Pulsar Surveys Present and Future: The Arecibo-PALFA Survey and Projected SKA Survey

Julia Deneva, Cornell University, USA

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Pulsar-ALFA Consortium

**USA**
- Bryn Mawr College
- Carleton College
- Cornell University
- Columbia University
- Franklin and Marshall College
- Harvard-Smithsonian Center for Astrophysics
- Harvard University
- NASA Goddard Spaceflight Center
- National Astronomy and Ionosphere Center
- National Radio Astronomy Observatory
- University of California-Berkeley
- U.S. Naval Research Laboratory

**Australia**
- Swinburne University of Technology

**India**
- Raman Research Institute

**China**
- National Astronomical Observatories of China

**UK**
- Jodrell Bank Observatory
- University of Manchester

**Netherlands**
- Astronomical Institute "Anton Pannekoek"

**Canada**
- McGill University
- University of British Columbia
The Arecibo L-band Feed Array (ALFA)

- ALFA receiver: 7 beams; 1.42 GHz
- PALFA (pulsar), GALFA (galactic), EALFA (extragalactic)
- PALFA survey to last 3-5 years and find hundreds of pulsars
- Started in Aug 2004
Multi Beam Pattern

Dense vs. sparse sampling:
- Tile pointings densely and do 1 pass?
- Tile pointings sparsely and do several (non-redundant) passes to fill in holes?

Survey efficiency depends on volume searched per time

Sparse sampling is more efficient because pulsars can also be detected with the *sidelobes*
Multi Beam Sky Footprint and Pointing Tiling Pattern

http://www.naic.edu/~pfreire/tiling/
Survey Comparison

- **Blue:** known pulsars from surveys other than Parkes MB
- **Red:** pulsars discovered by Parkes MB
- **Green:** simulated pulsar discoveries by PALFA (~1000)
### PALFA Survey Parameters

Comparing PALFA and Parkes Multibeam Surveys

<table>
<thead>
<tr>
<th>Item</th>
<th>ALFA + WAPPs</th>
<th>ALFA II</th>
<th>PMB</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>System Parameters:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SEFD(^a) (Jy)</td>
<td>3.6 (4.6)</td>
<td>3.6 (4.6)</td>
<td>36</td>
</tr>
<tr>
<td>FWHM/beam (arcmin)</td>
<td>3.6</td>
<td>3.6</td>
<td>14</td>
</tr>
<tr>
<td>No. of beams</td>
<td>7</td>
<td>7</td>
<td>13</td>
</tr>
<tr>
<td>Total Bandwidth (MHz)</td>
<td>100</td>
<td>300</td>
<td>288</td>
</tr>
<tr>
<td>Spectral channels</td>
<td>256</td>
<td>1024</td>
<td>96</td>
</tr>
<tr>
<td>Bandwidth/channel (MHz)</td>
<td>0.39</td>
<td>0.29</td>
<td>3.0</td>
</tr>
<tr>
<td>Dump time (µs)</td>
<td>64</td>
<td>64</td>
<td>250</td>
</tr>
<tr>
<td>Dwell time/position (s)</td>
<td>67, 134, 268</td>
<td>134, 268</td>
<td>2100</td>
</tr>
<tr>
<td>Sky coverage rate(^b) (deg(^2) hr(^{-1}))</td>
<td>1.2</td>
<td>3.6</td>
<td>0.95</td>
</tr>
<tr>
<td>(S_{min})(^c) in 1 min (µJy)</td>
<td>330 (420)</td>
<td>190 (241)</td>
<td>1900</td>
</tr>
<tr>
<td>(\Delta t_{DM}) (DM = 50) (µs)</td>
<td>59</td>
<td>44</td>
<td>453</td>
</tr>
<tr>
<td><strong>Survey Parameters:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(S_{min})^* (µJy)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1 s, DM = 0 pc cm(^{-3}))</td>
<td>119</td>
<td>48</td>
<td>150</td>
</tr>
<tr>
<td>(1 ms, DM = 50 pc cm(^{-3}))</td>
<td>700</td>
<td>460</td>
<td>6,600</td>
</tr>
<tr>
<td>(D_{max})^† (kpc)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1 s, 1 mJy kpc(^2))</td>
<td>2.9</td>
<td>4.6</td>
<td>2.6</td>
</tr>
<tr>
<td>(1 ms, 1 mJy kpc(^2))</td>
<td>1.2</td>
<td>1.5</td>
<td>0.4</td>
</tr>
<tr>
<td>(V_{max})^‡ (kpc(^3) sr(^{-1}))</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1 s, 1 mJy kpc(^2))</td>
<td>8.1</td>
<td>32</td>
<td>5.8</td>
</tr>
<tr>
<td>(1 ms, 1 mJy kpc(^2))</td>
<td>0.6</td>
<td>1.1</td>
<td>0.02</td>
</tr>
</tbody>
</table>
PALFA Pipeline

- **Quicklook software**—periodicity and giant pulse search in decimated data (on-site, while observing)
  - Discoveries so far were made by Quicklook output
  - Almost real time!

