Rotation Measure Synthesis of the Local Magnetized ISM

Maik Wolleben
Covington Fellow, DRAO
Outline

- Polarization, Faraday Rotation, and Rotation Measure Synthesis
- The Data: GMIMS – The Global Magneto Ionic Medium Survey
- RM-Synthesis of the Northern Sky
- B-Field of a local HI Bubble
- Compact source vs. diffuse emission
The Polarized Sky

Total Intensity: Haslam et al., 1982

Polarized Intensity: Wolleben et al. 2006
Polarized Emission Surveys

- Polarization surveys at 1.4, 2.8, 5 GHz
- Single frequency surveys (CGPS, EMLS, DRAO, Testori et al.)
- Data suffer from depolarization due to differential Faraday rotation and beam depolarization
- “Depolarization Band” towards the inner Galaxy
- Polarized filament of the North-Polar Spur (local)
- Rotation measures unknown from these observations
Polarization Angle at 1.4 GHz ($\lambda$21 cm)

(Testori et al. 2008; Wolleben et al, 2006)

Image produced using the “alice” algorithm developed by David Larson, Johns Hopkins University.
Polarized Synchrotron Emission

Depolarization:
- Internal Faraday dispersion (depth depolarization)
- Beam depolarization
- No Faraday rotation (high enough frequency): PA reveals $B_{\perp}$
- With Faraday rotation:
  - need to measure RM
  - intrinsic PA reveals $B_{\perp}$
  - RM reveals $B_{\parallel}$

(Beck et al. 2003)
Polarized Synchrotron Emission

- Above ~2-10 GHz: very little Faraday rotation

K Band

WMAP 23 GHz
(WMAP Science Team)
Faraday Rotation

Probes for Faraday rotation measurements:

- **extragalactic point-sources**
  - sightlines through entire Galaxy, have intrinsic RM (noisy probes), sampling

- **pulsars**
  - known distances, no intrinsic RM, usually only a few pulsars in the region of interest

- **diffuse galactic synchrotron emission**
  - high angular resolution, Rotation Measure Synthesis possible
From 2-D to 3-D Polarimetry

Since a few years:

- recent developments in digital signal processing
- design of wide-band antennas, motivated by the SKA
- spectro-polarimetry

=> High resolution, high sensitivity Rotation Measure surveys

<table>
<thead>
<tr>
<th>Name</th>
<th>Frequency MHz</th>
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<tbody>
<tr>
<td>LOFAR</td>
<td>110 – 250</td>
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<tr>
<td>MWA</td>
<td>80 – 300</td>
</tr>
<tr>
<td>SKAMP</td>
<td>700 – 1400</td>
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<td>GMIMS</td>
<td>300 – 1800</td>
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<td>GALFACTS</td>
<td>1225 – 1525</td>
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<tr>
<td>STAPS</td>
<td>1300 – 1800</td>
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<td>SPASS</td>
<td>2300</td>
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Rotation Measure Synthesis

- Usually polarization angle does not depend linearly on $\lambda^2$
- RM-Synthesis is a Fourier Transformation of Stokes $U$ & $Q$
- Derotation of Faraday-rotated emission using a set of assumed RM values
- Resolution in RM-space (Faraday depth $\phi$) depends on $\lambda^2$ coverage

Polarization angle for a simulated line-of-sight

the RM-Spectrum for this line-of-sight
RM-Synthesis can disentangle emission and rotation layers.
Rotation Measure Synthesis

-25 rad/m² \(B_\parallel n_e\) and 50 rad/m² \(B_\parallel n_e\)

\[\phi \text{ [rad/m}^2\text{]}\]
Rotation Measure Synthesis

Mixed emitting and Faraday-rotating region
Incomplete frequency coverage results in loss of information.
Rotation Measure Synthesis

- Requires wide-band spectro-polarimetry
- For the diffuse emission: requires absolute calibration of data
- 3 parameters important for RM-Synthesis observations:
  - resolution in Faraday depth
  - sensitivity to extended RM structures
  - the highest RM
- determined by frequency coverage (actually $\lambda^2$ coverage) and frequency resolution

Graphs showing frequency coverage ranges:
- GMIMS “High-Band” (1.3-1.8 GHz)
- GMIMS “Low-Band” (300-900 MHz)
- CMB
- 2.8, 5, 10 GHz
GMIMS: The Global Magneto Ionic Medium Survey

- ANTFT, Australia, E. Carretti
- Univ. of Tasmania, J. Dickey
- Univ. of Newcastle, UK, A. Fletcher
- Univ. of Sydney, Australia, B. Gaensler
- CAS, China, J.L. Han
- ASTRON, Netherlands, M. Haverkorn
- DRAO, Canada, T. Landecker
- Univ. of Manchester, UK, P. Leahy
- CSIRO ATNF, Australia, N. McClure-Griffith
- CSIRO ATNF, Australia, D. McConnell
- MPIfR, Germany, W. Reich
- Univ. of Calgary, Canada, R. Taylor
- DRAO, Canada, M. Wolleben (PI)

<table>
<thead>
<tr>
<th>Frequency Range (MHz)</th>
<th>Antenna</th>
<th>Status</th>
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<tr>
<td>300 - 800</td>
<td>Effelsberg 100-m</td>
<td>Rx under constr.</td>
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<tr>
<td>800 - 1300</td>
<td>Kunming 40-m</td>
<td>feas. study</td>
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<td>1300 - 1800</td>
<td>DRAO 26-m</td>
<td>55% complete</td>
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<td>300 - 900</td>
<td>Parkes 64-m</td>
<td>30% complete</td>
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<tr>
<td>800 - 1300</td>
<td>?</td>
<td></td>
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<tr>
<td>1300 - 1800</td>
<td>STAPS, Parkes 64-m</td>
<td>100% complete, PI: M. Haverkorn</td>
</tr>
</tbody>
</table>
GMIMS is a wide-band, spectro-polarimetric survey. GMIMS is bringing together three technologies:

