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Polarized Synchrotron Emission

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Covington Fellow, DRAO

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

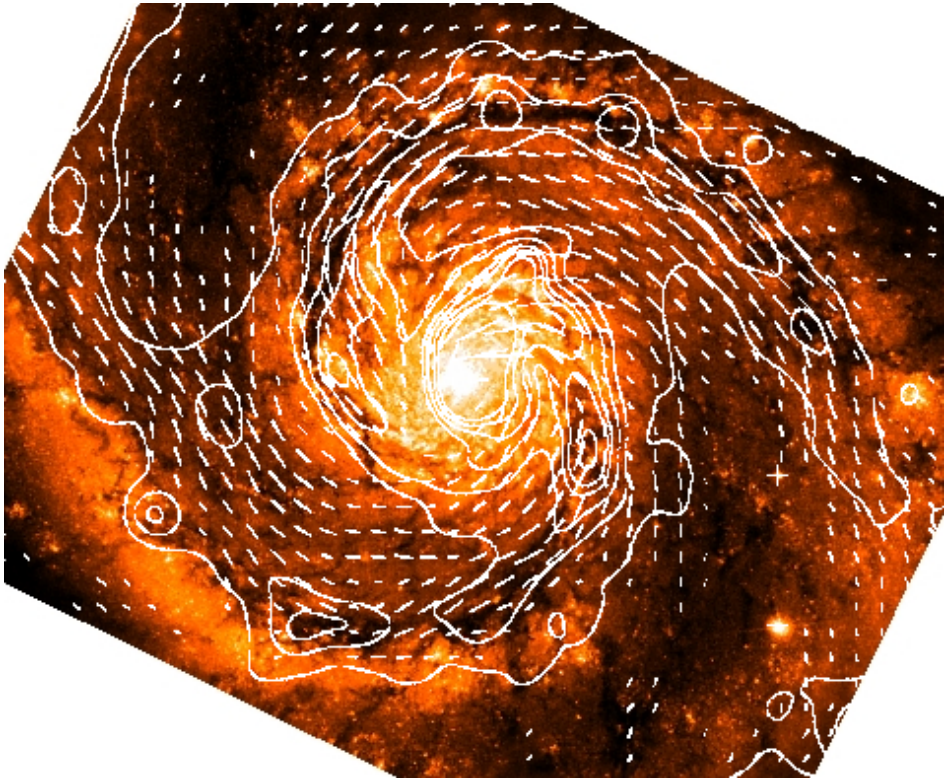
Introduction: The Polarized Sky at “Low” Frequencies

Synchrotron Emission

Galaxies have large-scale magnetic fields related to their structure

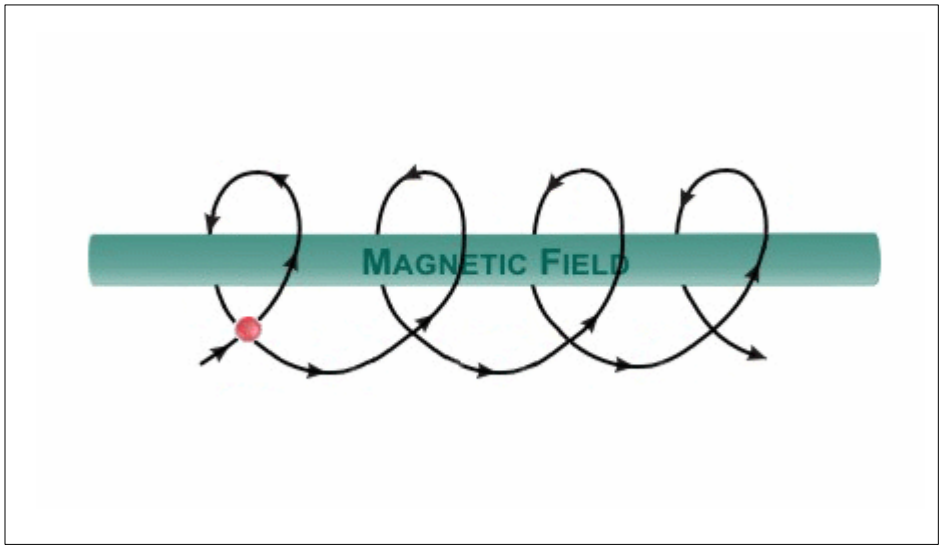
What is its effect on ISM processes?

What is the origin of the magnetic field?



M51 (Fletcher & Beck 2004)

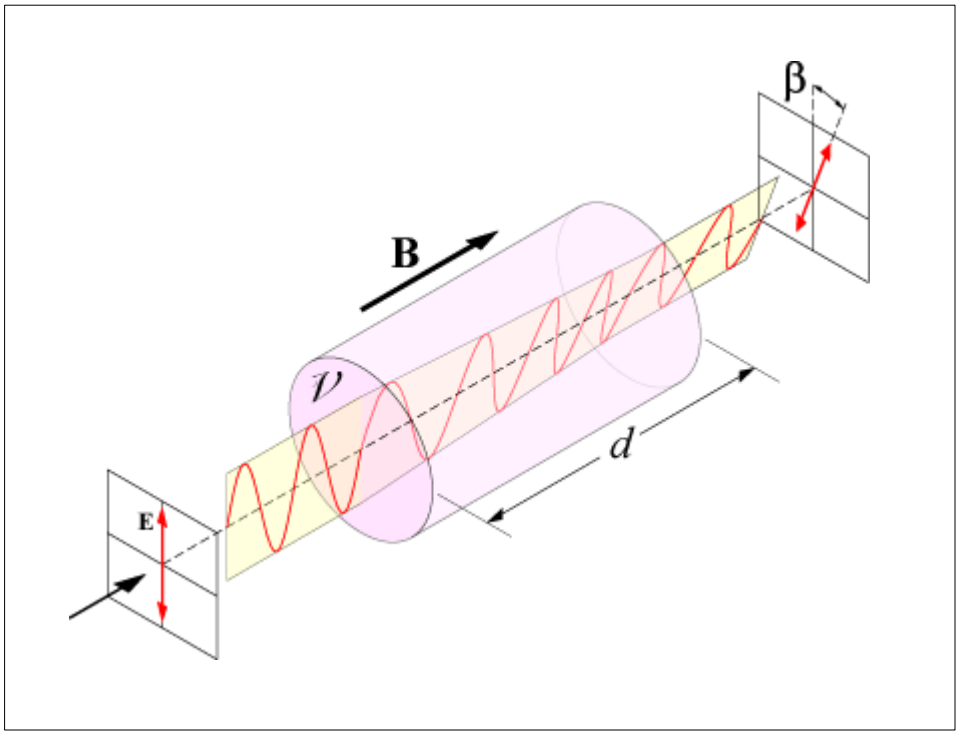
Synchrotron Emission



- synchrotron emission is linearly polarized
- degree of polarization: ~75%
- polarization direction perpendicular to the magnetic field direction

Faraday Rotation

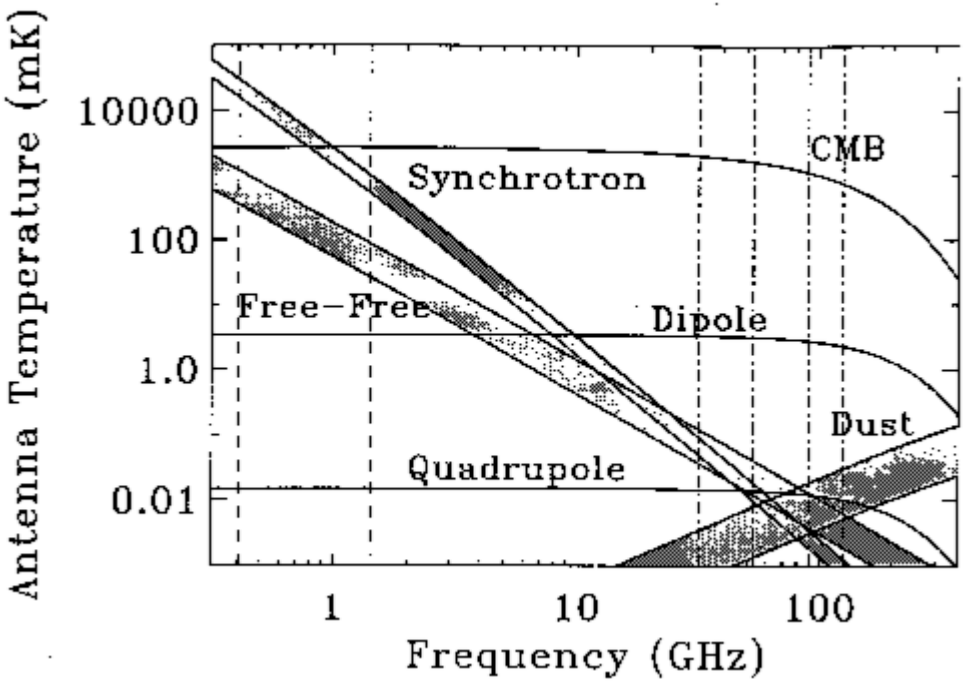
$$RM\ [rad/m^2] = 0.81 * l\ [pc] * B_{||}\ [\mu G] * n_e\ [cm^{-3}]$$



