ANOMALOUS PULSAR SCATTERING

AT LOFAR FREQUENCIES

THE LABYRINTH OF THE UNEXPECTED
UNFORESEEN TREASURES IN IMPOSSIBLE REGIONS OF PHASE SPACE
ANOMALOUS PULSAR SCATTERING AT LOFAR FREQUENCIES

THE LABYRINTH OF THE UNEXPECTED UNFORESEEN TREASURES IN IMPOSSIBLE REGIONS OF PHASE SPACE

Marisa Geyer, Aris Karastergiou at Oxford University
Collaborators: Members of LOFAR PWG
CONTENTS

1. OVERVIEW PULSAR SCATTERING
2. THEORETICALLY EXPECTED RESULTS
3. FITTING TECHNIQUES
4. ANALYSIS OF LOFAR DATA
5. IMPLICATIONS AND DISCUSSION
PULSAR SCATTERING THEORY

- Multi-path propagation of radio waves due to electron density gradients in the ISM
- Observe scattering tails in average pulse profiles at low frequencies
- Require description of distribution in scattering angles and time delays and their frequency dependencies
Scattering takes place at single location along the line of sight.
## Isotropic Scattering

Scattering screen scatters isotropically

Simple case: circularly symmetric Gaussian distribution in \( \mathbf{a} \)

\[
\begin{align*}
  f_t &= \tau^{-1} e^{-t/\tau} U(t) \\
  \tau &= D_s' \sigma_a^2 / c \\
  D_s' &= D_s (1 - D_s / D), \\
  \text{plasma scattering, } \sigma_a &\propto v^{-2} \\
  \text{leads to } \tau &\propto v^{-4}
\end{align*}
\]

## Anisotropic Scattering

Distribution scattering angles shows directionality

Simple case: asymmetric Gaussian distribution \( \sigma_x \neq \sigma_y \)

\[
\begin{align*}
  f_t &= \frac{1}{\sqrt{\tau_x \tau_y}} e^{-\frac{1}{2} \left( \frac{1}{\tau_x} + \frac{1}{\tau_y} \right)} I(0, \frac{t}{2} \left( \frac{1}{\tau_x} - \frac{1}{\tau_y} \right)) \\
  \text{in the extreme case 1D scattering} \\
  f_t &= e^{-t/\tau} / (\sqrt{\pi t \tau}) U(t)
\end{align*}
\]
PULSAR SCATTERING - BROADENING FUNCTIONS

1. OVERVIEW PULSAR SCATTERING

Isotropic Scattering

Anisotropic Scattering

Distribution scattering angles show directionality

Simple case: asymmetric Gaussian distribution distribution $\sigma_x \neq \sigma_y$

\[
f_t = \frac{1}{\sqrt{\tau_x \tau_y}} e^{-\frac{t}{2} \left(\frac{1}{\tau_x} + \frac{1}{\tau_y}\right)} I(0, \frac{t}{2} \left(\frac{1}{\tau_x} - \frac{1}{\tau_y}\right))
\]

in the extreme case 1D scattering

\[
f_t = e^{-t/\tau} / (\sqrt{\pi t \tau}) U(t)
\]

at 150MHz, midway screen at 1.5kpc
EXTERNAL EVIDENCE FOR ANISOTROPIC SCATTERING

- VLBI image of PSR B0834+06 at 327 MHz
- Brisken et al. 2010

- Organized patterns in dynamic spectra
- Parabolic arcs in secondary (power) spectra
- Enhanced for elongated (anisotropic) images
- Stinebring et al. 2001, Walker et al. 2004
2. THEORETICALLY EXPECTED RESULTS

THEORETICAL EXPECTATIONS

- Gaussian scattering: $\tau \propto \nu^{-4}$
- Kolmogorov Turbulence: $\tau \propto \nu^{-4.4}$

LITERATURE MEASURED $\alpha$ VALUES

- Löhmer et al. 2001: $\alpha = 3.44$ (9 sources, at high DMs)
- Lewandowski et al. 2013: $\alpha = 2.77 - 4.59$ (25 sources)
- Lewandowski et al. 2015: $\alpha = 2.61 - 5.61$ (60 sources)
- Smirnova et al. 2014 using RadioAstron: B0950+08, $\alpha = 3.00$
FITTING TECHNIQUE - ‘TRAIN MODELS’

