Exploring Magnetic Fields with LOFAR pulsar observations

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Outline

1. $\mu$G field of ISM
   - Faraday rotation
   - Latest LOFAR pulsar polarisation observations
   - Ionosphere calibration

2. ‘gargantuan’ field of pulsars
   - Emission properties
   - PSR B0823+26

Ongoing/Future Work & Conclusions
1) Galactic Magnetic Field

- **Important** for long list of astrophysical processes...
- GMF knowledge limited and often contentious

**Figure:** *left:* Cartoon of HECR deflection [A. Noutsos], *right:* Magnetic field strength and direction best fit model [van Eck et al. 2011]
1) Measuring the GMF

- Using Faraday Rotation: \( \chi = \chi_0 + RM \lambda^2 \)
- \( \langle B_{||} \rangle_{ne} = 1.232 \ \mu G \frac{RM=0.81 \int_{PSR}^{\oplus} n_e B_{||} dl (rad \ m^{-2})}{DM=\int_{PSR}^{\oplus} n_e dl (cm^{-3} \ pc)} \)
- **Improvements; sample size, precision & accuracy**

*Figure: left: Cartoon of electromagnetic wave propagating through magneto-ionic medium [wikipedia], right: Faraday sky [Oppermann et al. 2011]*
1) LOFAR pulsar polarisation observations

- LOFAR now providing highest quality polarisation profiles ever achieved at low frequencies (<300 MHz)

- Large collecting area of full core
- Large bandwidth (90 MHz)
- Raw data $\sim$86 GB per minute
- Precise dispersion measures (Pilia et al. in prep.)

*left:* PSR B0823+26 pulse dispersion
1) LOFAR obs: complimentary

- Quality polarisation profiles complimentary to higher frequencies

- PSR B0950+08 profile, Arecibo (1400), Lovell (900, 600, 400) & LOFAR Superterp HBA (150 MHz) [A. Noutsos]

- Pulsar spectral index
- Profile evolution (Hassall et al. 2012)
- Polarisation profiles (calibration – A. Noutsos, M. Kuniyoshi, T. Carozzi, et al.)
1) RM-synthesis

- Long wavelength & large fractional bandwidth from LOFAR = unprecedented precision
  (see Burn 1966, Brentjens & de Bruyn 2005)

**Effelsberg 100-m**

- \( \Delta t = 15 \text{ min} \)
- \( \nu = 1347 \text{ MHz} \)
- \( \Delta \nu = 200 \text{ MHz} \)
- FWHM = 260 rad m\(^{-2}\)

**WSRT**

- \( \Delta t = 20 \text{ min} \)
- \( \nu = 350 \text{ MHz} \)
- \( \Delta \nu = 80 \text{ MHz} \)
- FWHM = 12 rad m\(^{-2}\)

**LOFAR full core HBA**

- \( \Delta t = 10 \text{ min} \)
- \( \nu = 163 \text{ MHz} \)
- \( \Delta \nu = 68 \text{ MHz} \)
- FWHM = 1.2 rad m\(^{-2}\)
1) RM contribution from Ionosphere

- Ionosphere also magnetised plasma:
  \[ \Delta PA = (RM_{\text{ion}} + RM_{\text{ISM}} + RM_{\text{IGM}} + RM_{\text{int}}) \lambda^2 \]

- ionFR calculates ionospheric RM toward LOS using TEC maps & IGRF11 (Sotomayor-Beltran et al. A&A acc.)

- CODE, 2 hrs & 5° × 2.5°

- ROB, 15 mins & 0.5° × 0.5°
1) Ionospheric RM variation: minutes

- Ionospheric RM dynamic from minutes – yearly time-scales: time & position dependent calibration required

Figure: Daily RM variation as viewed from LOFAR Superterp toward Cassiopeia A. [Sotomayor-Beltran et al. 2013]
1) Ionospheric RM variation: yearly

- Weekly averages of the maximum and minimum absolute ionospheric RM (blue and red lines, respectively)
- Essential for monitoring RM in the ISM over several epochs
- 280 pulsars 300 pc above/below galactic plane: median RM $\sim39\ \text{rad} \ \text{m}^{-2}$