$$\Delta \varphi = RM\, \lambda^2$$

- 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



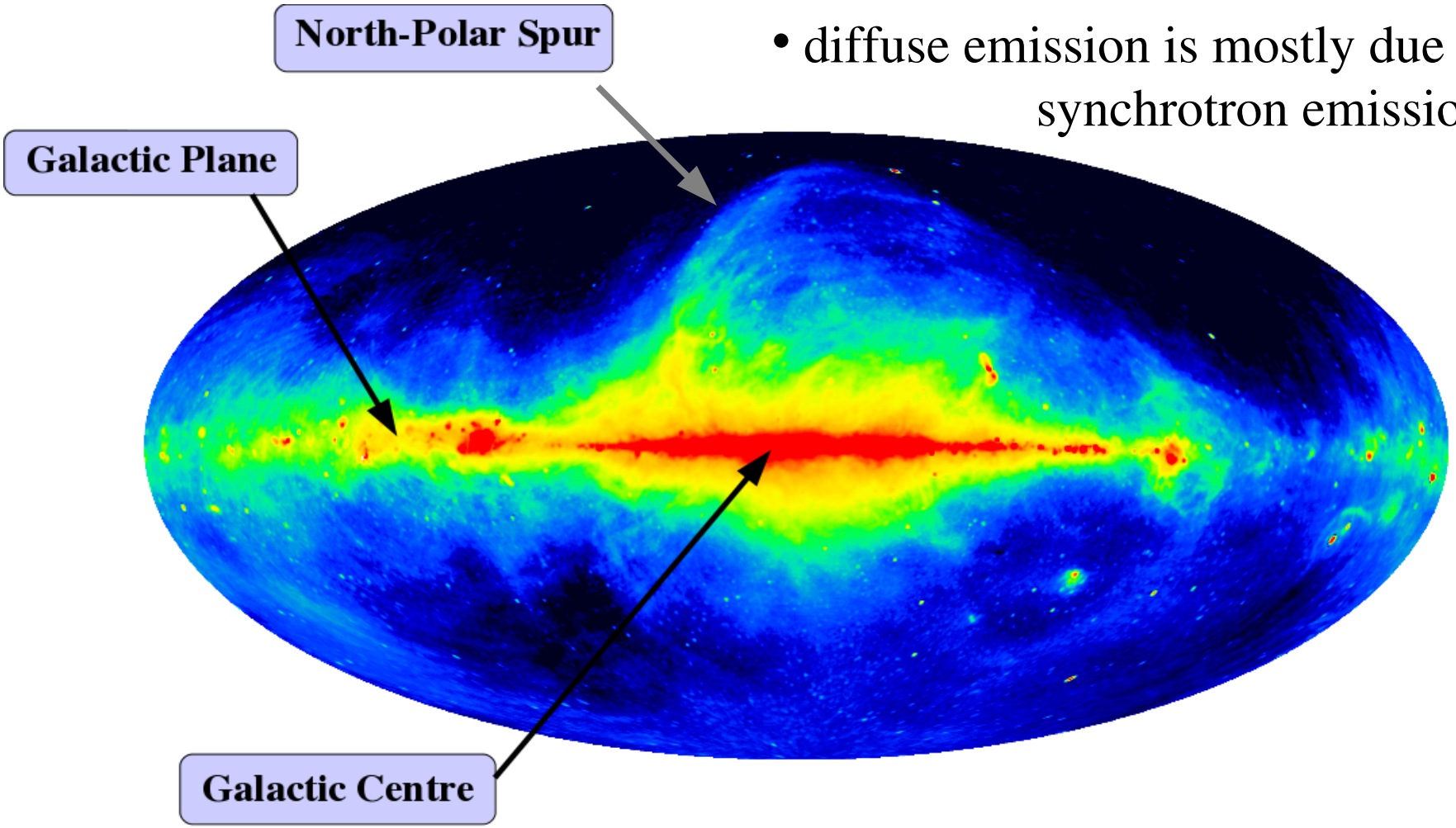
- ...is the dominating radiation process at "low" frequencies (few GHz or less)

- 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



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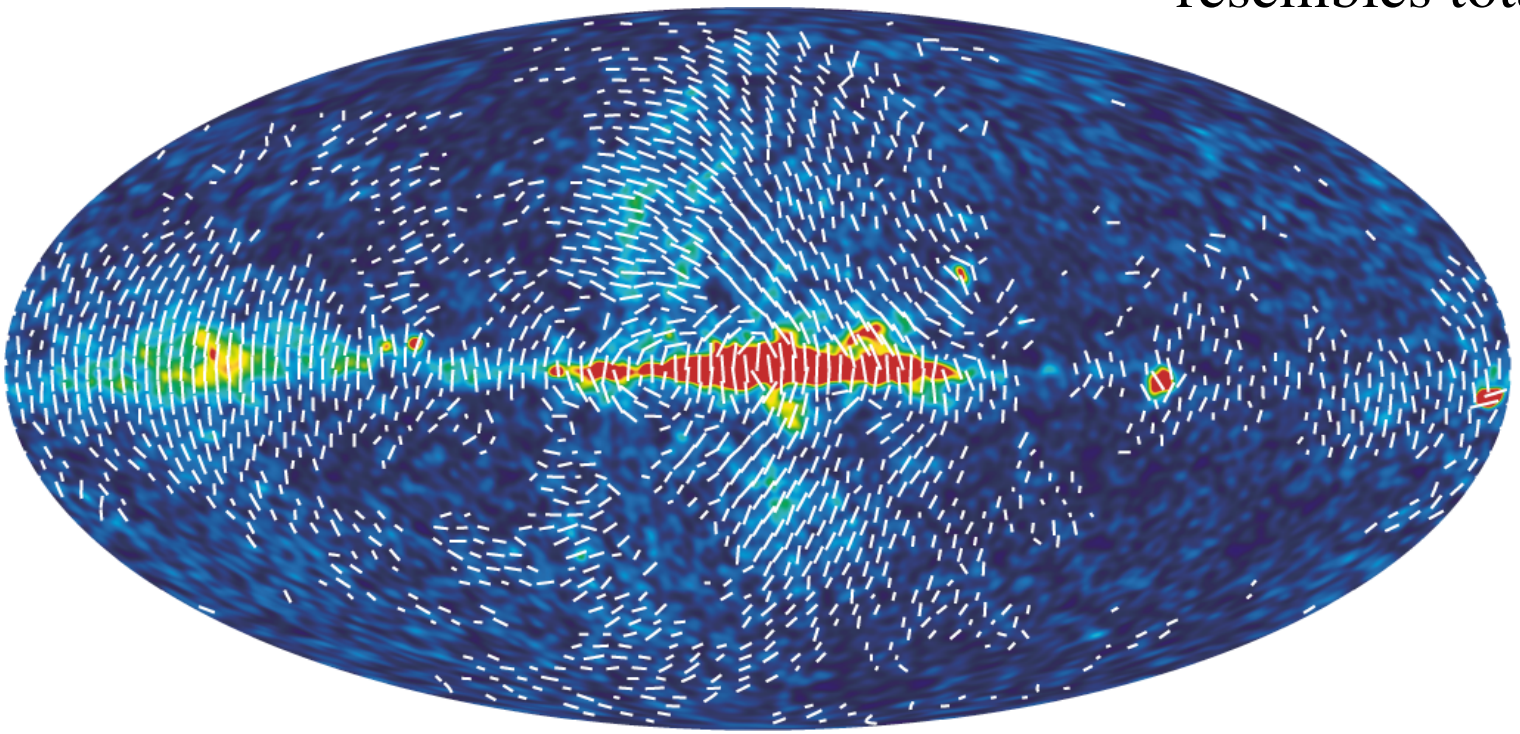
Polarized Intensity at 33 GHz

- no Faraday rotation at these frequencies: polarized intensity resembles total intensity



WMAP, Polarized Intensity (33 GHz)

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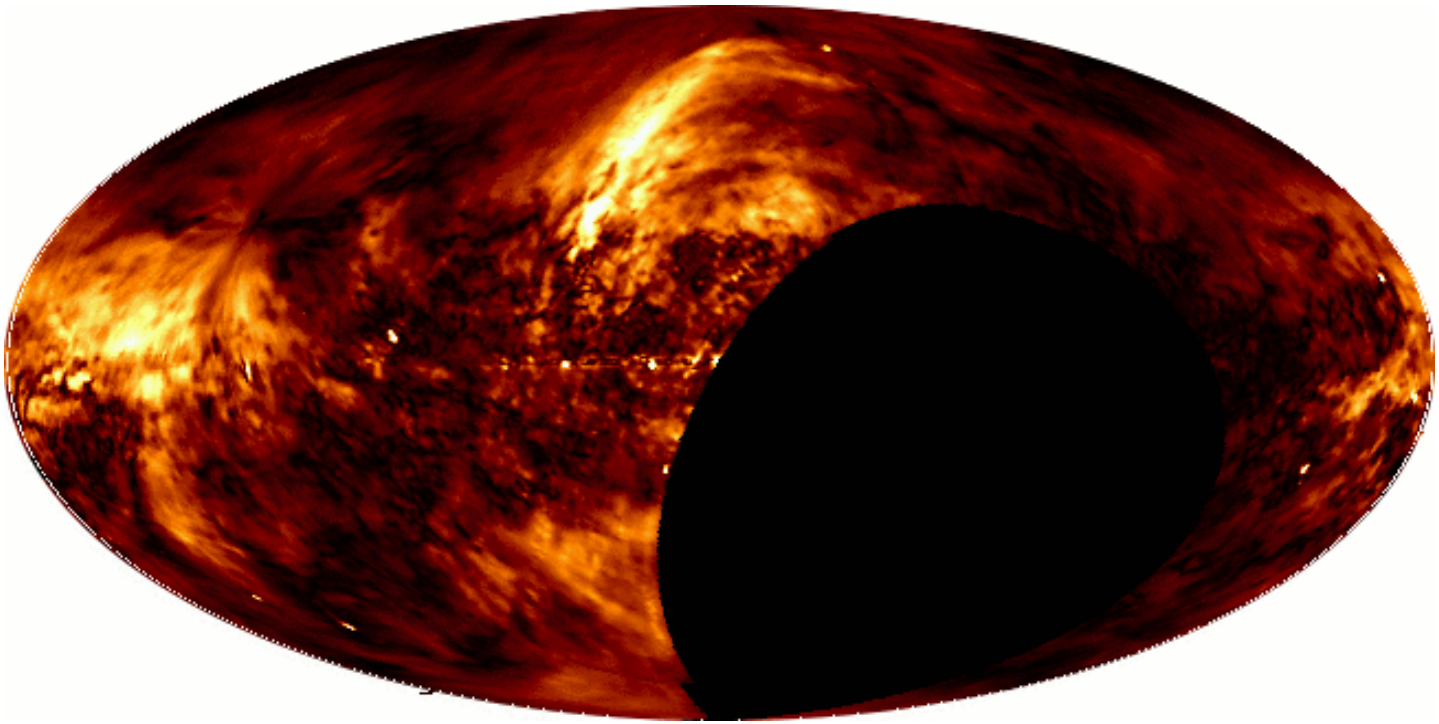
Polarized Intensity at 1.4 GHz

