The Diffuse Polarized Emission from the Milky Way
- revealing magnetic fields in the ISM

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Objectives of this talk

• To persuade you that observations of the diffuse polarized emission from the Milky Way can reveal magnetic fields at work in the Interstellar Medium
• Why we have had only limited success to date
• What we have learned
• Some ideas about where to go from here
Angular resolution $8^\circ$

The discovery of polarization was the final proof that the Galactic radio emission was generated by the synchrotron mechanism.

Equipartition between magnetic field and relativistic electrons

Magnetic field is about 5 $\mu$G
1. Magnetic fields are intimately tied to galactic structure.
2. Synchrotron emission shows where the field is strongest and its polarization shows the field orientation.
Large-scale field of the Milky Way (from Brown 2010). In the inner Galaxy the field is well aligned with the spiral arms. In the outer Galaxy it is close to azimuthal. Solid arrows are not controversial. Dotted arrows are less certain. Based on Rotation Measures of extragalactic sources and pulsars.

To determine field direction we need rotation measure
Mathewson & Milne (1965). Parkes observations at 408 MHz made with rotating dipole feeds.
Mathewson et al. (1966) Polarization at 408 and 620 MHz. Faraday rotation is evident.
Faraday Rotation

$$\psi = \lambda^2 \int n_e \mathbf{B} \cdot d\mathbf{l}$$

$$= \lambda^2 \text{RM}$$
Total intensity 1420 MHz

Polarized intensity 1420 MHz

Stockert and Villa Elisa

DRAO and Villa Elisa
ON THE DEPOLARIZATION OF DISCRETE RADIO SOURCES
BY FARADAY DISPERSION

B. J. Burn

(Received 1965 July 7)
Why did this work stop at Parkes?

- The pressure of extragalactic science?
- The rush to higher frequencies?
- Data collection and processing was difficult
“The diffuse polarized emission is difficult to interpret”

Why?
“The diffuse polarized emission is difficult to interpret”

- We have measured polarization angle and polarized intensity in narrow bands
- The quantity of interest is Rotation Measure (or Faraday depth)
- We need broadband polarimetry in many channels
- Rotation measure synthesis
“The diffuse polarized emission is difficult to interpret”

- Aperture-synthesis polarization data needs complementary data on large structure
- Aperture synthesis + single antenna
- The single-antenna polarization data do not exist
“The diffuse polarized emission is difficult to interpret”

- We need to consider the magnetic field as a constituent of the Interstellar Medium
- We need large-scale data on the other ISM constituents
- Those datasets now exist
  - Canadian Galactic Plane Survey
  - Southern Galactic Plane Survey
  - Galactic All-Sky Survey (Parkes) HI
  - Arecibo HI surveys
  - Infrared data
(3) Magnetic field in the ISM

Energy densities

NGC 6946
Beck (2011)

Milky Way
Haverkorn (2010)

- turbulence
- magnetic field
(2) The need for single-antenna data

Large scale

Small scale
What an aperture synthesis telescope sees

Small scale

(2) The need for single-antenna data
(2) The need for single-antenna data

Large scale gone  →  angles wrong
Angles wrong  →  cannot calculate RM
RM gone  →  physics is gone
<table>
<thead>
<tr>
<th>Survey</th>
<th>Ref.</th>
<th>$f$ [MHz]</th>
<th>$\theta$ ['']</th>
<th>A-S</th>
<th>S-A</th>
<th>Large Scale</th>
<th>RM Synth.</th>
<th>Coverage [Sr]</th>
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<tbody>
<tr>
<td>WSRT-150</td>
<td>(1)</td>
<td>139-153</td>
<td>2</td>
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<td>n</td>
<td>n</td>
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<td>y</td>
<td>n</td>
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<td>1420</td>
<td>1</td>
<td>y</td>
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<td>y</td>
<td>n</td>
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<td>n</td>
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<td>y</td>
<td>y</td>
<td>y?</td>
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Notes: (a) $f$, frequency in MHz. (b) $\theta$, beamwidth in arcminutes. (c) A-S denotes aperture synthesis, S-A denotes single antenna. (d) y or n under “Large Scale” indicates that large-scale structure is or is not represented. y? indicates that large-scale structure has been incorporated incompletely and/or derived from observations at another frequency. (e) y under RM Synth. indicates that the data are adequate for application of RM Synthesis. (f) Coverage gives the sky area observed in steradians.

Surveys of the Galactic polarized emission
Only one survey has aperture synthesis + single antenna
Only a few surveys are adequate for RM synthesis
Most single-antenna surveys do not truly represent the largest structure
CABB data on extragalactic source PKS B160-771

O’Sullivan et al. MNRAS submitted
CABB data on extragalactic source PKS B160-771

O’Sullivan et al. MNRAS submitted
Despite all these problems ......