- wideband feeds and receivers
- wideband, digital polarimeters
- rotation measure synthesis

Frequency coverage from 300 MHz to 1.8 GHz

All-sky, single-dish telescopes (absolutely calibrated)

6 component surveys (low-band, mid-band, and high-band)
GMIMS Science Goals

- Major science goals:
  - The morphology of the local MIM
  - The disk-halo transition
  - Interstellar turbulence
  - The large-scale Galactic magnetic field
  - The origin of objects only seen in polarization
  - Total intensity mapping of the sky

- Secondary science goals:
  - Zero-spacings for ASKAP, GALFACTS
  - CMB foregrounds
  - EoR foregrounds
  - Piggy-back transient surveys
RM-Synthesis of the Northern Sky
1.4 – 1.7 GHz
GMIMS: The Global Magneto Ionic Medium Survey

- RM-Synthesis Cube, Galactic coordinates, third dimension: Faraday depth $\varphi$
- First data from GMIMS North (1.3 – 1.8 GHz), 2048 frequency channels
- rms noise: 25 mK in a single channel, 1 mK in an RM-Synthesis frame
- RM cleaning performed
- Resolution in Faraday depth: 132 rad/m^2
- Largest scale in Faraday depth: 106 rad/m^2
Faraday Rotation Map

- Map shows $\phi$ of the dominant emission in each pixel
- (the position of the peak in the RM-Synthesis spectrum for each pixel)
- Grey scales chosen to make structures with positive $\phi$ more visible
- Contour line corresponds to $\phi = 0$ rad/m$^2$
- Four yellow lines, fitted by eye, indicate location of four filaments identified in the Faraday rotation map
- RM-Synthesis frames showing polarized intensity at various Faraday depths
- Four yellow lines are repeated at 60 rad/m²
- Blue and red lines indicate polarized filaments identified in the RM-Synthesis cube
HI Bubble

(LAB HI Survey, Kalberla 2005)

- Map of HI temperature at 15 kms$^{-1}$
- Polarized filaments associated with HI bubble
- Correlations and anti-correlations between polarized intensity and HI
- Position of the Upper-Scorpius OB association today and 5 Myr ago
The Local ISM

- Local Bubble, mean local B-field pointed towards l=90°
- Expanding shells sweep up and compress the ambient B-field
- Scorpius Centaurus association ~100pc away towards the Galactic centre
- Positive $\phi$ in the east changes to negative $\phi$ in the west, suggesting that the B-field is wrapped around the bubble.

- Polarized emission at $\phi=0$ rad/m$^2$ along the centre of the bubble links these two regions.

- Shape and implied B-field configuration of this HI bubble suggest that it has expanded asymmetrically.

- Expansion constrained to only one direction along the line-of-sight.
Distance and Origin

- Expanding HI shells associated with stellar winds and supernovae explosions originating in the stars of the Scorpius-Centaurus OB association
- Upper Scorpius sub-group is the furthest away (145 pc), in the centre of the western side of the HI shells.
- Linear size of bubble of the order of 200pc x 100pc
- Nearest is 95pc away, far side 195pc away
- Wall of Local Bubble about 80pc away in this direction
- The shells act as a Faraday-rotating screen to the strong background emission and also as a weaker mixed emitting and rotating slab
- These structures are not associated with the North Polar Spur as they do not resemble the shape of the spur
- No Hα emission found (VTSS/WHAM)
- RM must be due to enhanced B-field
- average $n_e$ approx 0.02 cm$^{-3}$
- shell thickness ~13pc, path length ~100pc
- 50-60 rad/m$^2$ corresponds to $B_{||}$ approx 20-34 μG
Antisymmetries in the FR Sky

(Han et al, 1999)

- Observed antisymmetry of RMs in the inner Galaxy.
- Indicates azimuthal B-field with reversed field directions.
- This seems to suggest an A0 dynamo acting in the halo.
This HI bubble produces a large-scale pattern in rotation measures on the sky that mimics the effect that the regular magnetic field of the Milky Way would have on the Faraday rotation of compact sources, both in magnitude and sign.
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Antisymmetries in the FR Sky

- Several authors have pointed out that the antisymmetry may be due to Loop I.
- Our data show that another local object (not the NPS) mimics the antisymmetric pattern of a large scale B-field.
- Detection made possible by high angular resolution RM-maps of the diffuse Galactic emission.

Pulsars (Han et al, 1999)  
EG sources (Taylor et al, 2009)
Diffuse Emission vs. Compact Source RMs

- RMs of compact sources from Canadian Galactic Plane Survey (Jo-Anne Brown, CGPS)
- RMs of diffuse emission from GMIMS High-Band North (DRAO 26-m Telescope)
First Data from Parkes 64-m (300-480 MHz)

Total Intensity

Polarized Intensity
Summary

- GMIMS is a wide-band, spectro-polarimetric survey from 300 MHz to 1.8 GHz, using single-dish telescopes.
- First RM-Synthesis of the Galactic diffuse emission with a single-dish telescope over the whole Northern sky.
- High angular resolution Faraday-rotation map reveals filamentary structures associated with a local HI bubble (not the North Polar Spur).
- These structures can be explained by a B-field wrapped around this bubble.
- The resulting signature in the Faraday rotation sky mimics that of a large-scale Galactic B-field.

(Wolleben et al., 2010, in prep.)

https://www.astrosci.ca/users/drao/gmims