- very little correlation between polarized and total intensity



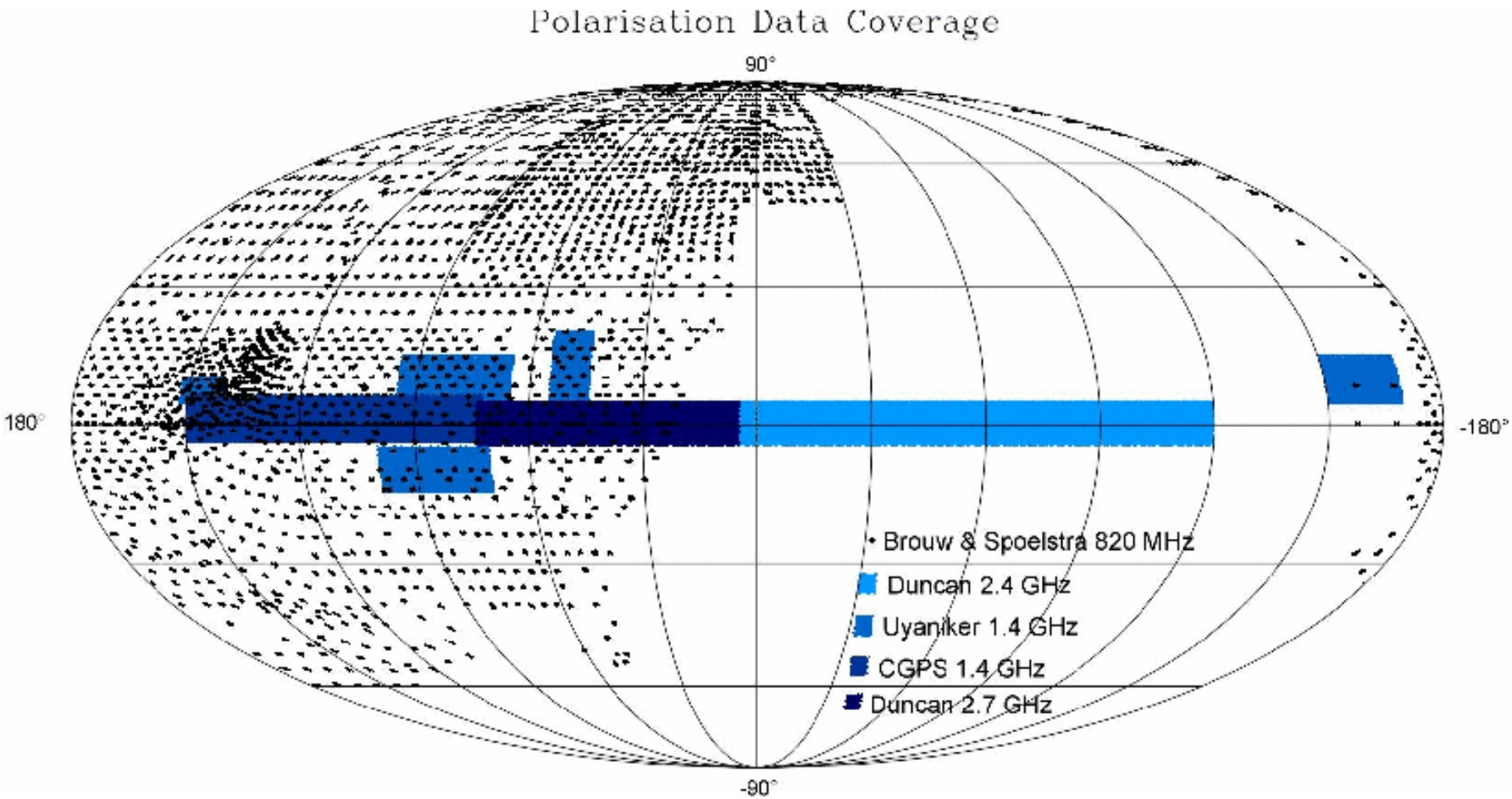
DRAO 26-m Polarization Survey, Wolleben et al. 2006, Polarized Intensity (1.4 GHz)

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

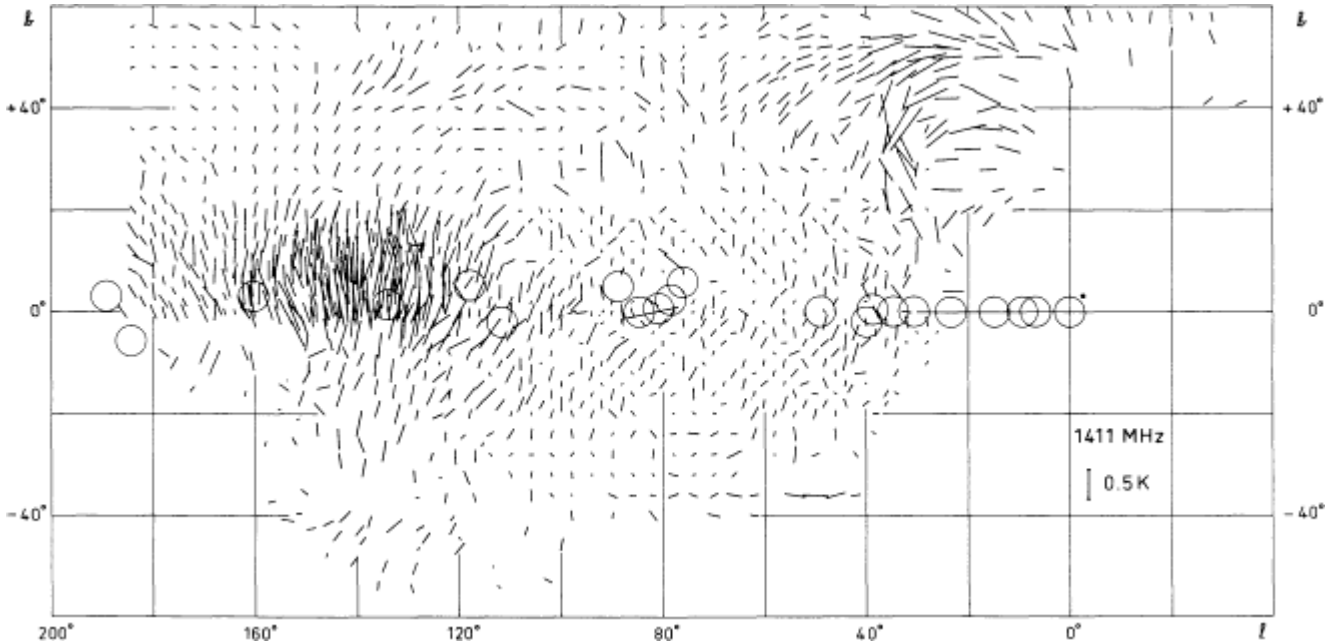


Surveys of Polarized Emission

- 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 -

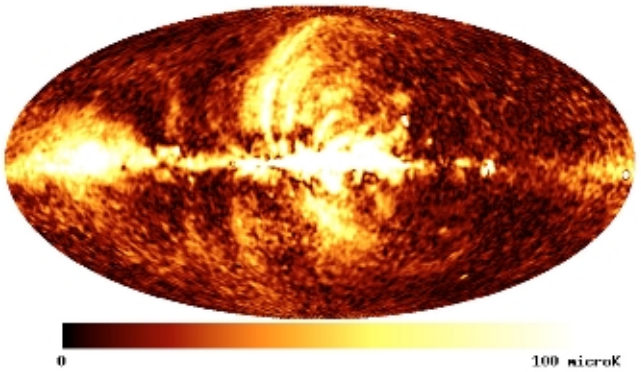


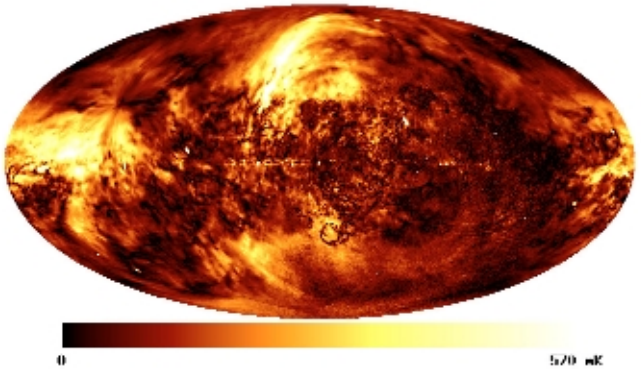
Surveys of Polarized Emission

Best all-sky polarization surveys available today:

