A Radio Imaging Survey for Pulsars

April 23, 2015
Outline

Introduction
  Pulsars
  Searching for Pulsars
  Pulsar Surveys

VLA Pulsar Survey
  Methodology
  Example Field

Source Finding
  Aegean
  Simple Clustering
  Cross-Match

Summary
What are Pulsars?

- Rotating dipole magnetic field $\rightarrow$ electromagnetic radiation
- Radiation beamed in cones aligned with magnetic axis
- Lighthouse Model: We see a pulse when the conal beam intersects the Earth
What are Pulsars?

Stable Rotators $\Rightarrow$ Precise timing

Pulsed Radio Emission $\Rightarrow$ Impulse response of ISM
Pulsars: What are they good for?

Key Properties of Pulsars:

- Some of the most extreme objects in the Universe (surface
  gravity, density, magnetic fields, etc)
- Stable rotators with rotational periods as small as a few
  milliseconds
- Can be timed very precisely over long time spans
- Broadband radio emitters

⇒ Excellent laboratories for extreme physics
Pulsars: What are they good for?

(Bottom) Demorest et al. (2010), Hobbs et al. (2009)
Pulsar Search - Basic Idea

Essentially, a pulsar search is a search for periodic signals in noise. Take FFT, look for peaks in power spectrum:

\[ s(t) \xrightarrow{\text{FFT}} |S(f)|^2 \]

Telescope Signal \hspace{1cm} Power Spectrum

Time Series

Power Spectrum

Time

Frequency
Searching for Pulsars

Pulsar Search - Complications

However, this "ideal" pulsar signal is distorted by various effects:

- Dispersion in ISM
- Scattering by ISM
- Pulsar orbital motion
Pulsar Search - Complications

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- Scattering by ISM
- Pulsar orbital motion
Pulsar Search - Complications

However, this "ideal" pulsar signal is distorted by various effects:

- Dispersion in ISM ⇒ "de-dispersion" (1)
- Scattering by ISM ⇒ cannot correct
- Pulsar orbital motion
Pulsar Search - Complications

However, this "ideal" pulsar signal is distorted by various effects:

- Dispersion in ISM ⇒ "de-dispersion" (1)
- Scattering by ISM ⇒ cannot correct
- Pulsar orbital motion ⇒ "accel search" (1), orbital fitting (3-6)
Introducing the VLA Pulsar Survey

Source Finding Summary

Searching for Pulsars

Scattering

\[ \tau_{sc}/P = 0.0 \]

Pulse Shape

Power Spectrum

Frequency

0.00
0.05
0.10
0.15
0.20
0.25
0.30

0.0
2.0
4.0
6.0
8.0
10.0

Time

0.0
200
400
600
800
1000

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Searching for Pulsars

Scattering

\[ \tau_{sc}/P = 0.1 \]
Searching for Pulsars

Scattering

\[ \tau_{sc}/P = 0.5 \]
Scattering

\[ \tau_{sc}/P = 1.0 \]
Scattering

- Multipath scattering in the ISM broadens the pulse

- Scattering time: \( \tau_{sc} \propto \nu^{-4} \)

- Can’t correct \( \Rightarrow \) move to higher frequencies

- But: \( S_\nu \propto \nu^{\alpha} \) (\( \alpha \sim -1.6 \), \( \Omega \propto \nu^{-2} \))

- Galactic plane surveys \( \nu \approx 1.5 \) GHz

- Angular Broadening, too:
  \( \theta_{sc} \propto \nu^{-2} \)
Searching for Pulsars

Orbital Motion

Image Credit: Lorimer and Kramer (2005)
Survey Strategies

Two main strategies:

1. Standard periodicity and DM search (P-DM)
2. Finding survey with follow-up (FS+F)

**P-DM**

- 1) Tile survey region with pointings
- 2) Take time series data at each pointing
- 3) Search over period and DM
- 4) Inspect top candidates

- Found almost all \( \approx 2300 \) known pulsars
- PMPS: \( \geq 800 \) pulsars

