Pulsars I.  
The Why and How of Searching for Exotic Pulsars  
Jim Cordes, Cornell University

- Why would you want to know about pulsars and why would you like to discover more?  
  - Science, the big questions
- How do I find new pulsars?
- How do I estimate pulsar distances?
- What can I learn about …
  - the inside of a NS?
  - the magnetosphere of a NS?
  - the space velocity of a pulsar?
  - the ISM along the path to a pulsar?

Pulsars…

- Embody physics of the EXTREME
  - surface speed ~0.1c
  - 10x nuclear density in center
  - some have $B > B_\odot = 4.4 \times 10^{13}$ G
  - Voltage drops ~ $10^{12}$ volts
  - $F_{\text{EM}} = 10^{15} F_\odot = 10^9 F_{\text{Earth}}$
  - $T_{\text{surf}} \sim 10^6 \text{ K}$
- Relativistic plasma physics in action ($\gamma \sim 10^5$)
- Probes of turbulent and magnetized ISM
- Precision tools, e.g.
  - Period of B1937+21 (the fastest millisecond pulsar)
  - $P = 0.0015578064924327 \pm 0.0000000000000004 \text{ s}$
    - Orbital eccentricity of J1012+5307: $e<0.0000008$
- Laboratories for extreme states of matter and as clocks for probing space-time and Galactic material

Pulsar Sounds

Radio signals demodulated into audio signals

<table>
<thead>
<tr>
<th>Pulsar</th>
<th>$P$ (ms)</th>
<th>$f=1/P$ (Hz)</th>
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<tbody>
<tr>
<td>B0329+54</td>
<td>714</td>
<td>1.4</td>
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<tr>
<td>B0950+08</td>
<td>253</td>
<td>3.9</td>
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<td>B0833-45 (Vela)</td>
<td>89</td>
<td>11.2</td>
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<tr>
<td>B0531+21 (Crab)</td>
<td>33</td>
<td>30.2</td>
</tr>
<tr>
<td>J0437-4715</td>
<td>5.7</td>
<td>174</td>
</tr>
<tr>
<td>B1937+21</td>
<td>1.56</td>
<td>642</td>
</tr>
</tbody>
</table>

Neutron Star Astrophysics

Surface quantities:

- $B = 10^{15}$ Gauss
- $B_{\odot} = 10^4$ Gauss
- $F_{\text{EM}} = 10^9 F_{\text{Earth}}$
- $\gamma = 10^3$ volts
Pulsar Populations: $P - \dot{P}$ diagram

- Canonical
  - $P \approx 20\text{ms} - 5\text{s}$
  - $B \approx 10^{17}\text{G}$
- Millisecond pulsars (MSPs)
  - $P \approx 1.5 - 20\text{ms}$
  - $B \approx 10^{12} - 10^{13}\text{G}$
- High field
  - $P \approx 5 - 8\text{s}$
  - $B \approx \text{few } 10^{13}\text{G}$
- Braking index $n$:
  - $P \propto P^{-3}$
  - $m$-3 magnetic dipole radiation
- Death line
- Strong selection effects

Manifestations of NS:

- Rotation driven:
  - "radio" pulsars (radio $\rightarrow$ gamma rays)
  - magnetic torque $\dot{E} \propto \Delta I \propto B^2 \Omega^2$
  - $\gamma \gamma \rightarrow e^+ e^- +$ plasma instability $\Rightarrow$ coherent radio
- Accretion driven:
  - X-rays $L_X \approx e\dot{M}c^2$
  - LMXB, HMXB
- Magnetic driven: Crustquakes?
  - Magnetars (AXPs, SGRs)
  - Spindown ... but $L_H \gg \dot{E}$
- Gravitational catastrophes?
  - Gamma-ray bursts, G-wave sources, hypernovae?