- WMAP

- Combined DRAO and Villa-Elisa Survey at 1.4 GHz





Picture taken from Sun, 2008

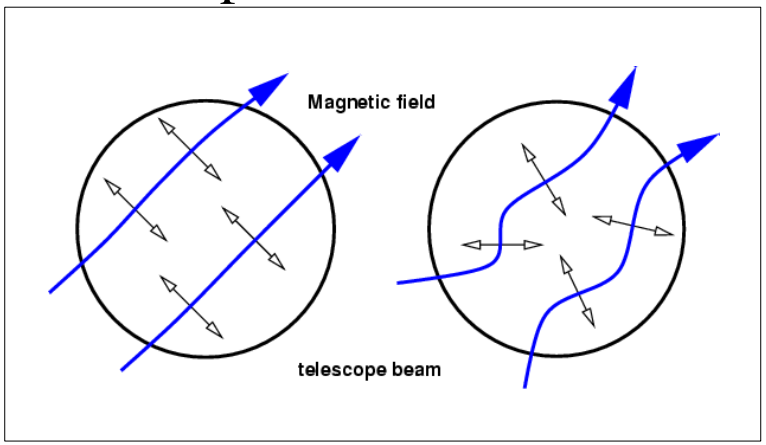
Faraday Rotation

Terrestrial Analog of the Effect of the Magneto-Ionic Medium

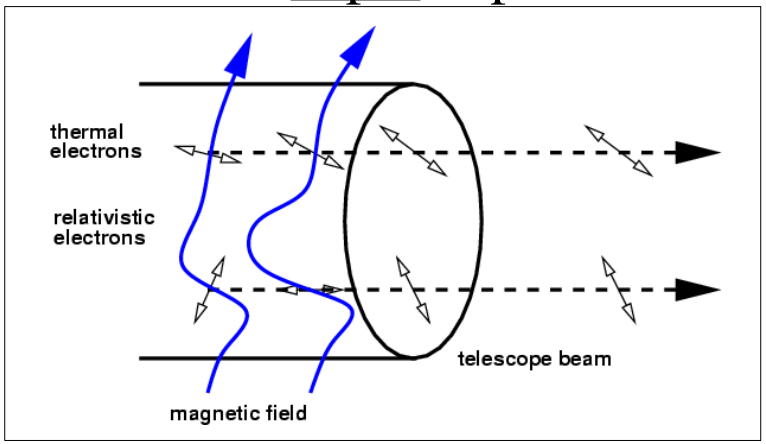
Depolarization

Depolarization

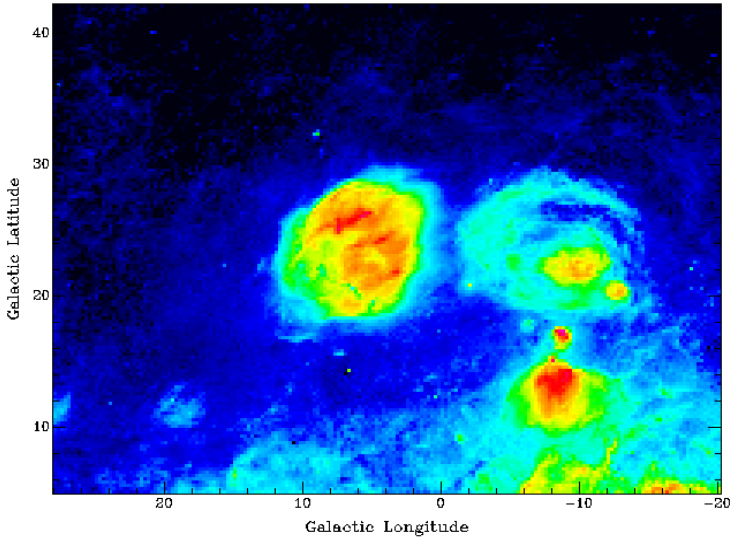
beam depolarization

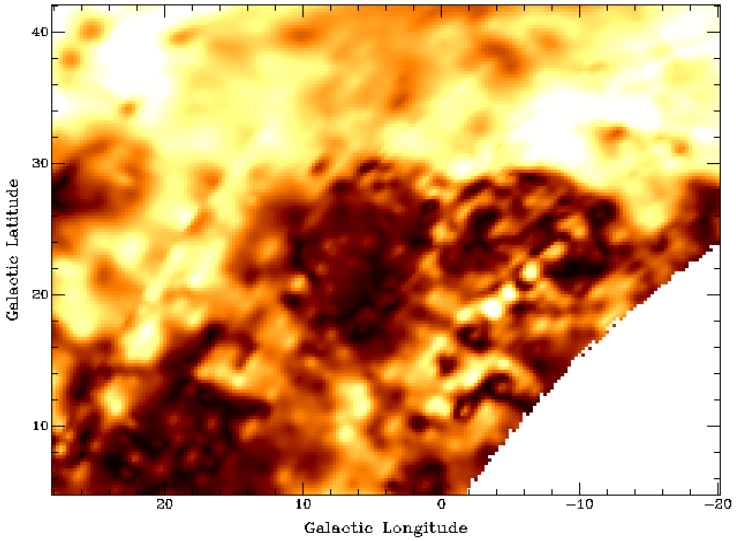


depth depolarization



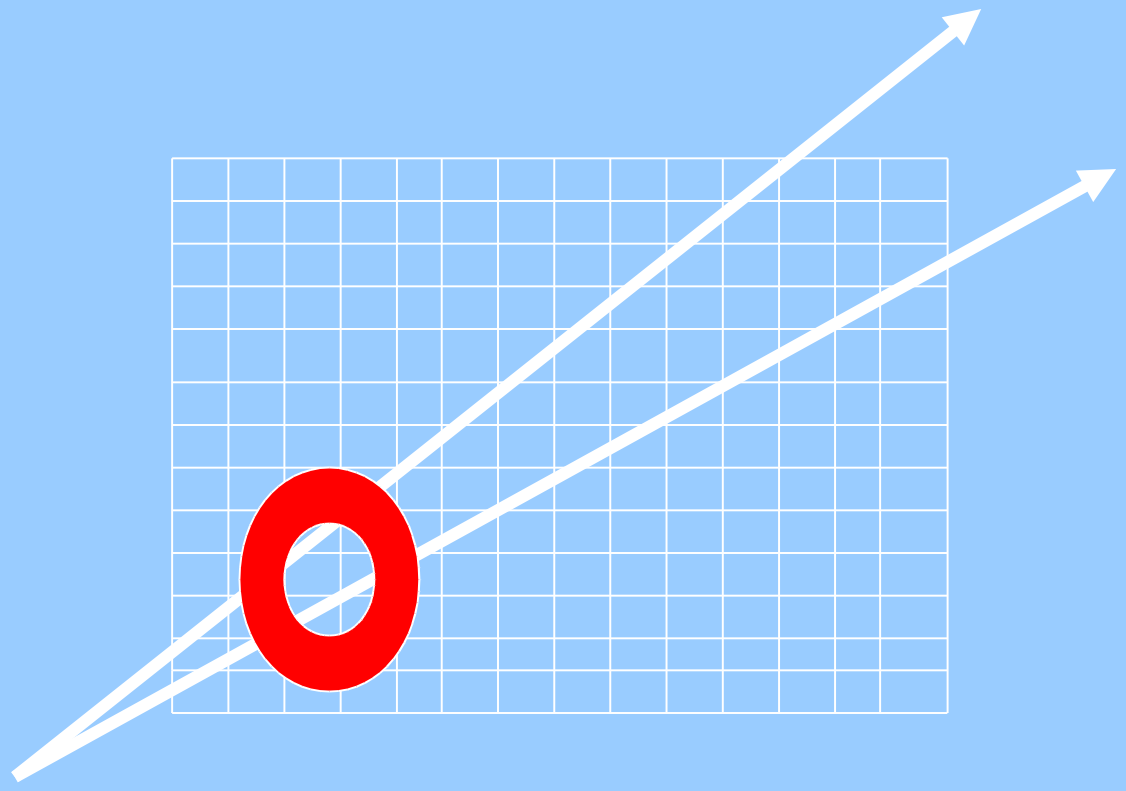
Polarization Horizon





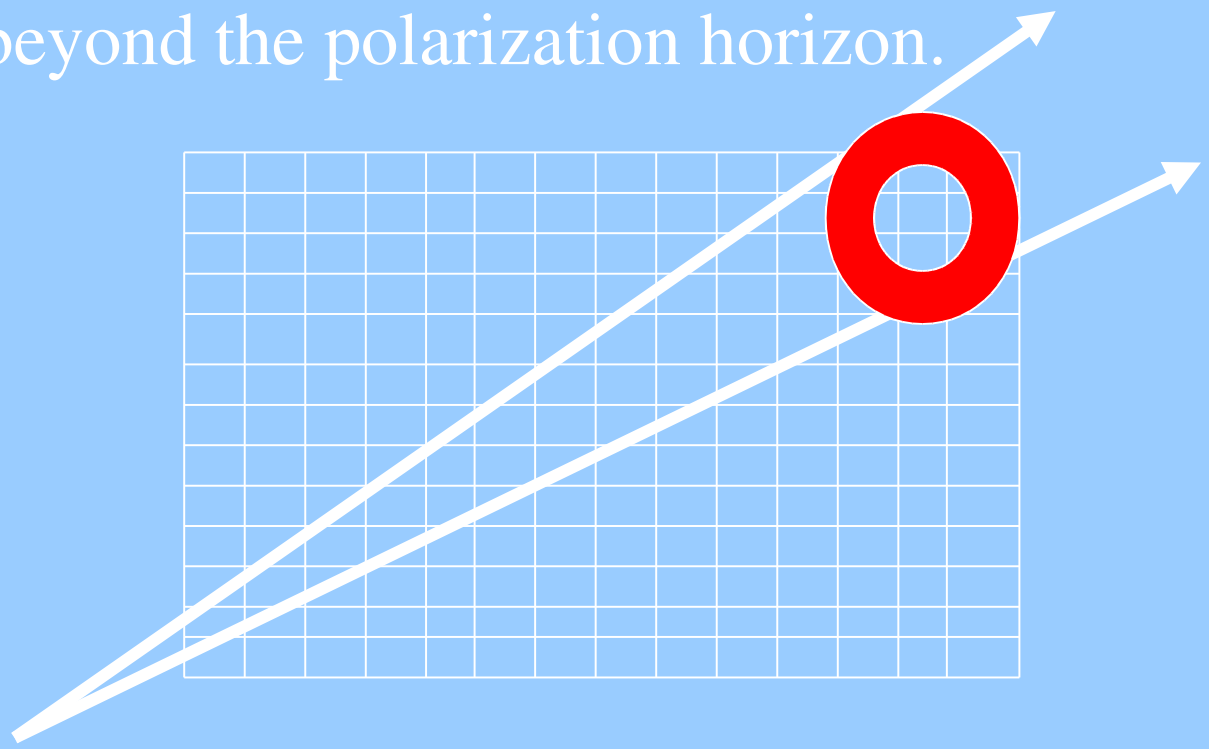
Polarization Horizon

Nearby HII regions will be seen as depolarization patches.

