PRECISE FARADAY ROTATION MEASURES FROM LOFAR PULSAR OBSERVATIONS... ...TOWARDS RECONSTRUCTING THE 3-D GALACTIC MAGNETIC FIELD

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Overview

- Motivation
 - * Galactic magnetic field 3-D structure
- Data
 - LOFAR pulsar observations
- * Methods
 - Faraday RM-synthesis
- Results
 - * >165 precise LOFAR RMs towards pulsars... so far!
- Summary and future outlook

Motivation: Galactic magnetic field

- Permeates diffuse ISM
- * Large-scale, ordered & ...
- Small-scale, random fields
- Observations suggest
 overall clockwise direction,
 with one field reversal in
 Scutum-Centaurus arm
- No reversals in other galaxies!



Why study pulsars at low-frequency?

- * Emission mechanism:
 - Spectral index/turn-over
 - Profile evolution
 - * Single-pulse properties
- * Probes of the ISM:
 - Dispersion (n_e)
 - Faraday rotation (n_eB)
 - * Scattering (Δn_e^2)
 - Scintillation (turbulence)
- * Surveys:
 - Large FOV, distinguish RFI [See Stappers et al. 2011 re LOFAR's pulsar modes]



LOFAR high-band antennas (HBAs)



LOFAR HBA pulsar data

* LOFAR's large fractional bandwidth and collecting area combine to produce the highest-quality polarisation profiles of pulsars below 200 MHz to date.



Data: HBA pulsar census +

- * HBA pulsar census:
 - * Large sample of 195 pulsars (158 detected), |b|>3°, dec>+8°
 - * 149 MHz, 78 MHz bandwidth, >= 20-minute integrations
- HBA timing
- * MSP census (c.f. Vlad Kondratiev's talk)
- * LOTAAS confirmation observations (c.f. Daniele Michilli's talk)

Data: HBA pulsar census profiles

[Anya Bilous et al., submitted] B0052+51 B0053+47 J0137+1654 B0136+57 B0011+47 B0037+56 B0045+33 J0106+4855 B0105+65 B0105+68 B0114+58 0152+0948 0006+1834 10033 + 57J0205+6449 J0212+5222 B0226+70 B0301+19 B0320+39 J0324+5239 J0329+1654 B0331+45 B0402+61 B0410+69 0417+35 J0413+58 J0419+44 0435+27 B0450+55 J0611+30 B0609+37 B0626+24 J0646+0905 J0647+0913 B0643+80 B0531+21 B0540+23 B0655+64 B0523+11 B0525+21 B0656+14 B0841+80 B0917+63 B0940+16 J0943+22 B0943+10 J0947+27 B1112+50 B1133+16 J1238+21 B1237+25 |1246+22 |1313+0931 0815+0939 B0823+26 B0809+74 B1322+83 |1503+2111 B1508+55 B1530+27 B1541+09 J1549+2113 J1612+2008 J1627+1419 B1633+24 J1645+1012 J1649+2533 J1652+2651 J1720+2150 J1740+1000 B1737+13 prevented halves MATCHER PHAT J1741+2758 J1746+2245 J1746+2540 J1752+2359 B1753+52 J1758+3030 J1806+1023 J1813+1822 B1811+40 J1814+1130 J1819+1305 J1821+1715 J1822+1120 J1828+1359 J1834+10 HANNING MALIN MARKEN MARKEN Amballahira J1837+1221 J1838+1650 B1839+56 B1839+09 J1842+1332 J1843+2024 B1842+14 J1848+0826 J1849+2423 B1848+13 B1848+12 J1853+0853 B1852+10 WHICH WHICH under northing hour Marin J1901+1306 J1903+2225 J1906+1854 B1905+39 J1908+2351 J1909+1859 J1911+1758 B1910+20 J1912+2525 J1913+3732 B1915+22 B1918+26 B1919+21 J1927+0911 B1929+10 WWWWWWW B1930+13 J1937+2950 J1941+1026 J1941+1341 B1942+17 B1944+17 J1947+0915 B1946+35 J1951+1123 B1949+14 J1953+1149 B1953+50 J1956+0838 J1959+3620 J2002+1637 j2007+0809 j2007+0910 j2008+2513 j2015+2524 j2017+2043 B2016+28 B2020+28 B2021+51 B2022+50 J2024+48 B2025+21 J2027+4557 B2028+22 B2000+40 2030+55 J2036+2835 B2034+19 B2036+53 J2040+1657 J2043+2740 J2045+0912 B2044+15 B2045+56 J2047+5029 J2048+2255 B2053+21 B2053+36 2102+38 2111+2106 J2111+40 HELMANA B2110+27 B2113+14 B2122+13 J2139+2242 B2148+63 J2151+2315 J2155+2813 J2156+2618 B2154+40 J2203+50 J2205+1444 J2206+6151 B2210+29 J2215+1538 B2217+47