Quarks to Cosmos: Relevant Questions

- Did Einstein have the last word on Gravity?
- How do cosmic accelerators work and what are they accelerating?
- What are the new states of matter at exceedingly high density and temperature?
- Is a new theory of light and matter needed at the highest energies?
A Double-Pulsar System: A Rare Laboratory for Relativistic Gravity and Plasma Physics

A. G. Lyne, 1,4 M. Burgay, 2 M. Kramer, 3 A. Possenti, 3,4 R.N. Manchester, 1 F. Camilo, 5 M. A. McLaughlin, 1 D. R. Lorimer, 1 N. D’Amico, 1,3 B. C. Joshi, 6 J. Reynolds, 4 P. C. Freire

The double properties of pulsars moving in the gravitational fields of their dense neutron-star companions have allowed unique tests of general relativity and provided evidence for gravitational radiation. We report here the detection of the 2.8-second pulsar J0737–3039 as the companion to the 23-millisecond pulsar J0737–3039A in a highly relativistic double neutron star system, allowing unprecedented tests of fundamental gravitational physics. We observed a short eclipse of J0737–3039A by J0737–3039B and orbital modulation of the flux density and the polar shape of J0737–3039A, probably because of the influence of J0737–3039A’s energy flux on its magnetosphere. These effects will allow us to probe magneto-tensor properties of a pulsar magnetosphere.

What are the Big Questions?

• Formation and Evolution:
  • What determines if a NS is born as a magnetar vs a canonical pulsar?
  • How fast do NS spin at birth?
  • How fast can recycled pulsars spin?
  • What is the role of instabilities and gravitational radiation in determining the spin state?
  • How do momentum thrusts during core collapse affect the resulting spin state and translational motion of the NS?
  • What processes determine the high space velocities of NS?
    • Neutrino emission
    • Matter rocket effects
    • Electromagnetic rocket effect (Harrison-Tademaru)
    • Gravitational-wave rocket effect
  • Are orbital spiral-in events at all related to high-energy bursts? (GRBs? Other transients?)

Bow Shocks

First Double Pulsar: J0737-3939

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Bow Shocks

Guitar Nebula:

• Ordinary pulsar
  • P = 0.68 s
  • B = 2.6 x 10^12 G
  • E > 1.1 Myr
  • E_m = 10^{51} erg s^-1
  • D = 1.9 kpc (from DM)
  • 1600 km s^-1 at nominal distance
  • Will escape the Milky Way

Radius of curvature of bowshock nose increased from 1994 to 2001, corresponding to a 33% decrease in ISM density
The pulsar is emerging from a region of enhanced density

Palomar H: image

Guitar Nebula: 1994

Chatterjee & Cordes 2004
What are the Big Questions?

• NS Structure:
  • Are neutron stars really neutron stars?
  • What comprises the core of a NS?
  • What is the mass distribution of NS?
  • In what regions are the neutrons in a superfluid state?
  • How large are interior magnetic fields?
• Magnetosphere and Emission Physics:
  • What QED processes are relevant for electromagnetic emissions?

• NS as Laboratories:
  • Can departures from General Relativity be identified in the orbits of compact binary pulsars?
  • Does the Strong-Equivalence Principle hold to high precision in pulsars with WD or BH companions?
• NS as Gravitational Wave Detectors:
  • Use pulsars to detect long-period gravitational waves
    - Early universe
    - Mergers of supermassive black holes
    - Topological defects (cosmic strings)
• Pulsars as Probes of Galactic Structure
  • What kind of spiral structure does the Galaxy have?
  • What is the nature of interstellar turbulence?

Forefronts in NS Science

• Understanding NS populations and their physical differences
  • Radio pulsars and their progenitors
  • Magnetars
  • Radio quiet/Gamma-ray loud objects
  • Branching ratios in supernovae
• The physics of NS runaway velocities
• Are “neutron stars” neutron stars?