- Gaussian pulse train
- IISM broadening function
- Scattered pulse train

**LONG TRAIN METHOD**

- Gaussian pulse train
- IISM broadening function
- Scattered pulse train

**TRAIN METHOD**

- Gaussian pulse train
- IISM broadening function
- Scattered pulse train
3. FITTING TECHNIQUES

FITTING TECHNIQUE - ‘TRAIN MODELS’

- Train Method - simplest, fastest
- Deals effectively with high levels of scattering where pulses are smeared into one another
- Keeps track of flux ‘lost’ due to high levels of scattering

Graph showing the difference in models with axes labeled as follows:
- X-axis: N
- Y-axis: Max. residual over pulse period
- Equation: $\tau = 2P$

Diagram illustrating the train method with intensity over time.
3. FITTING TECHNIQUES

FITTING TECHNIQUE - ‘TRAIN + DC MODEL’

- Fits for underlying Gaussian parameters (μ, σ, A)
- Fits for scattering timescale τ
- Add DC offset
- It works
LOFAR SOURCES

- Selected 13 slow (non-ms) pulsars
- Observed with LOFAR Core stations
- Scattered at HBA frequencies (110 - 190 MHz)
- LOFAR: Provides a large bandwidth at low frequencies (80MHz/150MHz)
- Simple profile shapes (approximated by single Gaussian component)
- DM range: 50 - 220 pc cm$^{-3}$
- Selected from Commissioning data, Census data (190, DEC > 8) and some overlapping Cycle 5 LOFAR timing data
3. LOFAR ANALYSIS AND RESULTS

**PSR J0614+2229 (B0611+22)**

- RED FIT: Isotropic model, BLUE FIT: Extreme Anisotropic (1D) model
- scattering indices ($\alpha$) are lower than theoretical models predict
- often closer to theoretical values for anisotropic models
- recover the flux lost due to scattering
3. LOFAR ANALYSIS AND RESULTS

PSR J1922+2110 (B1920+21)

- measure DM corrections due to scattering effects
- most often an overestimation
3. LOFAR ANALYSIS AND RESULTS

RESULTS TABLE

<table>
<thead>
<tr>
<th>Pulsar</th>
<th>Isotropic Scattering</th>
<th></th>
<th>Extreme (1D) Anisotropic Scattering</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \tau_{150} ) (ms)</td>
<td>( \alpha )</td>
<td>( \Delta DM ) (pc cm(^{-3}))</td>
<td>( \tau_{150} ) (ms)</td>
</tr>
<tr>
<td>J0040+5716</td>
<td>40 ± 2</td>
<td>2.2 ± 0.2</td>
<td>0.0378 ± 0.0024</td>
<td>86 ± 8</td>
</tr>
<tr>
<td>J0117+5914 (Co)</td>
<td>7 ± 0</td>
<td>2.2 ± 0.1</td>
<td>0.0082 ± 0.0009</td>
<td>14 ± 1</td>
</tr>
<tr>
<td>J0117+5914 (Ce)</td>
<td>8 ± 1</td>
<td>1.9 ± 0.2</td>
<td>0.0064 ± 0.0006</td>
<td>16 ± 2</td>
</tr>
<tr>
<td>J0543+2329</td>
<td>10 ± 1</td>
<td>2.6 ± 0.2</td>
<td>0.0155 ± 0.0020</td>
<td>17 ± 2</td>
</tr>
<tr>
<td>J0614+2229 (Co)</td>
<td>15 ± 1</td>
<td>1.9 ± 0.1</td>
<td>0.0030 ± 0.0007</td>
<td>44 ± 4</td>
</tr>
<tr>
<td>J0614+2229 (Cy)</td>
<td>15 ± 0</td>
<td>2.1 ± 0.1</td>
<td>−0.0053 ± 0.0006</td>
<td>44 ± 3</td>
</tr>
<tr>
<td>J0742−2822</td>
<td>20 ± 2</td>
<td>3.8 ± 0.4</td>
<td>0.0013 ± 0.0027</td>
<td>...</td>
</tr>
<tr>
<td>J1851+1259</td>
<td>6 ± 1</td>
<td>4.0 ± 0.4</td>
<td>0.0264 ± 0.0022</td>
<td>10 ± 1</td>
</tr>
<tr>
<td>J1909+1102</td>
<td>42 ± 3</td>
<td>3.5 ± 0.4</td>
<td>0.0351 ± 0.0085</td>
<td>120 ± 27</td>
</tr>
<tr>
<td>J1913−0440 (Co)</td>
<td>9 ± 0</td>
<td>2.7 ± 0.2</td>
<td>0.0240 ± 0.0009</td>
<td>16 ± 1</td>
</tr>
<tr>
<td>J1913−0440 (Cy)</td>
<td>7 ± 0</td>
<td>3.3 ± 0.1</td>
<td>0.0457 ± 0.0003</td>
<td>12 ± 0</td>
</tr>
<tr>
<td>J1917+1353</td>
<td>11 ± 1</td>
<td>2.8 ± 0.4</td>
<td>−0.1004 ± 0.0025</td>
<td>21 ± 2</td>
</tr>
<tr>
<td>J1922+2110</td>
<td>42 ± 2</td>
<td>2.0 ± 0.2</td>
<td>0.0829 ± 0.0025</td>
<td>85 ± 6</td>
</tr>
<tr>
<td>J1935+1616</td>
<td>20 ± 1</td>
<td>3.4 ± 0.2</td>
<td>−0.0635 ± 0.0030</td>
<td>46 ± 4</td>
</tr>
<tr>
<td>J2257+5909</td>
<td>31 ± 2</td>
<td>2.6 ± 0.4</td>
<td>−0.0317 ± 0.0058</td>
<td>68 ± 9</td>
</tr>
<tr>
<td>J2305+3100</td>
<td>9 ± 0</td>
<td>1.5 ± 0.1</td>
<td>0.0184 ± 0.0035</td>
<td>11 ± 0</td>
</tr>
<tr>
<td>( \langle \alpha \rangle )</td>
<td></td>
<td>2.7 ± 0.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4. IMPLICATIONS AND DISCUSSION