**FS+F**

- 1) Select high prob objects or regions from finding survey
- 2) Follow-up with P-DM search

- Fermi + Radio: 300 unidentified LAT sources \( \rightarrow \) 43 MSPs + 4 CPs
- Higher prior prob for pulsar
- **Requires** P-DM to confirm
Overview Hybrid Search

Basic Plan for Hybrid Imaging/P-DM Survey:
1. Conduct sub-mJy arcsec-resolution imaging with the VLA
2. Identify all compact (i.e., unresolved) sources
3. Rank compact radio sources by likelihood of being a pulsar
4. Follow-up highest ranked candidates with Arecibo, GBT, or VLA

Imaging measures the time-averaged flux density, which is unaffected by pulse broadening and orbital smearing.

Possible Targets:
- Scattered MSPs
- Tight binaries (e.g., DNS)
- Sub-ms pulsars (if they exist)
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Summary
Hybrid Imaging/P-DM Search Steps

Basic Plan:

1. Conduct sub-mJy arcsec-resolution imaging with the VLA
2. Identify all compact (i.e., unresolved) sources
3. Rank compact radio sources by likelihood of being a pulsar
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Step 1: Done
Step 2: "Easy"
Step 3: Possibly very hard
Step 4: Done
Methodology

Survey Field

![Survey Field Diagram]

- **PALFA Discovery**
- **ATNF Catalog Pulsar**
Background Radio Source Estimates

\[ N \sim 10^3 \text{ deg}^{-2} \text{ extragalactic sources } \gtrsim 0.1 \text{ mJy} \]

Expect \sim 8 \text{ pulsars per square deg}

\[ \Rightarrow \text{ Lots of cutting to do!} \]

Data: Hopkins et al. (2003), Bondi et al. (2008)
Ranking Criteria

Determining ranking criteria is main goal of this pilot survey

Compactness:
- Pulsars essentially point sources
- xgal: $\theta_{\text{med}} \approx 1 \text{ arcsec} (S_{1.4}/0.1 \text{ mJy})^{0.3}$ (Windhorst et al. 1990)

Multiwavelength Comparison:
- X-ray or gamma-ray counterpart $\Rightarrow$ higher ranking
- IR (from, e.g., GLIMPSE) counterpart $\Rightarrow$ lower ranking

Spectral Index:
- Pulsars have steep spectral indices, $\alpha \sim -1.6$
- xgal sources are shallower, $\alpha \sim -0.6$

Temporal / Spectral Variability, Polarization
$\Rightarrow$ Will calibrate rankings on known pulsars
Example Field

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Example Field
VLA Pulsar Survey

Source Finding Summary

Example Field

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</tbody>
</table>

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Aegean

- Flood/Fill algorithm
- "seed" and "fill" thresholds
- Use $\sigma_s = 4$ and $\sigma_f = 3$
- $4\sigma_{\text{rms}} \sim 0.2$ mJy
- Find 844 sources
- $\sim 1 \text{ min for } 10^4 \times 10^4 \text{ pixels}

Image Credit: Hancock et al. (2012)
Aegean

J1850-0031

282.645 282.640 282.635 282.630
-0.515-0.520-0.525

Source Finding

Survey

Introduction
Aegaeon
Source Properties

Major Axis for Two Aegean Releases

Integrated Flux Density for Two Aegean Releases
Aegean Summary

- Finds 844 sources
- Roll-over at around 0.2 mJy as expected
- About half have major axis comparable to beam
- Parameters seem fine, errors probably underestimated
- To get intrinsic size, we need to deconvolve
- Picks up sidelobes (not really its fault)
Clustering

- Main science goal is to find point sources
- Don’t really care about extend source characterization
- Can go straight to the CLEAN components
- But all CLEAN components are points, need way to cluster into sources
Very Simple Clustering

1. Get list of CLEAN components
2. Go to (next) largest amplitude component
3. If not assigned to a cluster, assign to next cluster
4. Search nearby for other CLEAN components within some radius
5. If found, add to current cluster
6. Go back to 2 and repeat
Simple Clustering