Forefronts in NS Science

• Finding compact relativistic binary pulsars for use as laboratories
  • Gravity
  • Relativistic plasma physics in strong B
• Finding spin-stable MSPs for use as gravitational wave detectors ($\lambda \sim$ light years)
  • $h \sim \sigma_{\text{TOA}} T^{-1}$ ($T =$ data span length)
• Complete surveys of the transient radio sky
  • pulsars as prototype coherent radio emission

Fulfilling the Promise of NS Physics and Astrophysics

• Find more pulsars
• Time them with maximal precision
• Phase-resolved polarimetry
• VLBI them to get high astrometric precision

Step 1: conduct surveys that optimize the detection of faint, pulsed emission that is dispersed and that may or may not be periodic.
### Arecibo + SKA Surveys

![Graph depicting Pulsar Search Domains](image)

<table>
<thead>
<tr>
<th>Region/Direction</th>
<th>Kind of Pulsar</th>
<th>Telescope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galactic Plane</td>
<td>Young pulsars (&lt; 1 Myr)</td>
<td>Arecibo, Effelsburg, GBT, Jodrell, Parkes, WSRT</td>
</tr>
<tr>
<td>Galactic Center</td>
<td>Young, recycled, binary, circ-SgrA*</td>
<td>GBT, SKA</td>
</tr>
<tr>
<td>Moderate Galactic latitudes</td>
<td>MSPs, binary, runaway</td>
<td>Arecibo, GBT, Parkes</td>
</tr>
<tr>
<td>Globular clusters</td>
<td>MSPs, binary, runaway</td>
<td>Arecibo, GBT, Parkes</td>
</tr>
<tr>
<td>Local Group Galaxies</td>
<td>Young (probably), Giant pulses</td>
<td>Arecibo, GBT, SKA</td>
</tr>
</tbody>
</table>

### Pulsar Search Domains

**Basic data unit = a dynamic spectrum**

- Fast-dump spectrometers:
  - Analog filter banks
  - Correlators
  - FFT (hardware)
  - FFT (software)
  - Polyphase filter bank

- E.g., WAPP, GBT correlator + spigot card, new PALFA correlator

**Refractive indices for cold, magnetized plasma**

\[
\hat{n}_{tr} \sim 1 - \frac{n_p^2}{2n^2} = \frac{n_p^2}{2} n_{B||} 2n^3
\]

\[n >> n_p \sim 2 \text{ kHz} \quad n >> n_{B||} \sim 3 \text{ Hz}\]

Group velocity \(\Rightarrow\) group delay = \(\Delta (\text{time of arrival})\)

\[
t = t_{DM} \pm t_{RM}
\]

\[
t_{DM} = 4.15 \text{ ms} \quad \text{DM} \quad \nu^{-2}
\]

\[
t_{RM} = 0.18 \text{ ns} \quad \text{RM} \quad \nu^{-3}
\]

Dispersion Measure \(\text{DM} = \int ds n_e \text{ pc cm}^{-3}\)

Rotation Measure \(\text{RM} = 0.81 \int ds n_e B_{||} \text{ rad m}^{-2}\)

**A Single Dispersed Pulse from the Crab Pulsar**

![Graph showing a single dispersed pulse](image)

\[S \sim 160 \times \text{Crab Nebula} \sim 200 \text{ kly}\]

Detectable to \(\sim 1.5 \text{ Mpc with Arecibo}\)

\[\text{DM} = 4.15 \text{ ms} \quad \nu^{-2}\]

\[\text{RM} = 0.18 \text{ ns} \quad \nu^{-3}\]

**Refractive indices for cold, magnetized plasma**

\[
n_{tr} \sim 1 - \frac{v_p^2}{2v^2} - \frac{v_p^2}{v_{B||}} 2v^3
\]

\[v >> v_p \sim 2 \text{ kHz} \quad v >> v_{B||} \sim 3 \text{ Hz}\]

Group velocity \(\Rightarrow\) group delay = \(\Delta (\text{time of arrival})\)
Issues In Pulsar Survey Optimization

- Combine the signal over time and frequency while maximizing S/N through matched filtering:
  - Dedispersion: sum over frequency while removing the dispersive time delays
  - Single pulses: match the shape and width of the pulse
  - Periodic pulses: match the period as well as the pulse shape and width
  - Orbital motion: match the change in pulse arrival times related to the changing Doppler effect