![Graph showing ionospheric RM variation](image)

**Figure:** *left:* towards CasA viewed from LOFAR, *right:* towards Eta Carinae viewed from average of Western Australian and South African SKA core sites. [Sotomayor-Beltran et al. 2013]
1) LOFAR observations and model comparison I

- Observations of PSR B0834+06 over several hours with Superterp HBAs in tied-array mode to measure RM as function of time
- Comparison: LOFAR observations vs. ionFR model

Figure: *left*: B0834+06 observed 7×10 mins every hour on 11th April 2011 over sunset at 120–126 MHz, *right*: B0834+06 observed 20×3 mins every 10 mins on 20th October 2011 over sunrise at 129–140 MHz. [Sotomayor-Beltran et al. 2013]
1) LOFAR observations and model comparison II

- PSRs B1642−03, B1919+21, B2217+47 with Superterp HBAs/LBAs in tied-array mode
- LOFAR observations vs. ionFR model towards three LOSs with large angular separation (>60°) quasi-simultaneously

![Figure: 12×3 min observations over sunrise towards; upper: PSR B1642−03, mid: PSR B1919+21, lower: PSR B2217+47. left: CODE data, right: ROB data. [Sotomayor-Beltran et al. 2013]](image_url)
1) LOFAR observations and model comparison III

- B0834+06 over midday with two international stations and LOFAR Superterp with HBAs, 119–129 MHz
- LOFAR observations vs. ionFR model towards three LOSs with large geographical separation (∼1270 km) quasi-simultaneously

**Figure:** B0834+06 observed 11×3 min on 10th July 2012 over midday using upper: SE607, middle: Superterp, lower: FR606. left: CODE data, right: ROB data. [Sotomayor-Beltran et al. 2013]
1) LOFAR Observations vs. ionFR Model

- Corrected for ionospheric RM (minimum $\chi^2$ offset between model and obs)
- Trend of RM with latitude as measured from Superterp, FR606 & SE607 suggests 3D model required, as compared with airmass

**Figure:** *left:* reduced chi squared between observation and model as a function of distance from target source (B1919+21)  *right:* RM of the ISM towards PSR B0834+06, as determined from HBA observations using the LOFAR FR606, Superterp and SE607 stations. [Sotomayor-Beltran et al. 2013]
1) Ionosphere-calibrated LOFAR observations

- Correcting LOFAR observations for the ionospheric RM have resulted in amongst the most accurate RMs determined to date.
- B0834+06: RM = 25.12±0.07 rad m$^{-2}$, DM = 12.889±0.006 pc cm$^{-3}$, $\langle B_\parallel \rangle_{n_e} = 1.949 \pm 0.003$ µG
- Future polarisation measurements will use highly accurate pulsar RMs for calibration