- Data shipped to Cornell for permanent archiving
  - Tape archive at Cornell Theory Center
  - Tools for remote access and data processing

- Full-resolution processing at Cornell and other institutions

- Several different codes (sanity check): *Presto*, *Sigproc*

- Collaboration on harvesting most efficient parts of each code and combining them
PALFA Discoveries

- 29 pulsars total (from real-time processing of decimated data)
- 2 in Anticenter
- 1 RRAT-like object (J0628+09)
- 1 relativistic binary (J1906+07)
Rotating RAdio Transients (RRATs)

- Newly defined class of radio-loud neutron stars
- 11 found in Parkes data (McLaughlin et al. 2006)
- 1 found by PALFA so far
- Sporadic bright bursts with distribution different from giant pulses
- Emission mechanism likely different from GPs
- B at light cylinder much lower than for GP-emitting pulsars
- Re-assessment of total Galactic pulsar population
- On/off ratio very low--how many RRATs are there?
**J0628+09**

**Discovery observation**

Arrecibo ALFA RealTime Search Candidate: G202.12–00.82, 53269.000


Searched 133 s of 32 × 325.0–kHz filterbank data ($\tau_{\text{amp}} = 1024\mu$s)

P: 413.583352000 ms DM: 106.00 cm$^{-3}$ pc FINT S/N: 7.6

P: 413.797879920 ms $\dot{N}_{\text{rms}}$: 123 DC: 5.8% PROF S/N: 4.0
J1906+07 Discovery

Folded Parkes data from 1998
24.05.2005

Discovery observation 27.09.2004
J1906+07 Parameters

- $P = 144$ ms
- $P' = 2.03 \times 10^{-14}$ s/s
- $P_b = 3.98$ h
- Eccentricity: $e = 0.085$
- $DM = 217$
- $S_{1.4} = 0.55$ mJy
- Characteristic age, $\tau_c = P/2P' = 112,000$ yr
- Magnetic field: $B = 1.7 \times 10^{12}$ G
- Spectral index: $\sim -1.3$
- Total system mass, $M = 2.61 M_{\text{sun}}$
- Gravitational wave coalescence time, $\tau_g \sim 300$ Myr

Evolution of interpulse due to geodetic precession: data taken at Parkes in 1998 (top) and 2005 (bottom).
Getting the Goods

- Tape archive at Cornell Theory Center—to grow to ~1PB (ideally 40000+ pointings)
- Database of data products hosted at CTC—to grow to ~25TB
- Dedicated 16-processor Unisys machine to process full-resolution data and run MS SQL server
- Web service for querying database and retrieving info in VOTable format
- Web service clients written by PALFA members (or any user of the archive)
# Square Kilometer Array Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency range</td>
<td>100 MHz - 25 GHz Goal: 60 MHz - 35 GHz</td>
</tr>
<tr>
<td>Simultaneous independent observing bands</td>
<td>2 pairs (2 polarizations at each of two independent frequencies, with same FoV centers)</td>
</tr>
<tr>
<td>Instantaneous bandwidth of each observing band</td>
<td>Full width = 25% of observing band center frequency, up to a maximum of 4 GHz BW for all frequencies above 16 GHz</td>
</tr>
<tr>
<td>Configuration</td>
<td>Minimum baselines 20 meters, 20% of total collecting area within 1 km diameter, 50% of total collecting area within 5 km diameter, 75% of total collecting area within 150 km diameter, maximum baselines at least 3000 km from array core (angular resolution &lt; 0.02 / fGHz arcsec)</td>
</tr>
<tr>
<td>Contiguous imagingfield of view (FoV)</td>
<td>1 sq. deg. within half power points at 1.4 GHz, scaling as $\lambda^2$, 200 sq. deg. within half power points at 0.7 GHz, scaling as $\lambda^2$ between 0.5-1.0 GHz</td>
</tr>
</tbody>
</table>
Complete Galactic Pulsar Census

~10000-20000 projected pulsar discoveries!

Statistically likely to include exotic objects:
- double pulsars binaries, pulsar-BH binaries, sub-millisecond pulsars

High-precision timing of binary and MSPs
- Measuring relativistic orbital effects
- Many objects to follow up—multiplexed timing and astrometry with separate sub-arrays
Find them!
Time them!
VLBI them!

Blue: known pulsars from surveys other than PMB
Red: pulsars discovered by PMB
Green: simulated pulsar discoveries by PALFA (~1000)

Black: known pulsars
Blue: simulated pulsar discoveries by SKA (~10000) -- 64 μs samples, 1024 channels, 600 s per beam
Galactic Payoffs

- Galactic Center pulsars
  - Probing location and depth of GC ionized gas “screen”
  - Movement in potential of central BH
  - Measuring spin of BH from timing
- Probing electron number density
- Star formation history
- Galactic grav. potential
- Proper motions and parallaxes
Extragalactic Payoffs

- Giant pulse detection: pulsars in other galaxies
  - Current: a few pulsars known in LMC and SMC
  - Searches for giant pulses from M31

- Missing baryon problem
  - 4% of energy density in Universe as baryonic matter
  - Only a fraction of that accounted for by observations; what about not easily observable, compact dense objects?

- Probes of inter-galactic medium
  - Analogous to probing interstellar medium in the Galaxy

- Formation and population statistics
Pulsar Astrophysics Payoffs

- Magnetospheric properties
- Emission processes
- Pulsar wind nebulae, bow shocks and jets
- Equations of state
  - Properties of matter under extreme conditions
  - Fastest, slowest, most massive, least massive pulsar?
Gravitational Wave Detection

- Pulsar serve as arms of a huge grav. wave detector
- Oscillations in space-time can be detected in timing residuals
- Maybe hidden in timing noise—how to process and extract them?
- “Strain” \( h_c(f) \)—measure of space-time distortion:

\[
h_c(f) \sim \frac{\sigma_{TOA}}{T}
\]