Polarized Synchrotron Emission

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Outline

- The polarized sky
  - synchrotron emission
  - existing surveys
  - Faraday effects
  - radio polarization as a tool for exploring the Milky Way
- Relevance for CMB
- Future / On-going Surveys
Introduction: The Polarized Sky at “Low” Frequencies
Galaxies have large-scale magnetic fields related to their structure

What is its effect on ISM processes?

What is the origin of the magnetic field?

M51 (Fletcher & Beck 2004)
Synchrotron Emission

- Synchrotron emission is linearly polarized

- Degree of polarization: ~75%

- Polarization direction perpendicular to the magnetic field direction
Faraday Rotation

\[ \text{RM} [\text{rad/m}^2] = 0.81 \times 1 \text{[pc]} \times B_{||} [\mu \text{G}] \times n_e [\text{cm}^{-3}] \]

\[ \Delta \varphi = \text{RM} \lambda^2 \]

- the plane of polarization is rotated by the Faraday effect
- the Faraday rotation angle depends on magnetic field strength, electron density, and line-of-sight length
- the higher the frequency the lower the Faraday rotation
Synchrotron Emission

- ...is the dominating radiation process at “low” frequencies (few GHz or less)

- in total intensity: map synchrotron emission at low frequencies, apply spectral index, done!

- in polarization: not so simple!
Total Intensity at 1.4 GHz

- diffuse emission is mostly due to synchrotron emission
Polarized Intensity at 33 GHz

- no Faraday rotation at these frequencies: polarized intensity resembles total intensity
Polarized Intensity at 1.4 GHz

- very little correlation between polarized and total intensity

DRAO 26-m Polarization Survey, Wolleben et al. 2006, Polarized Intensity (1.4 GHz)
Surveys of Polarized Emission

• Existing sky polarization surveys (mostly 1.4 GHz):
  – all-sky
    • Leiden/Dwingeloo surveys (1960 – 70)
    • DRAO 26-m Polarization Survey (recent)
    • Villa-Elisa Southern Sky Polarization Survey (recent)
  – Galactic plane
    • Effelsberg Medium Latitude Survey (not yet released)
    • Canadian Galactic Plane Survey (soon)
    • Southern Galactic Plane Survey
  – “Patches”
    • WSRT surveys
Surveys of Polarized Emission

• Recently, Galactic plane surveys have been carried out
Surveys of Polarized Emission

• Until recently, the Leiden/Dwingeloo surveys were the best whole-sky polarization surveys available!

Brouw & Spoelstra (1976)
- Leiden/Dwingeloo polarization surveys at 408, 465, 610, 820, 1411 MHz -
Best all-sky polarization surveys available today:

- WMAP

- Combined DRAO and Villa-Elisa Survey at 1.4 GHz

Picture taken from Sun, 2008
Faraday Rotation
Terrestrial Analog of the Effect of the Magneto-Ionic Medium
Depolarization

beam depolarization

depth depolarization
Polarization Horizon
Nearby HII regions will be seen as depolarization patches.
Distant HII regions will not depolarize: they are beyond the polarization horizon.
Polarization Horizon
A Tool for Exploring the Milky Way
The Polarized Sky
Canadian Galactic Plane Survey

Linear Polarization at 1420 MHz of Phase I and II of the Canadian Galactic Plane Survey,
Using Data From DRAO's Synthesis and 26m Telescopes,
and the Effelsberg 100m Telescope

brightness -> polarized intensity
color -> polarization angle

• 1.4 GHz
• 1 arcmin resolution
• 4 frequency channels
The Polarized Sky

Canadian Galactic Plane Survey

ionized gas in Cygnus X
The Polarized Sky
Canadian Galactic Plane Survey
The Polarized Sky
Effelsberg Medium Latitude Survey

- 1.4 GHz
- 9 arcmin resolution
- single frequency
- sensitivity: 9 mK
The Polarized Sky

Effelsberg Data

- 2.7 GHz
- 4 arcmin resolution
- single frequency
The Polarized Sky

- WSRT data at 349 MHz
- Canals: random network of depolarized filaments
- Not related to any physical structures in the ISM
- Carry information about interstellar turbulence
- Strong Faraday rotation gradients?
- Line-of-sight effect?
Magneto-Ionic Medium
Sharpless 216

The closest planetary nebula
Distance 120 pc
Size 1.6 degrees

Ransom et al., 2008

Polarized intensity

Optical

Polarization angle
Sharpless 216

Ransom et al., 2008
Anticentre Bubble

1420 MHz Stokes I
Anticentre Bubble

1420 MHz Stokes U
The Galactic Neighbourhood

Orion

Taurus (HII, H2)

Local Bubble

Centaurus

Scorpius

Aquila Rift

0° 50 pc 270° 180° 90°

P. Frisch, U. Chicago (10/14/02)
The Galactic Neighbourhood

B-Field of an Expanding Shell

- common idea: expanding shells sweep up and compress the ambient B-field

Tomisaka, 1992
The Galactic Neighbourhood

Weaver, 1979

- HI shell, radio loop
- shells produced by stellar winds or supernova activity
- refined model: 2 synchrotron emitting shells (Wolleben, 2007)
• a previous large-scale B-field has probably been tangled up by the complex evolution of the Local Bubble / Loop-I region

• Local Bubble is not a unique circumstance, so most regions in the Galaxy may not be characterized by a large-scale uniform B-field
Other Radio Loops