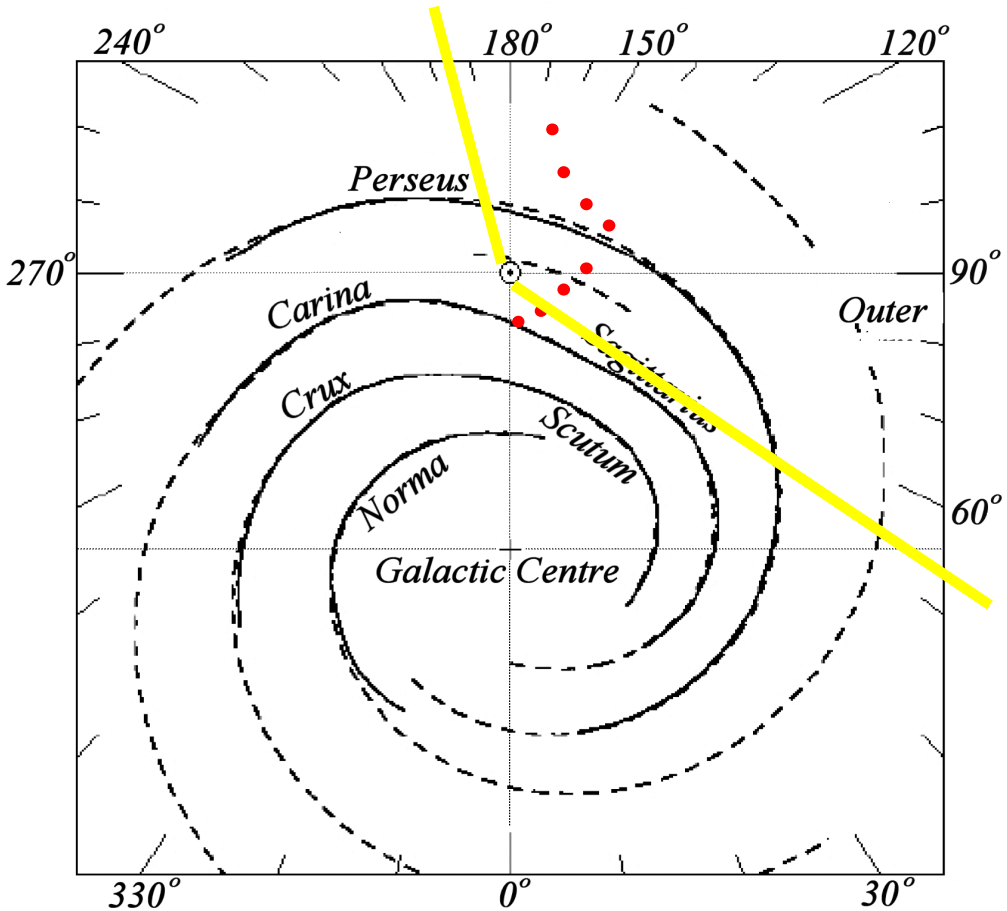


Polarization Horizon

Distant HII regions will not depolarize:
they are beyond the polarization horizon.



Polarization Horizon



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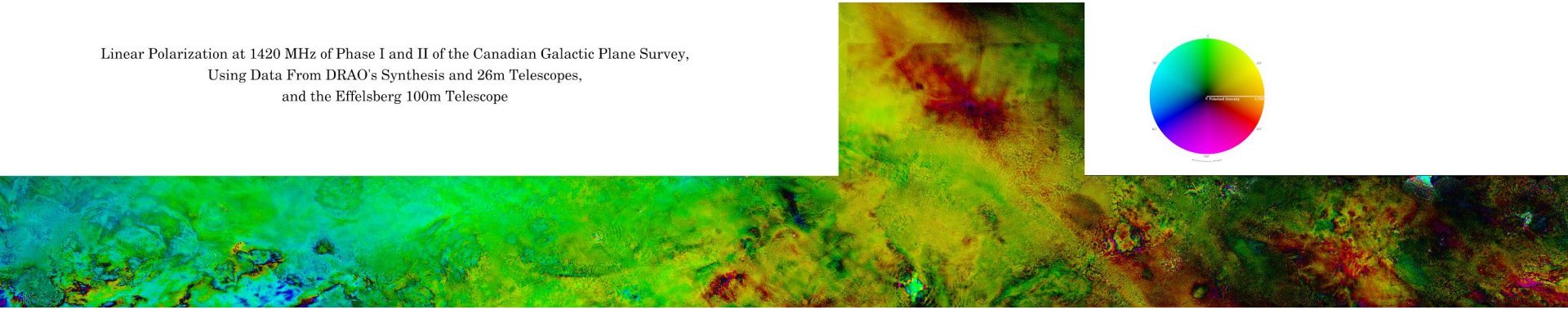
A Tool for Exploring the Milky Way

The Polarized Sky

Canadian Galactic Plane Survey

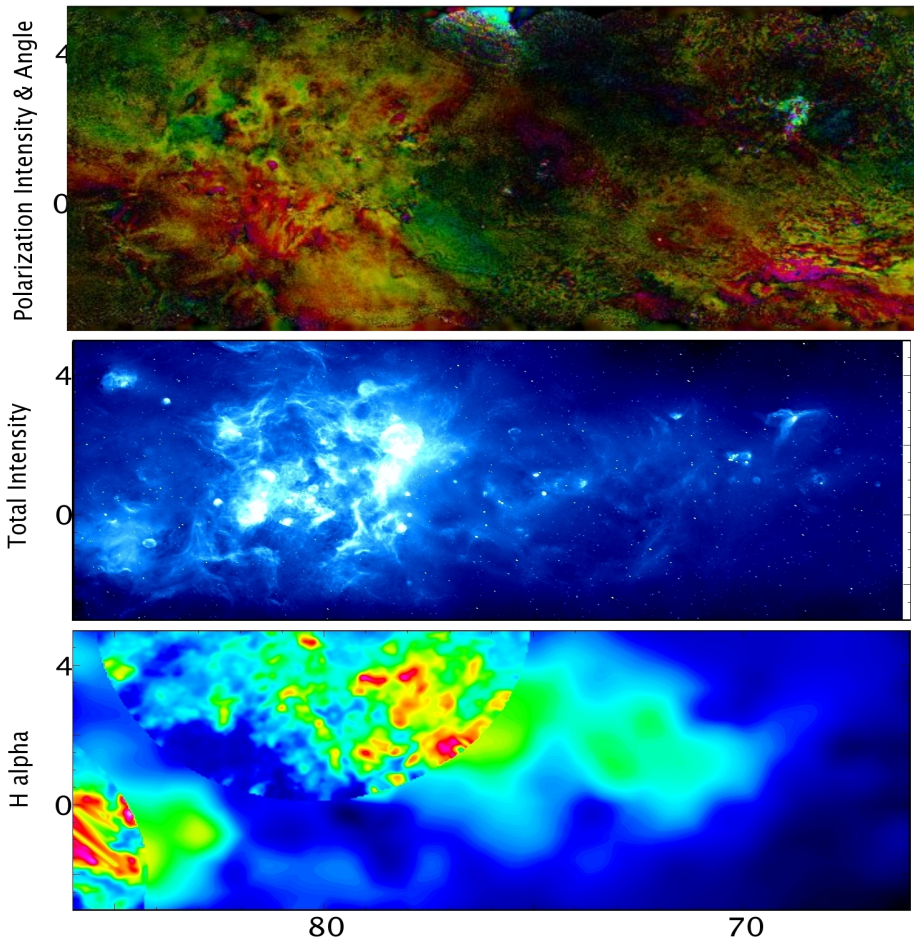


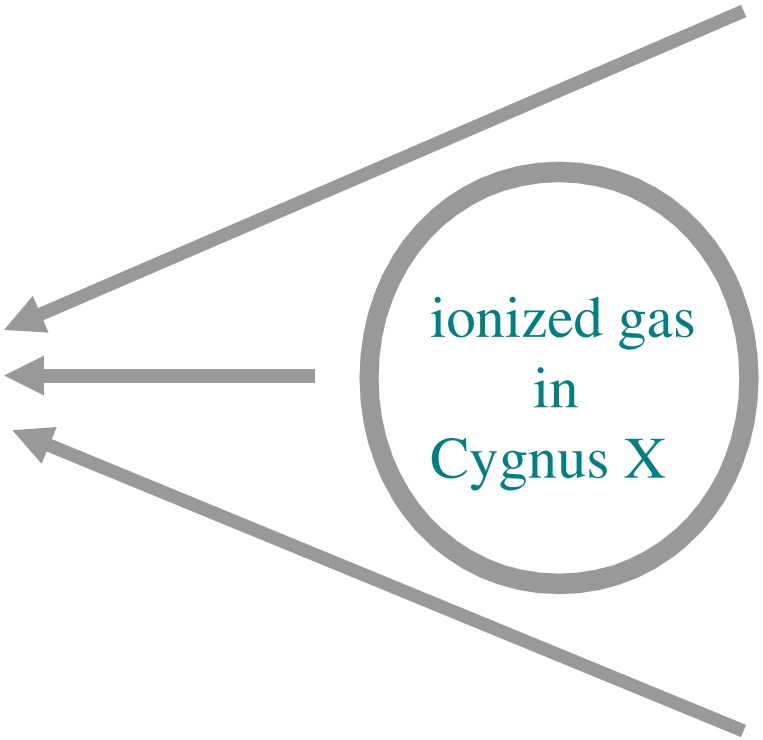
brightness -> polarized intensity
color -> polarization angle