  ⇒ Single-pulse searches:
  - Search vs. (DM, W)
  ⇒ Periodicity searches:
  - Search vs. (DM, W, P, [orbital parameters])

Issues In Pulsar Survey Optimization

- Broad luminosity function for pulsars
  - Beam luminosity
  - Geometric beaming
- Pulse sharpness
  - Intrinsic pulse width W
  - Smearing from propagation effects
    - Dispersion across finite bandwidth (correctable)
    - Multipath propagation (scattering in the ISM)
  - Smearing from orbital acceleration
- Intermittency of the pulsar signal
  - Nulling, giant pulses, precession, eclipsing
  - Interstellar scintillation

Dedispersion

Two methods:

Coherent:
- operates on the voltage proportional to the electric field accepted by the antenna, feed and receiver
- computationally intensive because it requires sampling at the rate of the total bandwidth
- “exact”

Post-detection:
- operates on intensity = |voltage|^2
- computationally less demanding
- an approximation
Basic data unit = a dynamic spectrum

Fast-dump spectrometers:
- Analog filter banks
- Correlators
- FFT (hardware)
- FFT (software)
- Polyphase filter bank

E.g. WAPP, GBT correlator + spigot card, new PALFA correlator

Coherent Dedispersion
pioneered by Tim Hankins (1971)

Dispersion delays in the time domain represent a phase perturbation of the electric field in the Fourier domain:

$$E_{\text{measured}}(\omega) = E_{\text{emitted}}(\omega)e^{iK(\omega)z}$$

Coherent dedispersion involves multiplication of Fourier amplitudes by the inverse function,

$$e^{-iK(\omega)z}$$

For the non-uniform ISM, we have

$$k(\omega)z \rightarrow \frac{1}{dz} k(\omega) \propto \omega^2 DM + \text{constant}$$

which is known to high precision for known pulsars.

The algorithm consists of

$$\text{FFT}[\text{FFT} \{E_{\text{measured}}(t) \times e^{-iK(\omega)z}\}] \approx E_{\text{emitted}}(t)$$

Application requires very fast sampling to achieve usable bandwidths.

Coherent Dedispersion works by explicit deconvolution:

$$E_{\text{measured}}(t) = E_{\text{emitted}}(t) \ast \text{FFT} \{e^{iK(\omega)z}\}$$

$$\Rightarrow E_{\text{emitted}}(t) \approx E_{\text{measured}}(t) \ast \text{FFT} \{e^{-iK(\omega)z}\}$$

Comments and Caveats:
- Software implementation with FFTs to accomplish deconvolution (Hankins 1971)
- Hardware implementations: real-time FIR filters (e.g. Backer et al. 1990s-present)
- Resulting time resolution: 1 / (total bandwidth)
- Requires sampling at Nyquist rate of 2 samples $\times$ bandwidth
  - Computationally demanding
- Actual time resolution often determined by interstellar scattering (multipath)
- Most useful for low-DM pulsars and/or high-frequency observations

Micropulses coherently dedispersed (Hankins 1971)

Nanostructure in Crab pulsar giant pulses
Interstellar scattering from electron density variations

- Pulsar velocities >> ISM, observer velocities
- Scattering is strong for frequencies < 5 GHz
- Electron density irregularities exist on scales from ~100’s km to Galactic scales

Interstellar Scattering Effects

- Angular broadening (seeing)
- Pulse broadening
- Diffractive interstellar scintillations (DISS)
- Refractive interstellar scintillations (RISS)
- TOA fluctuations (multiple effects)
- Superresolution phenomena: stars twinkle, planets don’t ⇒ pulsars show DISS, AGNs don’t

Pulse broadening from interstellar scattering:
\[ \tau_d \sim \text{rms excess path length} \sim \frac{\Delta \rho^2}{2c} \propto \nu^{-4} \]

Postdetection Dedispersion:
Sum intensity over frequency after correcting for dispersion delay