CLEAN Components
Simple Clustering

Clusters of CLEAN Components

RA (deg)

Dec (deg)
Hough Transform

The Hough transform maps cartesian coordinates to sinusoids:

\[(x, y) \mapsto (R, \theta)\]

where

\[R = x \cos \theta + y \sin \theta \quad \theta \in [0, \pi)\]

So a point \((x, y)\) is mapped to the sinusoid \(R(\theta)\). Note that

\[y = (-\cot \theta) x + (R \csc \theta)\]

So each point in \((R, \theta)\) maps back to a line in \((x, y)\)
Simple Clustering

Hough Transform

*Image Credit: Wikipedia*
From this, we see a nice way to use the Hough transform for finding lines. The basic procedure goes something like this:

1. For a given point \((x, y)\) map to \((R(\theta), \theta)\) for \(\theta \in [0, \pi)\)
2. Bin the values of \(R\) and \(\theta\) and make 2D accumulator matrix, \(H\)
3. Add one to each \((R, \theta)\) bin in \(H\) from the \((x, y)\) mapping
4. Go back to Step 1 if more, else continue
5. Set some threshold in \(H\) and get all the \((R, \theta)\) values above that threshold
6. The resulting \((R, \theta)\) values define lines in the image plane
Simple Clustering

Clusters of CLEAN Components (After Flagging)
Simple Clustering

Clusters of CLEAN Components (After Flagging)
Source Properties

**RMS Distance from Cluster Center of Mass**
- **Flagged**
- **Unflagged**

**Number of Components per Cluster**
- **Flagged**
- **Unflagged**
Simple Clustering

Clustering Summary

- Start with 13184 CLEAN components
- Group into 3023 clusters
- After Hough filtering, 1642 clusters remain
- Simple to implement
- Poor source characterization (e.g., size, flux)
Overlap between Aegean and Clustering?

- Aegean is effective, but contaminated with sidelobe
- Clusters are filtered, but poor characterization
- Compare the 1645 unflagged clusters to 844 Aegean sources
- Find 426 matches
Cross-Match

Aegean / Cluster No Match (to 5 arcsec)

CC Cluster

Aegean
Cross-Match
## Cross-Match Summary

- Compare 1645 unflagged clusters to 844 Aegean sources
- Find 426 matches for high quality candidates
- Detect both known pulsars
- Seem to have excess over background sources
- Next step is to look for more ways to make cuts
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Summary

- Illustrated some common problems with source finding in radio imaging
- This will continue to be an issue as surveys go deeper
- Vast amounts of data require robust automated source finding
- Source finders find sources
- Making sure they are the right "sources" requires classification
This is the end.
Temporal and Angular Broadening at 1.5 GHz

\[ \tau_{\text{red}} = 1 \text{ ms}, \quad \tau_{\text{blue}} = 10 \text{ ms}, \quad \tau_{\text{green}} = 20 \text{ ms} \]

\[ \theta_{\text{red}} = 0.1 \text{ arcsec} \]

Image Credit: Jim Cordes
Orbital Motion

Orbital motion causes a time-varying apparent spin frequency
  ▶ Spreads power over many frequencies
  ▶ Reduces the Fourier amplitudes in spectrum

Acceleration Search:
  ▶ Search over constant acceleration values
  ▶ Additional search parameter and statistical trials
  ▶ Approximate, valid for $T_{\text{obs}} \lesssim 0.1P_{\text{orb}}$

Orbit Fitting:
  ▶ Search over and fit all orbital parameters
  ▶ Additional search parameters and statistical trials
  ▶ Can be approximate or exact, computationally intensive
Orbital Motion

\[ T_{\text{obs}} \approx 5 \text{ min} \]

Binary pulsars with \( P_{\text{orb}} \lesssim 1 \text{ hr} \) selected against

Imaging survey unaffected

Image Credit: Jim Cordes