- 1.4 GHz
- 1 arcmin resolution
- 4 frequency channels

The Polarized Sky

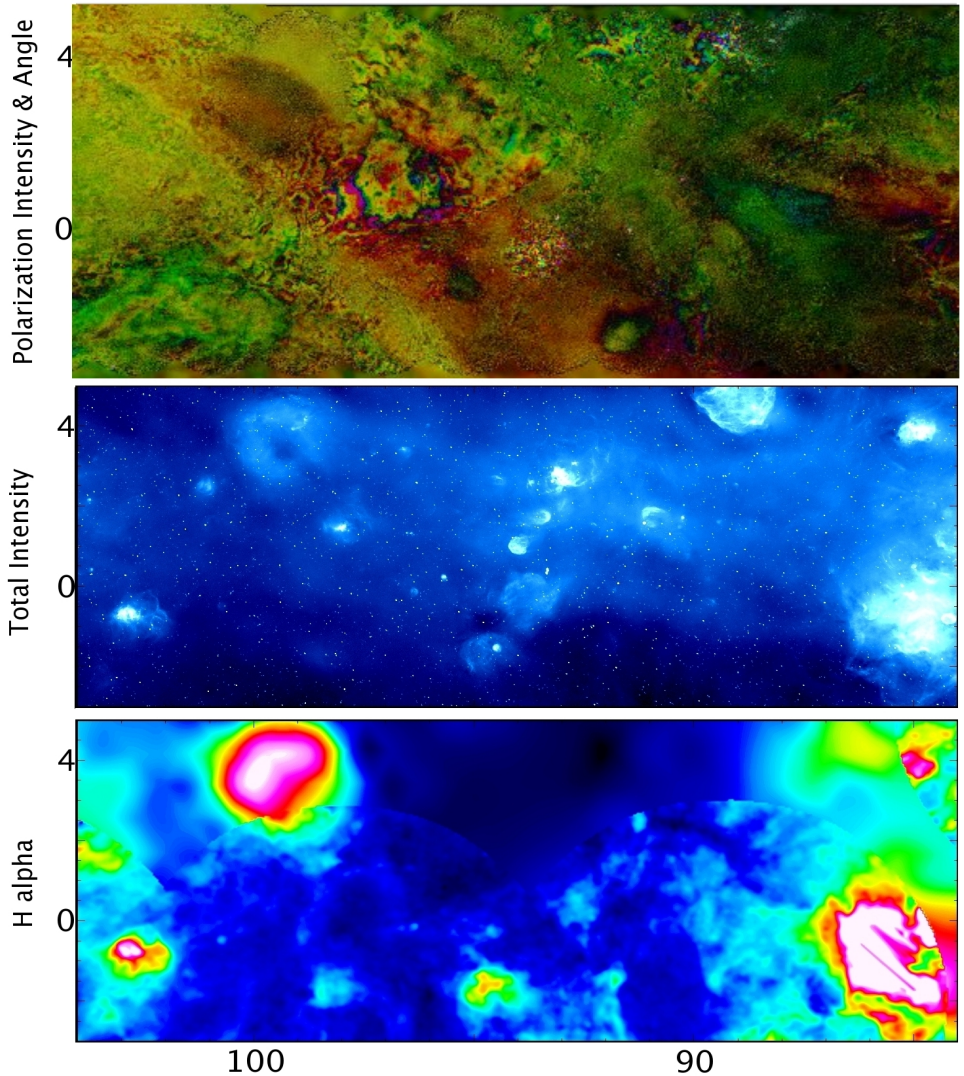
Canadian Galactic Plane Survey





The Polarized Sky

Canadian Galactic Plane Survey



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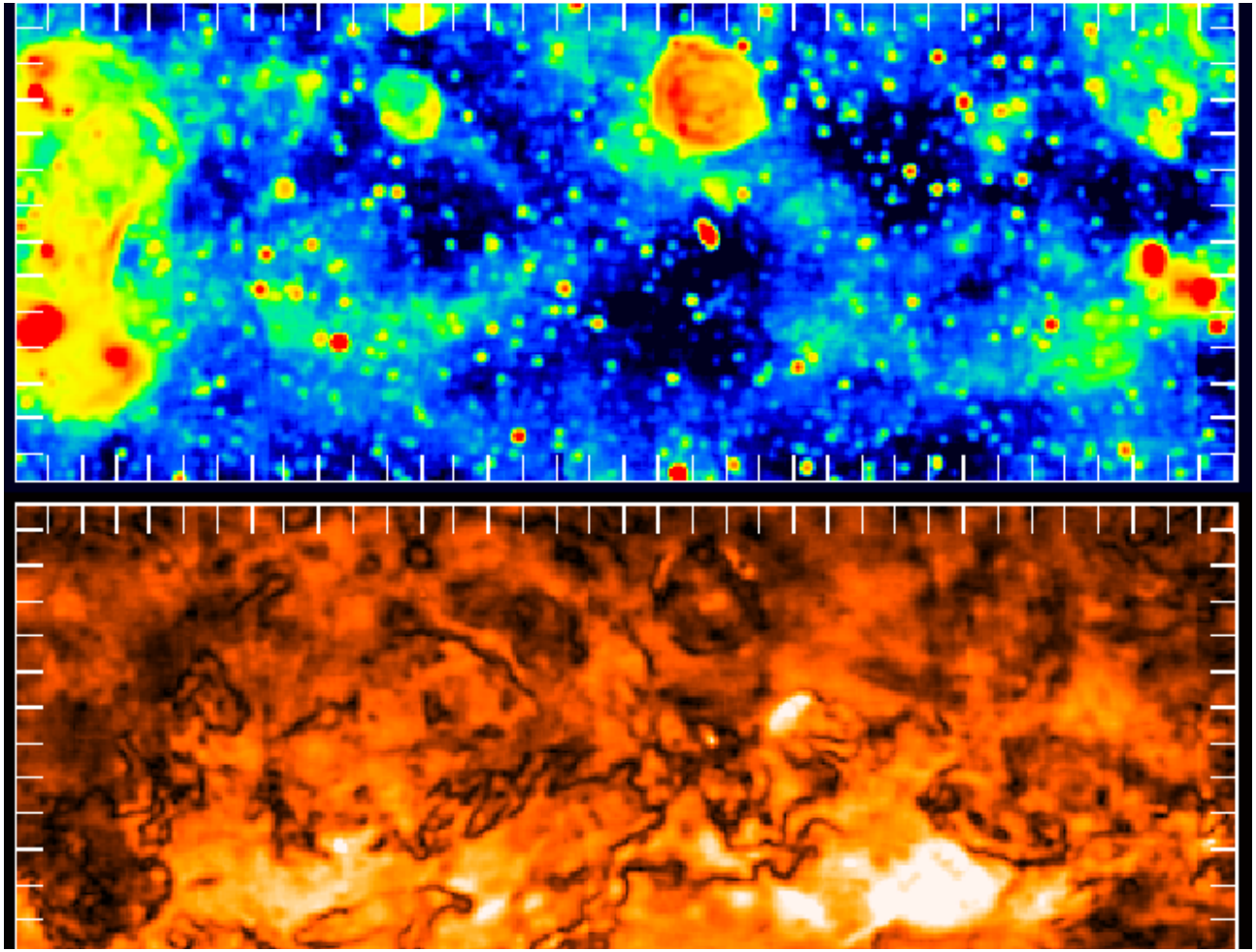
The Polarized Sky

Effelsberg Medium Latitude Survey

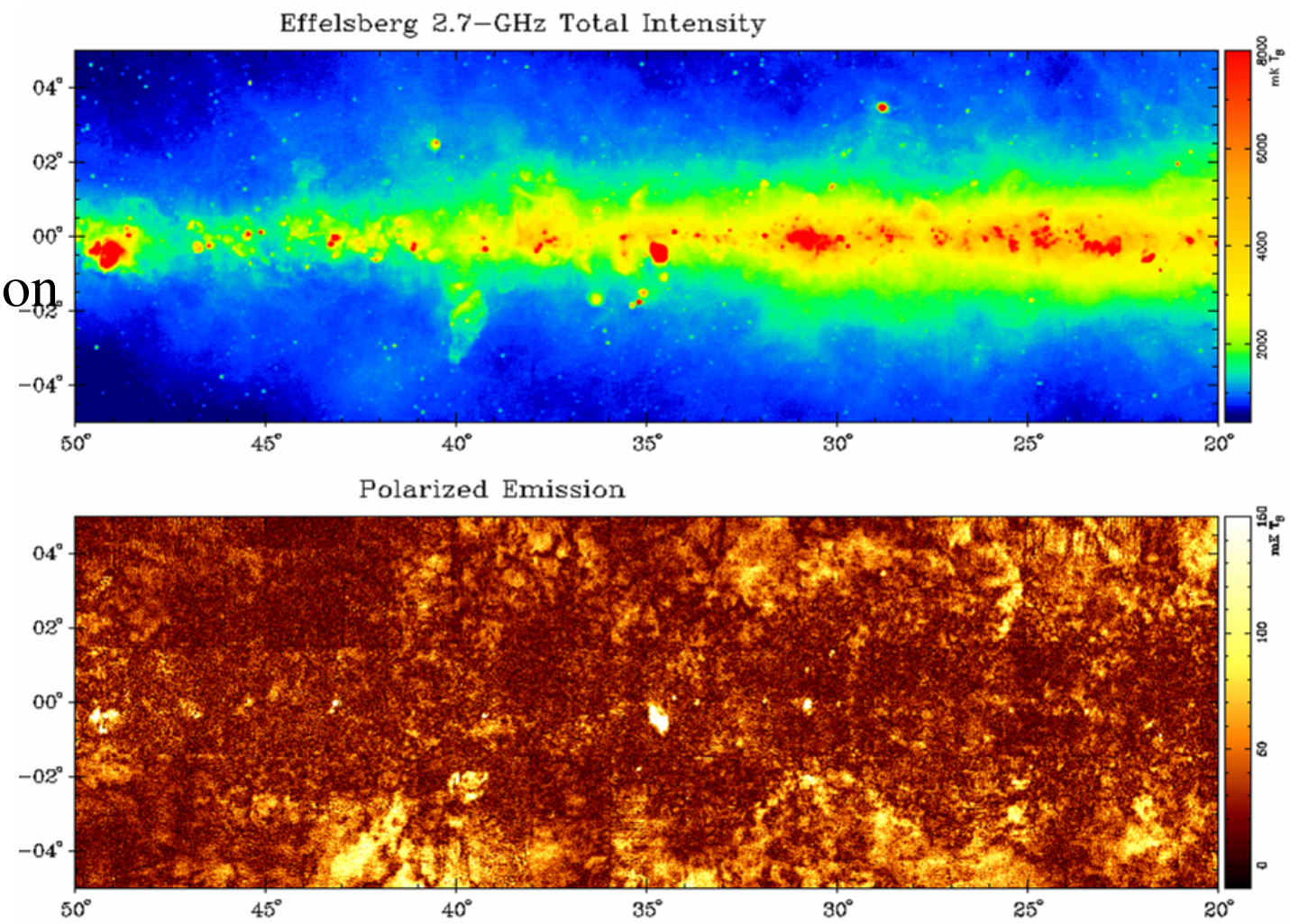
- 1.4 GHz
- 9 arcmin resolution
- single frequency
- sensitivity: 9 mK