• 4 radio loops identified

• theory 1: loops are SNR, spurs are the brightest segments of these SNRs

• theory 2: loops are inflated by stellar winds

• theory 3: bubbles reheated by supernovae

• theory 4-x: ...
Summary: The Polarized Sky

- Large-scale structures:
  - Fan-Region
  - North Polar Spur
  - Depolarization Band
  - High Latitude Polarized Emission
  - “New Loop”
Summary: The Polarized Sky

- Small-scale structures:
  - Polarized structures without counterparts in total intensity
  - Depolarized structures
  - Canals
Summary: The Polarized Sky

- The polarized sky bears almost no resemblance to the total intensity sky

- The polarization features are (largely) the products of Faraday rotation
1. Polarized structures exist on all scales
2. Wide variety of interstellar phenomena accessible to polarimetry
3. Objects many degrees in size, detectable only with arcminute resolution
4. Telescopes more sensitive to Faraday rotation than to total-power emission
5. There is a limit to how far we can “see” -- the Polarization Horizon
Summary: The Polarized Sky

- Correlation of polarization data with any other tracer of the ISM
- Statistical examination of the data
  - Structure functions
  - Pattern recognition
- Search for entirely new phenomena
  - Canals
  - Magnetic features
Relevance for CMB Studies
A Model of Diffuse Galactic Radio Emission from 10 MHz to 100 GHz

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Figure 1: The maps show (from left to right, top to bottom) the 0.001 GHz, 0.0035 GHz, 0.0175 GHz, 0.022 GHz, 0.025 GHz, 0.035 GHz, 0.04 GHz, 0.045 GHz, 0.05 GHz, 0.055 GHz, 0.06 GHz, 0.065 GHz, 0.075 GHz, 0.08 GHz, 0.085 GHz, 0.09 GHz, 0.095 GHz, 0.1 GHz, 0.12 GHz, 0.14 GHz, 0.15 GHz, 0.17 GHz, 0.2 GHz, 0.22 GHz, 0.23 GHz, 0.25 GHz, 0.26 GHz, 0.28 GHz, 0.3 GHz, 0.32 GHz, 0.34 GHz and 0.36 GHz surveys, and the CMB-free WMAP foreground maps at 23, 33, 41, 61 and 94 GHz.
3.1 Criteria: accuracy and simplicity

In this paper, our main criterion for choosing a method is accuracy. In other words, we wish to find the method that most accurately predicts the Galactic emission in any arbitrary sky direction and at any frequency between 0.010 to 94 GHz, independently of whether it is based on physical assumptions or is “blind” and purely statistical. In practice, we implement this criterion as follows: for each of the 11 frequencies where a high-quality sky map is available, we quantify how accurately a method can predict this map by using only information from the other 10 maps.
Modeling Polarization

100 GHz
Summary

• In total power: low frequency data are extrapolated adopting a constant spectral index
• Faraday rotation plays a role only at low frequencies
• Goal: develop a model of diffuse Galactic polarized emission from xx MHz to xxx GHz
• Questions:
  – Can such a model be developed based on >2 GHz data, where Faraday rotation is negligible?
  – How much physics is required?
On-going / Future Surveys
Future Surveys

• Recent advances in digital signal processing are bringing us into the era of 3-dimensional imaging of the polarized sky.
• Wide-band data with high spectral resolution (spectro-polarimetry) enable rotation measure synthesis
Spectro-Polarimetry

\[ \text{RM} \, [\text{rad/m}^2] = 0.81 \times 1 \, \text{[pc]} \times B_|| \, [\mu \text{G}] \times n_e \, [\text{cm}^{-3}] \]

\[ \Delta \varphi = \text{RM} \, \lambda^2 \]

\( n_e = 0.05 \, \text{cm}^{-3} \)

\( L = 150 \, \text{pc} \)

\( B_|| = -4...4 \, \mu \text{G} \)

\( \text{RM} = -25...25 \, \text{rad/m}^2 \)
Rotation Measure Synthesis

\[ \text{RM} = 100 \text{ rad/m}^2 \]
## Future / On-going Polarization Surveys

<table>
<thead>
<tr>
<th>Name</th>
<th>Frequency MHz</th>
<th>Comments</th>
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<tbody>
<tr>
<td>LOFAR</td>
<td>110 – 250</td>
<td></td>
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<tr>
<td>MWA</td>
<td>80 – 300</td>
<td></td>
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<tr>
<td>SKAMP</td>
<td>700 – 1400</td>
<td>Final frequency range</td>
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<tr>
<td>GMIMS</td>
<td>300 – 1800</td>
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<td>GALFACTS</td>
<td>1225 – 1525</td>
<td>Arecibo sky</td>
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<td>EMLS</td>
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<td>Galactic plane survey</td>
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<tr>
<td>GEMS</td>
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<td>C-BASS</td>
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<tr>
<td>Sino-German</td>
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GMIMS

• The Global Magneto-Ionic Medium Survey
• All-sky rotation measure survey using large single-antenna telescopes
• Proposed frequency coverage: 300 MHz – 1.8 GHz

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Scientific objectives:

- Study of the Galactic magneto-ionic medium and the role of magnetic fields in the Milky Way
- CMB foregrounds
- (Contributions to SKA pathfinder experiments)

Galactic B-field studies $\Rightarrow$ more physics
CMB foregrounds $\Rightarrow$ less physics
\[ \Delta \varphi = R \cdot M \cdot \lambda^2 \]

- CMB
- 1300 – 1800 MHz
- GMIMS “Low-Band” (300-900 MHz)
- SPASS (2.8 GHz),
  C-BASS (5, 10 GHz)