Residual time smearing:
\[ \Delta t = \left[ \left( \frac{\Delta \nu}{\nu} \right)^2 + \left( \frac{\Delta \nu}{\nu} \right)^2 \right]^{1/2} \]
\[ = \left[ \left( \frac{\Delta \nu}{\nu} \right)^2 + \left( \frac{\Delta \nu}{\nu} \right)^2 \right]^{1/2} \]
\[ \Rightarrow \text{minimum smearing time across a channel when} \]
\[ \Delta \nu = \left( 1.3 \, \mu \text{s DM}^{-3} \right)^{1/2} \]
Choose $\Delta t \Rightarrow$ maximum DM

Dedispersion at a single known DM

Dedispersion over a set of DMs

Single Pulse Studies & Searches

Nano-giant pulses (Hankins et al. 2003)

Giant pulse from the Crab pulsar
$S \approx 160\times$ Crab Nebula
$\sim 200$ kly
Detectable to $\sim 1.5$ Mpc
with Arecibo

2-ns giant pulses from
the Crab (Hankins et
al. 2003)

Giant Pulses seen
from B0540-69 in
LMC (Johnston &
Romani 2003)
Single pulse searches

A pulsar found through its single-pulse emission, not its periodicity (c.f. Crab giant pulses).

Algorithm: matched filtering in the DM-t plane.

ALFA’s 7 beams provide powerful discrimination between celestial and RFI transients.

Pulsar Periodicity Search

Example Periodicity Search Algorithm
Harmonic Sum

The FFT of periodic pulses is a series of spikes (harmonics) separated by 1/P.

To improve S/N, sum harmonics. This procedure is an approximation to true matched filtering, which would give optimum S/N.

Sum how many harmonics?

The answer depends on the pulse “duty cycle” = (pulse width / P) (unknown a priori)
⇒ need to use trial values of \( N_h \):

\[
\sum h(\nu_h) = N_h^{-1/2} \sum_{j=0}^{N_h} \text{FFT}(\nu_j) \quad \nu_j = \frac{j}{P}
\]

Maximize \( h(\nu_j) \) with respect to \( N_h \) to identify candidate pulsars.

Noise and RFI conspire to yield spurious candidates.

∴ Need a high threshold. How high?

Minimum detectable flux density for a single harmonic:

\[
S_{\text{min, single}} = m \times \sigma_{\text{rademeter}}
\]

Minimum detectable flux density for harmonic sum:

\[
S_{\text{min, sum}} = \frac{S_{\text{min, single}}}{\sqrt{N_h}}
\]
Dealing With Orbital Motion

Orbital acceleration yields a time-dependent period, potentially destroying the power of the straightforward FFT + HS.

- **Long-period binaries:** $T = \text{data span length} \ll P_{\text{orb}}$
  - Do nothing different
- **Intermediate-period orbits:** $T < 0.1 P_{\text{orb}}$
  - Acceleration search: compensate the time domain or match filter in the frequency domain according to an acceleration parameter
  - Adds another search parameter: DM, P, W, a
- **Very short-period orbits:** $T > P_{\text{orb}}$ (potentially $>> P_{\text{orb}}$)
  - Do conventional FFT but search for orbital sidebands

How Far Can We Look?

$$D_{\max} = D \left( \frac{S}{S_{\min}} \right)^{1/2} N_h^{1/4}$$

$S_{\min}$ = single harmonic threshold = $m S_{\text{sys}}/(\Delta \nu \Delta T)^{1/2}$

$m$ = no. of sigma ~ 10

$N_h$ = no. of harmonics that maximize harmonic sum

$N_h \rightarrow 0$ for heavily broadened pulses (scattering)

**Regimes:**

- Luminosity limited $D_{\max} \propto S_{\min}^{-1/2}$
- DM/SM limited $D_{\max} \propto S_{\min}^{-x}$, $x<1/2$

**Implications:**

- **Optimal integration time:**
- **Fast-dump spectrometers:**
- **Better to cover more solid angle than to integrate longer on a given direction**