The Polarized Sky

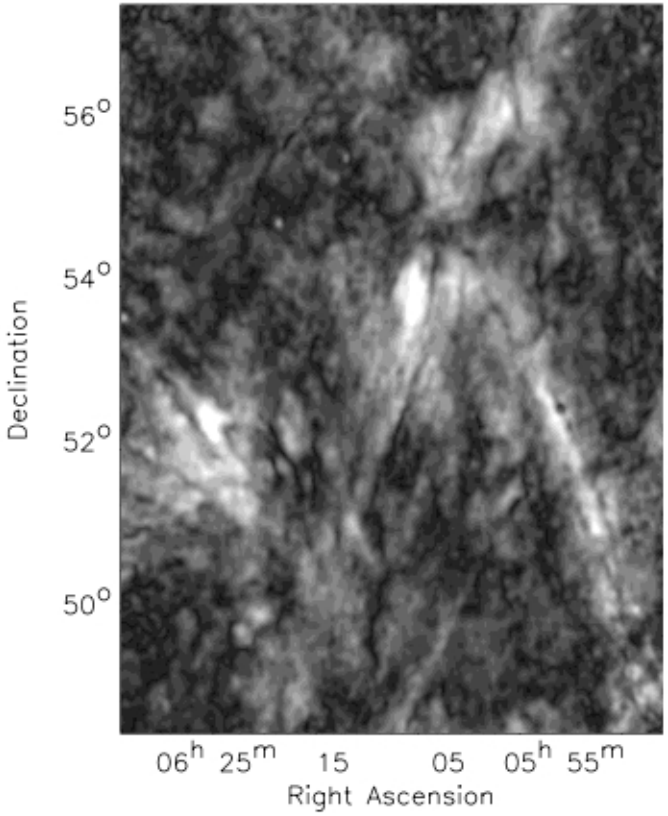
Effelsberg Data

- 2.7 GHz
- 4 arcmin resolution
- single frequency

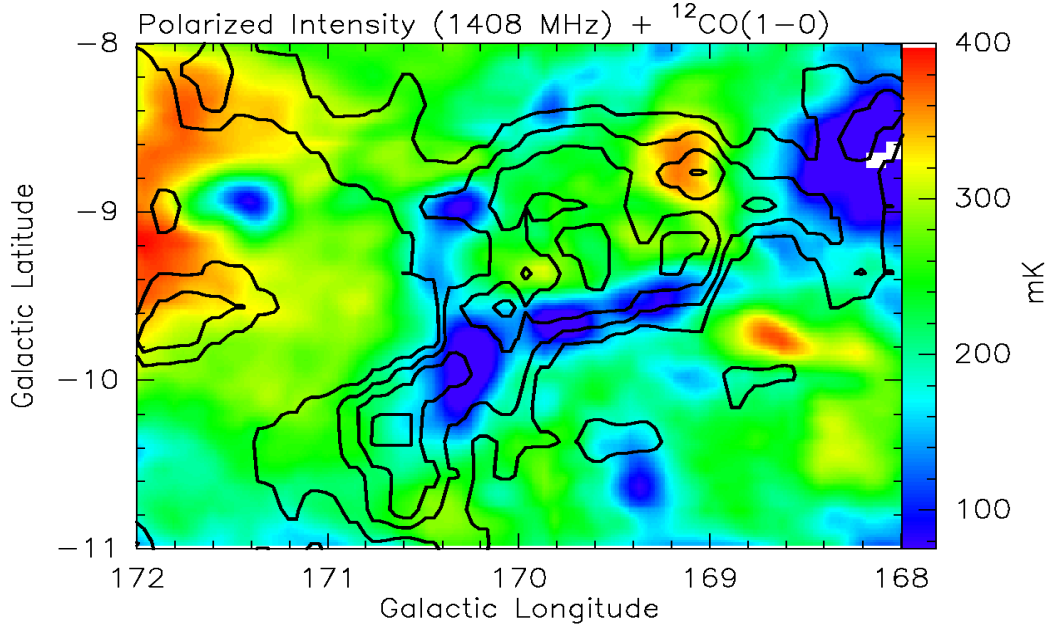


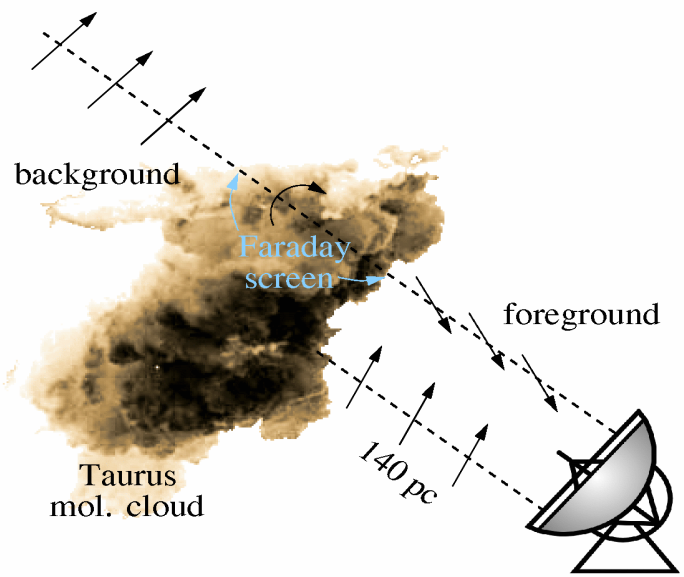
The Polarized Sky

- 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





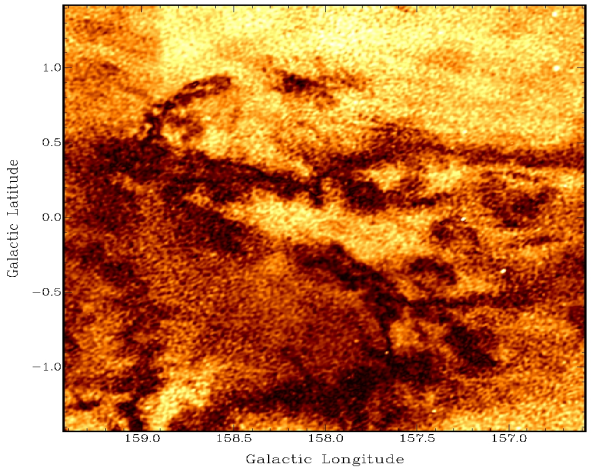
Sharpless 216

The closest planetary nebula

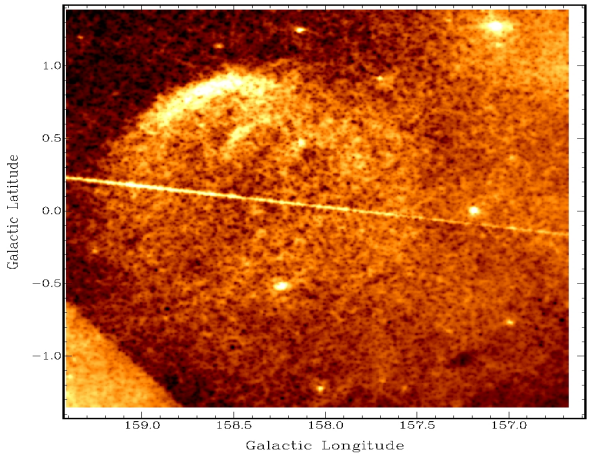
