned to the Einstein@Home servers where they are collated, diagnostics plots are created, and heuristic pulsar-identification algorithms are run.

No single pulse search is performed in the Einstein@Home analysis.

The Einstein@Home pipeline can make use of volunteers' GPUs, if permitted. Processing on GPUs accounts for ∼75% of the pipeline's processing power. The performance

† http://www.clumeq.ca/index.php/en/about/computers/guillimin

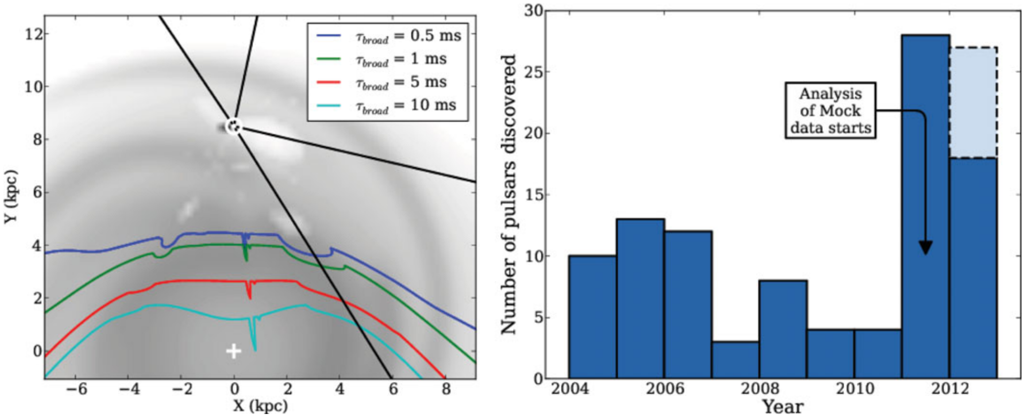

Figure 1. *Left.* A top-down view of the Galactic plane showing Galactic MSP overlaid with the depths corresponding to various pulse broadening times as predicted by the NE2001, for the PALFA survey's observing parameters. *Right.* Number of PALFA discoveries per year since the start of the survey. The projected number of discoveries for 2012 is shown with a dashed extension.

of the pipeline, and more importantly the GPU code, is constantly being improved, reducing the time required for analysis with each iteration. Currently, the Einstein@Home pipeline searches ~3000 observations per month.

2.3. *Candidates*

The PALFA collaboration uses a centralized database to store metadata and diagnostics for each observation, and details for candidates identified by processing. The database holds approximately six million candidates.

Candidates are primarily inspected using an online viewer available on the PALFA Survey's portal on the CyberSKA website.† The viewer allows users to select candidates based on information in the database, including scoring heuristics, AI recommendations, and the usual observation/candidate information. The user interface provides one-click access diagnostic information and plots about the candidate being viewed, and the observation in which it was found. The candidate viewer also provides direct access to another web-application designed to track the most promising candidates, and their follow-up. Both applications, and others not mentioned here, are hosted at McGill University.

3. Results

By the end of August 2012, the PALFA survey has discovered 100 pulsars. The discovery rate increase significantly when the analysis of the Mock data began (see Figure 1, right). This is partly due to the increase of computing resources available. However, the number of discoveries per sq. deg. is higher for Mock data, owing to their higher sensitivity. The WAPP spectrometers have been used to discover 56 pulsars in 164 sq. deg. of PALFA data (1 pulsar per 2.9 sq. deg.) whereas 44 pulsars have been discovered in only 70 sq. deg. of Mock data (1 pulsar per 1.6 sq. deg.).

3.1. *Highlights*

The PALFA survey has made several exciting discoveries since its start, including:

† www.cyberska.org/palfa. Access is restricted to members of the PALFA Consortium.

PSR J1906+0746 (*P=144 ms; DM=212 pc cm^{-3}*) This binary pulsar has a characteristic age of $\tau_c = \frac{P}{2\dot{P}}$=112 kyr, making it the youngest known binary pulsar (Lorimer *et al.* 2006). Also, it is the second most relativistic binary pulsar system known. (See also, Kasian 2012).

PSR J1903+0327 (*P=2.15 ms; DM=298 pc cm^{-3}*) This Galactic MSP is in a binary orbit whose eccentricity of $e = 0.44$ challenges the standard MSP formation picture (Champion *et al.* 2008). Pulsar timing has measured the Shapiro delay, and the relativistic advance of periastron, allowing the determination of the pulsar's mass ($M_p = 1.67(2)M_\odot$) and the companion's mass ($M_c = 1.029(8)M_\odot$). Near-IR spectroscopic observations have identified the companion as a main-sequence star. Simulations suggest the current binary was formed from a triple-star system (Freire *et al.* 2011; Portegies Zwart *et al.* 2011).

PSR J1856+0245 (*P=80.9 ms; DM=650 pc cm^{-3}*) This young (τ_c = 27 kyr), highly energetic ($\dot{E} = 4\pi^2 I\dot{P}P^{-3} = 4.6 \times 10^{36}$ erg s^{-1}) pulsar is coincident with the TeV γ-ray source HESS 1857+026, as well as a faint X-ray source AX J185651+0245 (Hessels *et al.* 2008; Rousseau *et al.* 2012).