<table>
<thead>
<tr>
<th>PSR</th>
<th>Date [dd.mm.yy]</th>
<th>Telescope</th>
<th>Station(s)</th>
<th>Freq [MHz]</th>
<th>$\phi_{\text{CODE ISM}}$ [rad m$^{-2}$]</th>
<th>$\chi^2_{\text{red CODE}}$</th>
<th>$\phi_{\text{ROB ISM}}$ [rad m$^{-2}$]</th>
<th>$\chi^2_{\text{red ROB}}$</th>
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<tr>
<td>B0834+06</td>
<td>11.04.11</td>
<td>LOFAR</td>
<td>Superterp</td>
<td>120–126</td>
<td>25.15 ± 0.18</td>
<td>1.1</td>
<td>N/A</td>
<td>N/A</td>
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<tr>
<td>B0834+06</td>
<td>20.10.11</td>
<td>LOFAR</td>
<td>Superterp</td>
<td>129–140</td>
<td>24.94 ± 0.24</td>
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<td>N/A</td>
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<tr>
<td>B1642−03</td>
<td>23.03.12</td>
<td>LOFAR</td>
<td>Superterp</td>
<td>119–125</td>
<td>15.98 ± 0.23</td>
<td>0.8</td>
<td>16.04 ± 0.18</td>
<td>1.3</td>
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<tr>
<td>B1919+21</td>
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<td>-16.95 ± 0.12</td>
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<td>-16.92 ± 0.07</td>
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<td>B2217+47</td>
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<td>LOFAR</td>
<td>Superterp</td>
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<td>-35.72 ± 0.15</td>
<td>1.0</td>
<td>-35.60 ± 0.11</td>
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<td>B0834+06</td>
<td>22.04.12</td>
<td>WSRT</td>
<td>N/A</td>
<td>310–390</td>
<td>25.4 ± 1.8</td>
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<td>25.1 ± 1.5</td>
<td>N/A</td>
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<td>LOFAR</td>
<td>Superterp</td>
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<td>25.16 ± 0.13</td>
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<tr>
<td>B0834+06</td>
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<td>LOFAR</td>
<td>FR606</td>
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<td>25.21 ± 0.15</td>
<td>0.4</td>
<td>25.16 ± 0.10</td>
<td>1.2</td>
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<tr>
<td>B0834+06</td>
<td>10.07.12</td>
<td>LOFAR</td>
<td>SE607</td>
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<td>25.22 ± 0.18</td>
<td>0.6</td>
<td>25.39 ± 0.14</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Table: Summary results of four LOFAR and one WSRT observing campaign [Sotomayor-Beltran et al. 2013]
1) Ongoing/Future Work

- LOFAR observations of known, nearby pulsars without RMWs
- Observations and data analysis highly complimentary for detecting magnetic fields in, e.g., globular clusters and the heliosphere

Figure: left: Hubble space telescope image of M15 [P. Guhathakurta et al., NASA, ESA] right: The Sun and Coronal mass ejection [SOHO Consortium, ESA, NASA]
2) Pulsar Emission

- A model for radiation from $\sim 10^{12}$ G pulsar magnetosphere still elusive...
- Intricacies: nulling, mode-changing, intermittent behaviour...
- Linked by changes in neutron star magnetosphere

- B0809+74 drifting and nulling [van Leeuwen et al. 2003]
- B0943+10 quiet & bright modes [Hermsen et al. 2013]
- Intermittent B1931+24 [Kramer et al. 2006]
2) LOFAR polarisation observation: B0823+26

- PSR B0823+26 shows nulling (<5%) and intermittent behaviour
- ‘flickering’ behaviour – ‘off’ before and after below obs
- High circular polarisation in mode change \(\sim 45\%\)

3-min, 143 MHz, 9.6 MHz bandwidth LOFAR observation

Pulse profile of first pulse after mode transition
2) LOFAR obs B0823+26: bright and quiet modes

- LOFAR observation reveals emission during quiet mode

- 3-hr, 143 MHz, 48 MHz b/w LOFAR observation

- S/N of bright and quiet modes across bandwidth (gradients -0.283, -0.035, respectively)
2) Speculation

- Current density and/or structure of open magnetic field lines change
- How/why this could occur in single rotation remains unclear

Pulsar magnetosphere depicting mode change [Timokhin 2010]

- Two states with different geometries
- Closed field lines change size
- And/or change in current distributions
- Nulling/mode-changing high timing noise
- Seen in older pulsars due to increased current density freedom
2) Ongoing/Future work

- Consequences for pulsar population studies
- Intermittent pulsars now known – more discoveries
- Case for single pulse searching and...
  for surveying sky multiple times (LOTAAS – J. Hessels)...

- P–Pdot diagram, with known intermittent pulsars
- Case for ‘multi-pass’ surveys
Summary

- LOFAR observations of pulsars used to explore magnetic fields
- LOFAR’s low frequency, large bandwidth, high sensitivity provide high-quality polarisation profiles and unprecedented precision on RMs
- Calibration for ionospheric RM essential, especially monitoring RMs over several epochs
- LOFAR RM catalog most accurate to date – to be expanded
- PSR B0823+26 change perspective of ‘intermittent’ pulsars
- May help provide link between nulling, mode-changing, intermittency and insight into emission mechanism

Thank you for listening!