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12222+2923 B2224+65 B2227+61 12234+2114 B2241+69 12243+1518 12253+1516 B2303+30 B2303+46 12307+2225 B2306+55 B2310+42 B2315+21 12319+6411

Method: Faraday rotation measures

 Faraday rotation effect: rotation of the plane of polarisation through magneto-ionic medium



Method: RM-synthesis

- * Noiseless RMSF for HBA pulsar data: FWHM $_{150MHz} \sim 0.8 \ rad/m^2$
- * (For comparison: FWHM_{1.4GHz} ~ 300 rad/m² & FWHM_{350MHz} ~ 10 rad/m²)



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Results: Selection of Faraday spectra



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But wait!: Ionospheric Faraday rotation

- Magneto-ionic medium
- * Introduces time & position dependence $\mathrm{RM}_{\mathrm{obs}} = \mathrm{RM}_{\mathrm{ISM}} + \mathrm{RM}_{\mathrm{ion}}$
- ionFR code (see Sotomayor et al. 2013)
 calculates ionospheric RM(LOS) using:
 - * Total electron content (TEC) maps
 - International Geomagnetic Reference
 Field (IGRF)



Comparison to LOFAR observations



Results

- * 165 precise & ionosphere-corrected RMs (so far!)
 - * 75 without previous RM measurements
 - * 90 with ^ (LOFAR uncertainties 30x smaller, on average)

Table 1: LOFAR observations centred at 148.925 MHz, using 78.125 MHz bandwidth and 400 channels, included in this summary. Note: nd = no convincing detection yet! * = check (low S/N or high instrumental).