AO at S,L,P bands

Add slides showing sensitivity curves for Arecibo
Survey Selection Against Binaries

Hardware for Pulsar Science

Predetection Samplers and Analyzers:
- ASP, GASP (Arecibo & Green Bank)
  - Real-time dedispersion and folding
- New Mexico Tech burst sampler
  - Off-line dedispersion
- Generic baseband samplers (c.f. radar samplers)

Postdetection Samplers:
- WAPP (Arecibo), SPIGOT (GBT) (correlators)
  - Searching and timing machines
- New PALFA spectrometer (polyphase filter bank)
  - Primarily a search machine

Software for Pulsar Searching

- Many proprietary packages
- Sigproc/Seek package
- PRESTO
- Cornell Code
- Berkeley Code
- PALFA: the PALFA Consortium is testing and consolidating codes to produce a new "standard" pulsar search package

Massive ALFA Pulsar Surveys

10^5 new pulsars
- Reach edge of Galactic population for much of pulsar luminosity function
- High sensitivity to millisecond pulsars
- \( D_{\text{max}} \approx 2 \) to 3 times greater than for Parkes MB

Sensitivity to transient sources
Commensal SETI Search (Wertheimer UCB)

Data management:
- Keep all raw data (~1 Petabyte after 5 years) at the Cornell Theory Center (CISE grant: $1.8M)
- Database of raw data, data products, end products
- Web based tools for Linux-Windows interface (mysql ↔ ServerSql)
- VO linkage (in future)
**SKA: What is It?**

- An array telescope that combines complete sky coverage and complementary sampling of the time, frequency and spatial domains, with a 200-600 increase in collecting area (~1 km²) over existing telescopes.
- Frequency range 0.1 – 25 GHz (nominal).
- Limited gain from reducing receiver noise or increasing bandwidth once the EVLA is finished.
- Innovative designs are needed to reduce cost.
- 10⁶ meter² = ~10,000 per meter².
- An international project from the start.
- International funding.
- 17-country international consortium.
- Can do science as you go.
- The existing US radio astronomy portfolio is the foundation on which to build the SKA.

**Pulsar Distances**

<table>
<thead>
<tr>
<th>Type</th>
<th>Number</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parallaxes:</td>
<td>~13</td>
<td>1 mas @ 1 kpc</td>
</tr>
<tr>
<td>Interferometry</td>
<td>~ 5</td>
<td>1.6 μs @ 1 kpc</td>
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<tr>
<td>timing</td>
<td>~ 1</td>
<td>HST, point spread function</td>
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<td>optical</td>
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<td>Associations</td>
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<td></td>
<td>GCs 16</td>
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<td></td>
<td>LMC/SMC~6</td>
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<td>HI absorption</td>
<td>74</td>
<td>bright pulsars, galactic rotation model</td>
</tr>
<tr>
<td>DM + n_e model</td>
<td>all radio pulsars (~1400)</td>
<td>ISM perturbations</td>
</tr>
</tbody>
</table>

**NE2001: Galactic Distribution of Free Electrons + Fluctuations**

Paper I = the model (astro-ph/0207156)

Paper II = methodology & particular lines of sight (astro-ph/0301598)

Based on ~ 1500 lines of sight to pulsars and extragalactic objects

Code + driver files + papers:
But … if you want a good distance, measure the parallax!

\[ \text{e.g. Arecibo + GBT + VLA} + \text{VLBA} \]

will be a powerful parallax and proper motion machine

**Very Long Baseline Array**

PSR B0919+06
S. Chatterjee et al. (2001)
\[ \mu = 88.5 \pm 0.13 \text{ mas/yr} \]
\[ \pi = 0.83 \pm 0.13 \text{ mas} \]

**Proper motion and parallax using the VLBA** (Brisken et al. 2001)

**PSR B1929+10**
Chatterjee et al. 2003

\[ D = 1.2 \text{kpc} \]
\[ V = 505 \text{ km/s} \]