..... we have learned a lot
Polarization surveys with the DRAO Synthesis telescope

Canadian Galactic Plane Survey
DRAO Planck Deep Fields

1.4 GHz
1 arcmin
CGPS Polarization Survey 1.4 GHz

DRAO Synthesis Telescope
600-m baseline

Effelsberg 100-m

DRAO 26-m
CGPS Polarization Survey: combining data

Wolleben et al. 2006

Effelsberg Medium-Latitude Survey
Reich et al. 2004
CGPS Polarization Survey

- 1420 MHz  1 arcmin
- Combination of DRAO Synthesis Telescope, Effelsberg 100-m & DRAO 26-m data
- The first extensive polarization survey with arcminute resolution and single-antenna data
- $1.5 \times 10^7$ data points, 1208 square degrees
  – biggest polarization survey ever

Landecker et al. 2010 – A&A
polarized intensity $\rightarrow$ brightness    angle $\rightarrow$ colour
1420 MHz Stokes I -- SNR VRO42.05.01 (top) and HII region OA184 (bottom)
1420 MHz Stokes U
HI at -20 km/s (Perseus Arm velocity)
Polarized Background Emission

Expanding HI Shell

Shocked Wind Zone

Toroidal Magnetic Field Lines

Stellar Wind

Faraday Rotated Background

Polarized Foreground Emission
In the shocked wind zone:

\[ \Delta S = 0.36 \, R \]
\[ n_e = 0.02 \, \text{cm}^{-3} \]
\[ B_\parallel = 34 \, \mu \text{G} \]
at outer edge
\[ P_{I_{\text{foreground}}} = 325 \, \text{mK} \]
\[ P_{I_{\text{background}}} = 65 \, \text{mK} \]

Kothes et al. in preparation

Shocked wind zone
Anti-centre bubble

- Requires arcminute angular resolution to detect
- Detected by its Faraday rotation
- Impossible to interpret without single-antenna data
- Need data on other ISM components
- Field generated from stellar winds contributing to the ISM
upper shell – limited by thermal pressure  lower wing – magnetic pressure
Parkes 2.4 GHz       Duncan et al. (1997)
Anti-centre bubble

- Age 10 - 20 x $10^6$ years, 10 from SNRs, 20 from stellar winds
- Near centre – group of B2 - B4 stars, earliest – B2 giant
- Possible trace of SNR near centre
- X-ray emission – hard to localize
- Sequential star formation – everything around the bubble is $\sim 1 \times 10^6$ yr old
- HII complex at higher longitude – $1 \times 10^6$ yr old
- VRO 42.05.01 – blowout – shaped by magnetic field pressure
- OA 184 and its O6.5 star – is it in the near face of the bubble?
Faraday rotation dominates the appearance of the polarized sky

• The quantity of interest is Rotation Measure
• We have to make measurements in many frequency channels
• We need broadband receivers with many frequency channels
Polarized intensity
Polarized intensity
“canals” long thin filaments where the polarized intensity drops to zero
349 MHz

Haverkorn & Heitsch (2004)
data from SGPS – Gaensler et al (2001)
Gradient of the Stokes vector \((Q,U)\) ……

\[
|\nabla P| = \sqrt{\left(\frac{\partial Q}{\partial x}\right)^2 + \left(\frac{\partial U}{\partial x}\right)^2 + \left(\frac{\partial Q}{\partial y}\right)^2 + \left(\frac{\partial U}{\partial y}\right)^2}
\]

… provides an image of magnetized turbulence

Gaensler et al., Nature (2011)
Comparison with simulations …..

….. sub-sonic or trans-sonic turbulence
Diffuse polarized emission reveals ISM turbulence structure in atomic hydrogen is also a tracer of turbulence
• This is what arcminute resolution shows us about the structure of the local HI
• are magnetic fields involved in making or maintaining the filaments?
SGPS HISA vs. Magnetic Field

McClure-Griffiths et al. (2006)
SGPS HISA map of Riegel & Crutcher (1972)
Cold Cloud toward Galactic centre with optical starlight polarization vectors, showing magnetic field structure parallel to HI filaments
Field strength in the filaments

- Chandrasekhar & Fermi (1953)
- Turbulence tends to randomize the field
- A strong regular field resists randomization
- Equipartition argument implies 30 µG
From Steve Gibson

CGPS H I Emission vs. Magnetic Field

CGPS HI at +5 km/s smoothed to 3' beam

CGPS Local HI emission smoothed to 3' beam vs. starlight polarization from Heiles (2000).
CGPS H I Emission vs. Magnetic Field

CGPS Local H I emission smoothed to 3’ beam vs. starlight polarization from Heiles (2000).
CGPS H\textsc{i} Emission vs. Magnetic Field

From Steve Gibson

CGPS Local H\textsc{i} emission smoothed to 3' beam vs. starlight polarization from Heiles (2000).
CGPS H I Emission vs. Magnetic Field

From Steve Gibson
We need robust statistical tools to measure the significance of the apparent correlations in HI compared with starlight polarization. HI compared with diffuse polarized emission.

Jörn Geisbüsch (DRAO) in preparation
Power spectrum of polarized intensity

\[
\begin{align*}
A &= 1.6e^{-7} \pm 4.e^{-9} \\
B &= 8.1e+2 \pm 3.e+2 \\
\alpha &= 2.96 \pm 0.06 \\
\sigma &= 3.26e+3 \pm 2.e+1
\end{align*}
\]
total intensity

polarized intensity

e坡度of power spectrum

Stutz et al. in prep.
…. and finally,
back to Parkes
The **Global Magneto-Ionic Medium Survey**

- **Aim:** to understand the role of magnetic fields in the Milky Way
- **Survey** radio polarization over the whole sky
- North and South
- Big single antennas - 300 MHz to 1800 MHz
- **Multi-channel polarimetry**
- **RM synthesis**
The GMIMS Consortium

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Conclusions

• Magnetic field is a significant component of the ISM
• The diffuse polarized emission can tell us about field configuration, strength, and scale
• Faraday rotation can reveal objects undetected by other means
• We need multi-channel polarimetry over very broad bands
• We need complementary data from single antennas to make sense of aperture-synthesis data