ORIGIN OF LOW SCATTERING INDICES?

|-------------|-------------|----------------------|-------|--------------|--------------|-----------------|-----------------|

Truncated screens - can reproduce the $\alpha$ distribution with ~100 AU screens

The dominance of truncated screen could decrease with increase in distance/DM

Löhmer 2001 suggested lower $\alpha$ with an increase in DM

We see low $\alpha$ at low DMs
SIDE NOTE: ‘TRUNCATED PROFILES’

- Simulated midway screen 120 AU, distance 1.5 kpc
- Pulsars appear much less scattered
ANISOTROPY REQUIRED?

- Does our data require anisotropic scattering models?
- Not strictly
- Tempting in some cases (4 pulsars):
  - goodness of fit ($\chi^2$, KS) slightly better for anisotropic model
  - anisotropic $\Delta$DM corrections between epochs lead to more similar DMs
  - $\alpha$ values isotropic and anisotropic models are well separated
  - anisotropic $\alpha$ values closer to theoretical values

Geyer et al. MNRAS (2016) 462 (3)
ANISOTROPY REQUIRED?

- Does our data require anisotropic scattering models?
  - Not strictly

- It definitely is a mechanism that can cause perceived low $\alpha$ values

- Simulated data: shown that fitting anisotropic data (e.g. $A = 3$) with isotropic model lead low $\alpha$ values

- Existing evidence for anisotropy - e.g Brisken pulsar, parabolic arcs in secondary spectra

---

Geyer et al. MNRAS (2016) 462 (3)
4. IMPLICATIONS AND DISCUSSION

EVOLUTION OF SPECTRAL INDICES WITH FREQUENCY?

- $\tau$ at 1 GHz vs DM
- Compare Bhat 2004
- Our data (along with Lewandowski et al. 2013 and 2015) promote higher $\tau$ at low DM
- For Bhat relation to hold at 1 GHz, $\alpha$ must change with frequency
- Implications?
Time domain analysis is not the most sensitive to analyzing IISM properties

But even in time domain we see anomalous effects

Interferometric imaging, including space-ground experiments, could be key in investigating the typical sizes of scattering surfaces

Scintillation results are required for precise scattering measurements at higher frequencies to aid the investigation of the frequency dependence of $\alpha$. (Break in power law?)

Best tests for anisotropy come from high resolution dynamic spectra

Test whether estimated flux loss is regained in pulsar imaging - ongoing work (Will not be so, if flat spectra are due to inner scale instead)
WE DID IT! WE CLEARED EARTH’S ORBIT!

MARS, HERE WE COME!

ARE YOU SURE THIS IS THE WAY? WHAT? DIDN’T YOU BRING THE MAP?!