PSR J1949+3106 (*P=13.1 ms; DM=164 pc cm^{-3}*) This binary MSP is in a circular ($e = 4 \times 10^{-5}$), whose inclination ($i = 80°$) makes the detection of Shapiro delay possible in the timing data (Deneva *et al.* 2012). The measurement of Shapiro delay provides mass measurements of the pulsar ($M_p = 1.47^{+0.43}_{-0.31}\ M_\odot$) and of the companion ($M_c = 0.85^{+0.14}_{-0.11}\ M_\odot$). Detection of relativistic advance of periastron, which could be possible within a few years, will greatly reduce the uncertainties on the masses. Also, the absence of timing noise, the decent timing precision ($RMS_{TOA} = 3.96\mu$s), and the as-of-yet unresolved pulse profile, coupled with Arecibo's new PUPPI backend could make this pulsar useful for Pulsar Timing Array experiments.

3.1.1. *Global distributed volunteer computing discoveries*

The Einstein@Home platform's first discovery was found in 2010 in a WAPP PALFA data (J2007+2722, Knispel *et al.* 2010). Since then, the Einstein@Home pipeline has discovered 22 additional pulsars, including four MSPs, and three binaries.

3.1.2. *Distant MSPs*

The PALFA survey has discovered 17 MSPs (defined here as P < 30 ms). These pulsars are amongst the highest DM MSPs in the Galactic plane. The ratio DM/P can be used as a rough measure of the difficulty of finding a pulsar, since the smearing in time caused by DM is more detrimental to shorter period pulsars. The MSPs found in the PALFA survey make up a large proportion of the highest DM/P pulsars known (see Figure 2, left).

Also, by assuming the NE2001 model for the Galactic distribution of free-electron density (Cordes and Lazio 2002), it is possible to infer distances given the sky-position and DM of a pulsar. Figure 2 (right) shows the inferred positions of PALFA-discovered MSPs projected onto the plane of the Galaxy, compared to all other Galactic plane MSPs. The median distance to PALFA MSPs is 5.8 kpc, double that of other known Galactic MSPs (D_{median} = 2.9 kpc), highlighting PALFA's ability to find distant MSPs.

4. Future Outlook

The PALFA survey has observed only 10% of its nominal survey region with the Mock spectrometers, which are proving to be superior to the WAPPs due to their tripled bandwidth. The Mock spectrometers will be used as the survey continues, and will eventually be used to re-observe regions covered with the WAPPs.

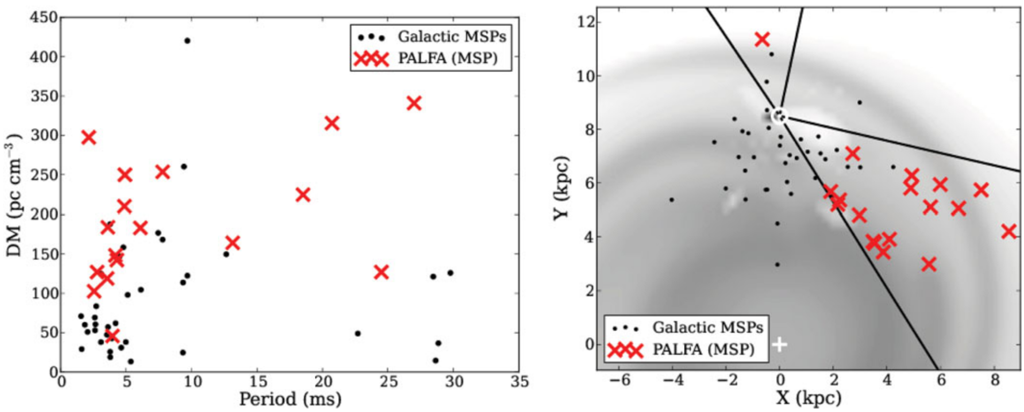

Figure 2. *Left.* DM vs. Period for Galactic MSPs. Notice that red Xs, PALFA-discovered MSPs tend towards the top of the plot. These pulsars are generally thought to be harder to find. *Right.* A top-down view of the Galactic plane showing Galactic MSP. The PALFA-discovered MSPs (red Xs) are generally located deeper into the plane of the Galaxy. Distances are inferred from the DM using the NE2001 model.

In addition, an updated version of the PRESTO pipeline, including enhanced RFI mitigation, improved candidate optimization, additional diagnostic information, and a few bug fixes, is being beta-tested on the Guillimin supercomputer. The updated pipeline is already finding pulsars missed by the first analysis. Improved single pulse analyses based on the work of Spitler *et al.* (2012) are also being applied to the PALFA data taken thus far, and will be integrated into the survey's standard data reduction, as will a modified version of the algorithm developed by Karako-Argaman *et al.* (in these proceedings).

With the 100 pulsars discovered to date, the improved data quality, additional computing resources available, and enhancement to the data reduction, the PALFA survey is well on its way to discovering hundreds of pulsars, including expanding the population of faint, distant MSPs it has already been successful at finding.

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