PSR (name)	OBSID	Date (dd.mm.yy)	Time (UT)	$\tau_{\rm int}$ (min)	$\begin{array}{c} \mathbf{DM}_{\mathrm{psrcat}} \\ \mathrm{(pccm^{-3})} \end{array}$	$\frac{\mathbf{R}\mathbf{M}_{\mathrm{psrcat}}}{(\mathrm{rad}\mathrm{m}^{-2})}$	$\begin{array}{c} \mathbf{DM}_{\mathrm{LOFAR}} \\ \left(\mathrm{pc}\mathrm{cm}^{-3}\right) \end{array}$	$\frac{RM_{\rm LOFAR}}{\rm (radm^{-2})}$
J0006+1834	L204692	15.02.2014	13:47	20	12.0(6)	_	11.406696	nd
B0011 + 47	L221897	26.04.14	10:57	21	30.85(7)	_	30.404790	-13.06(5)
B0037 + 56	L215805	06.04.14	09:58	20	92.595(9)	9(13)	92.514581	-155.71(20)
B0045 + 33	L204694	15.02.14	14:29	21	39.94(4)	_	39.922037	-80.22(7)
B0052 + 51	L222340	29.04.14	07:24	36	44.125(15)	_	44.012725	-61.84(5)
B0053 + 47	L204693	15.02.14	14:08	20	18.09(4)	-23(22)	18.135353	-42.56(10)
B0105 + 65	$\mathrm{L}227584$	07.05.14	09:30	22	30.46(5)	-29(3)	30.548183	-24.37(5)
B0105 + 68	L204695	15.02.14	14:51	20	61.092(16)	-46(19)	61.061654	-30.51(5)
B0114 + 58	L227167	03.05.14	11:08	20	49.423(4)	_	49.420675	$-0.27(5)^{*}$
J0137 + 1654	L204696	15.02.14	15:18	20	26.6(4)	_	26.083760	-13.4(2)
B0136 + 57	L215807	06.04.14	10:40	20	73.779(6)	-90(4)	73.811406	-90.26(5)
J0152 + 0948	$\mathrm{L}227585$	07.05.14	10:02	46	21.87(2)	_	22.881164	5.55(18)
B0153 + 39	L221899	26.04.14	11:40	31	60.0(6)	_	59.833422	65.8(1)
J0212 + 5222	L221900	26.04.14	12:12	20	38	_	38.235546	-11.14(5)
B0226 + 70	L204697	15.02.14	15:58	25	46.64(3)	-56(21)	46.679440	-41.6(1)
B0301 + 19	L204698	15.02.14	16:24	24	15.737(9)	-8.3(3)	15.656766	-5.47(3)
B0320 + 39	L204699	15.02.14	16:49	51	26.01(3)	58(3)	26.189752	62.24(4)
J0324 + 5239	L227168	03.05.14	11:39	20	119	_	115.463559	244.19(20)
				•				
				•				



New precise pulsar RMs using LOFAR

LOFAR HBA RMs (165 so far, squares) + Current pulsar RM catalogue (Manchester + 2005, 680 circles) + Oppermann + 2014 (background)

RM & DM Results



Data: Selection of polarisation profiles



Summary & Future Work

- LOFAR data provide precise (& accurate) RMs for nearby pulsars (165 so far, 75 new)
- * Provide much improved information about GMF in northern sky
- * Ongoing:
 - * Obtaining more RMs, including for further ~40 pulsars with parallax
 - * Further analysis
- * Technique can also be applied for further investigations of B-fields:
 - * Targeted search of globular clusters for polarised pulsars
 - Heliosphere

THANK YOU FOR LISTENING!

...more interesting pulsar papers using LOFAR data: * Stappers et al. 2011: Observing pulsars and fast transients with LOFAR * Hassall et al. 2012: Wide-band simultaneous observations of pulsars:... * Hermsen et al. 2013: Synchronous X-ray and Radio Mode Switches:... * Sotomayor-Beltran et al. 2013: Calibrating high-precision Faraday rotation measurements for LOFAR and... * Hassall et al. 2013: Differential frequency-dependent delay from the pulsar magnetosphere Coenen et al. 2014: The LOFAR pilot surveys for pulsars and fast radio transients * Bilous et al. 2014: LOFAR observations of PSR B0943+10: profile evolution and... * Archibald et al. 2014: Millisecond Pulsar Scintillation Studies with LOFAR: Initial Results * Dolch et al. 2014: A 24 Hr Global Campaign to Assess Precision Timing of the Millisecond Pulsar J1713+0747 * Noutsos et al. 2015: Pulsar polarisation below 200 MHz: Average profiles and propagation effects * Karako-Argaman et al. 2015: Discovery and Follow-up of Rotating Radio Transients with the Green Bank and LOFAR... * Karastergiou et al. 2015: Limits on fast radio bursts at 145 MHz with ARTEMIS, a real-time software backend * Sobey et al. 2015: LOFAR discovery of a quiet emission mode in PSR B0823+26 * Pilia et al. 2015: Wide-Band, Low-Frequency Pulse Profiles of 100 Radio Pulsars with LOFAR * Kondratiev et al. 2015: A LOFAR Census of Millisecond Pulsars * Bilous et al. 2016 (submitted to A&A): A LOFAR census of non-recycled pulsars: average profiles, dispersion measures...

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