Distance 120 pc

Size 1.6 degrees

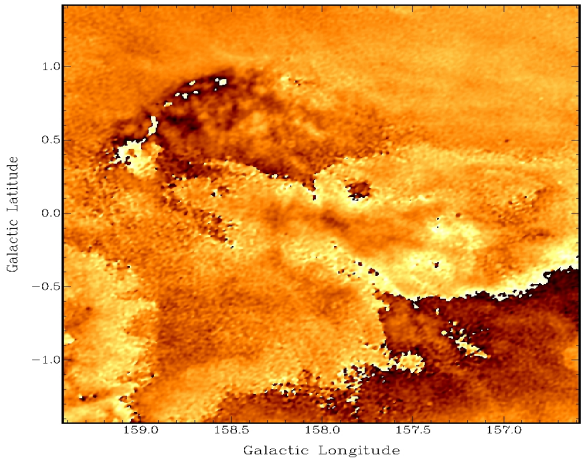
Ransom et al., 2008



Polarized intensity

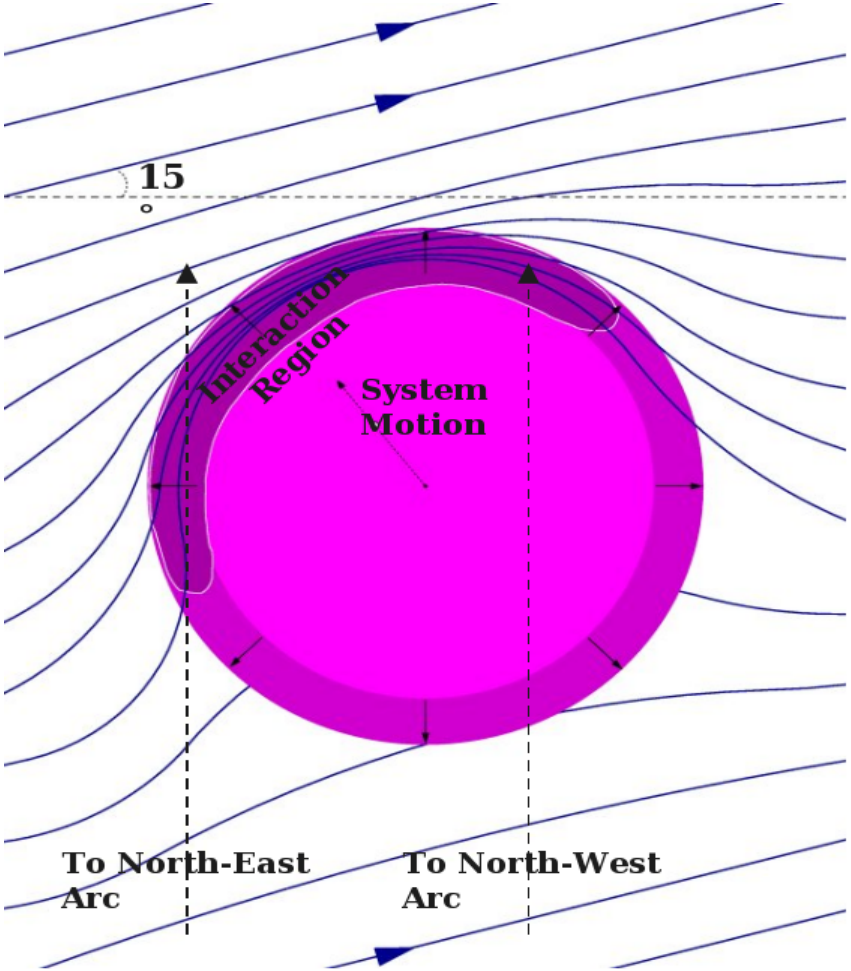


Optical



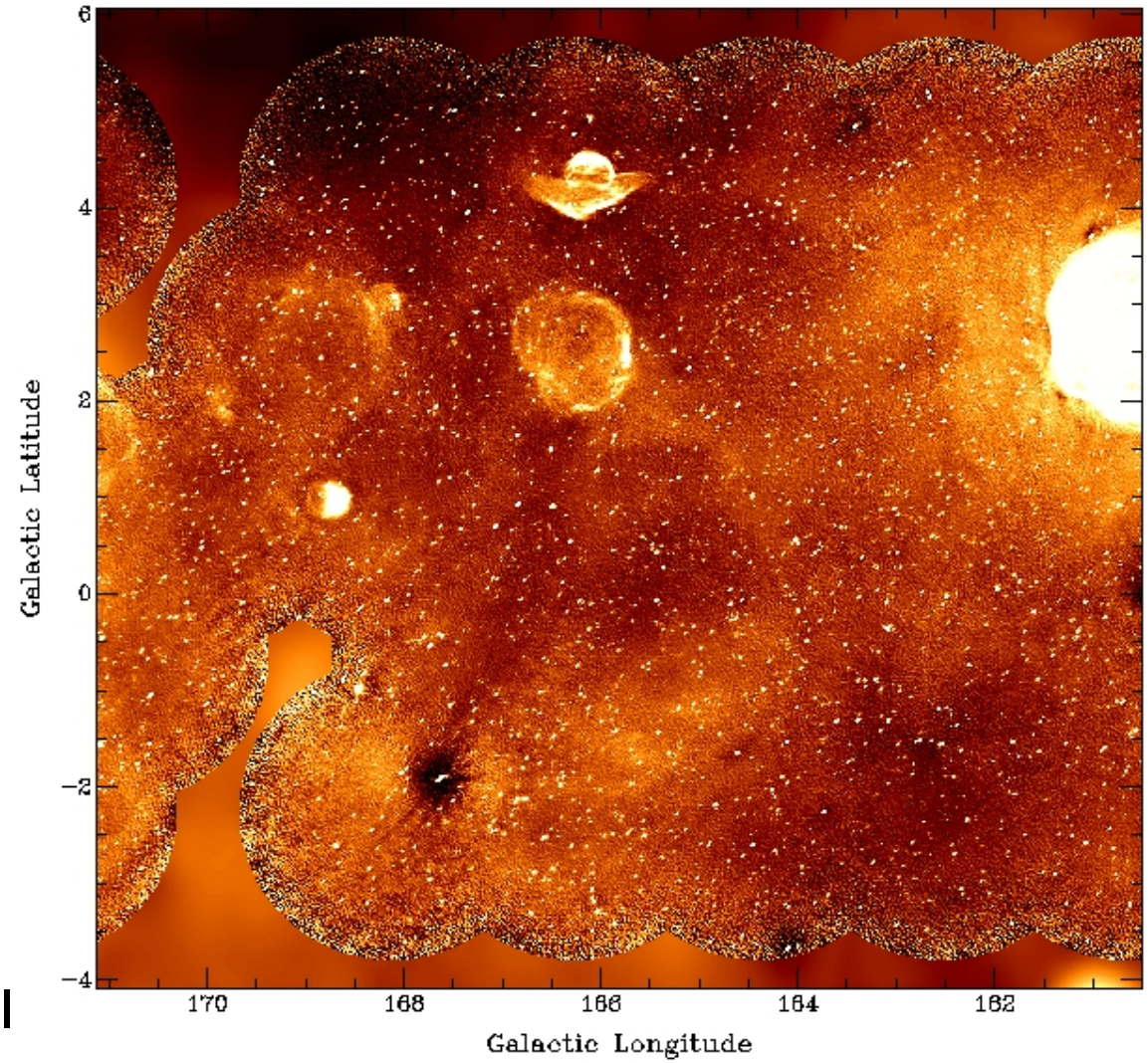
Polarization angle

Sharpless 216



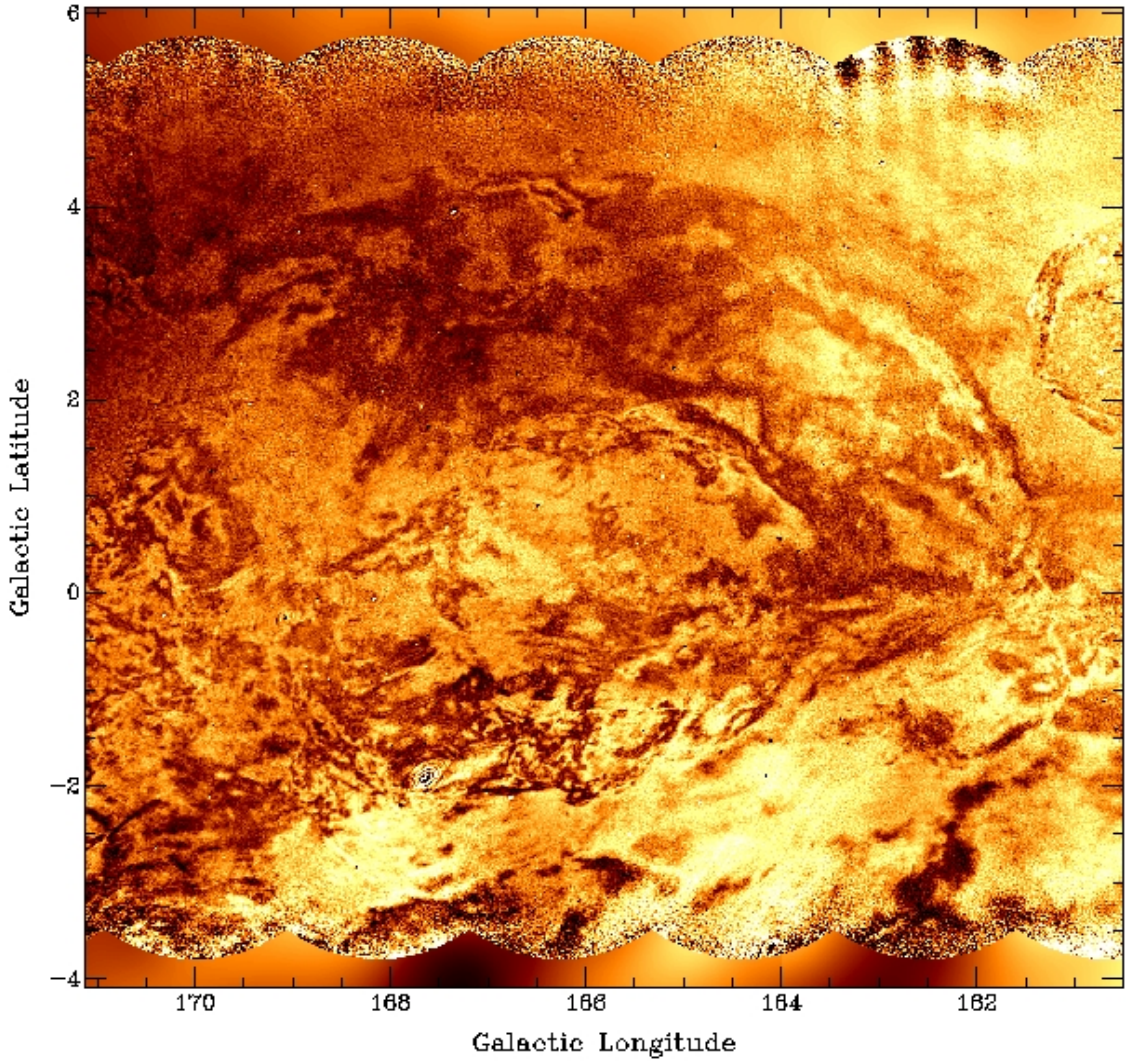
Ransom et al., 2008

Anticentre Bubble



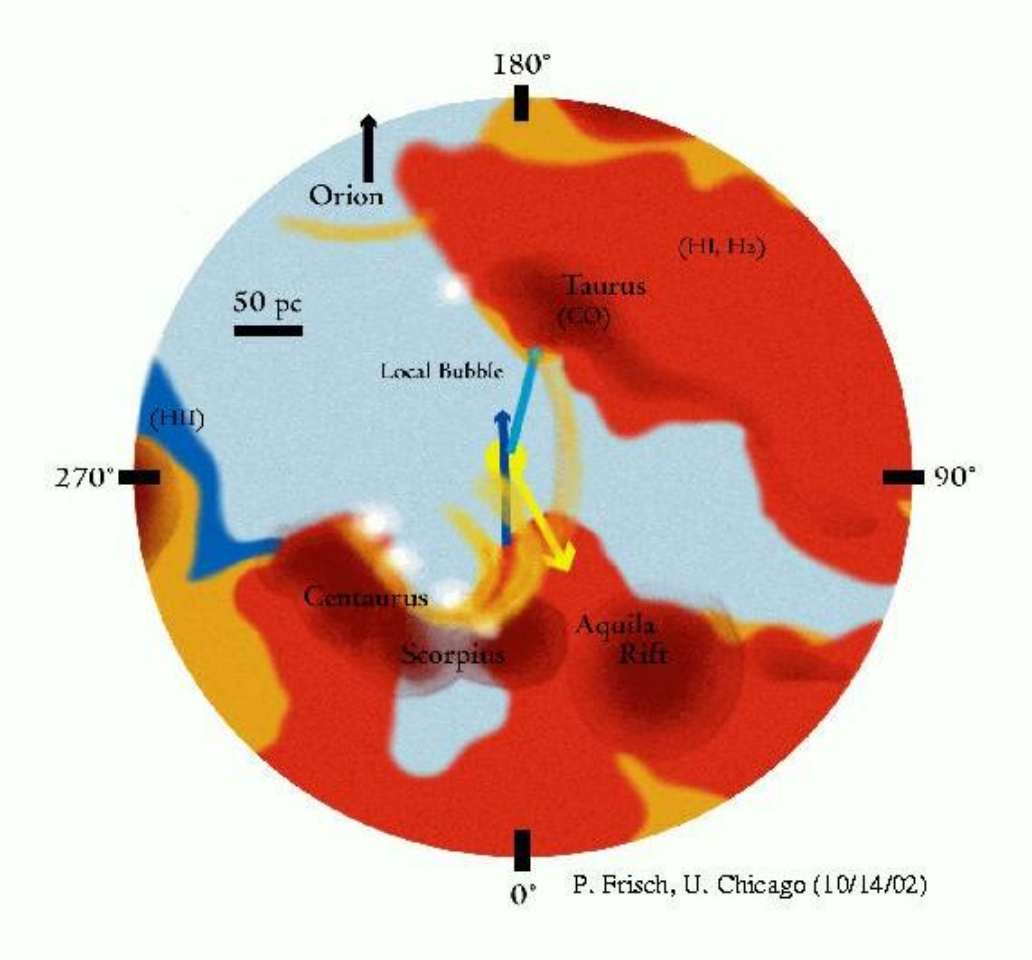
1420 MHz Stokes I

Anticentre Bubble



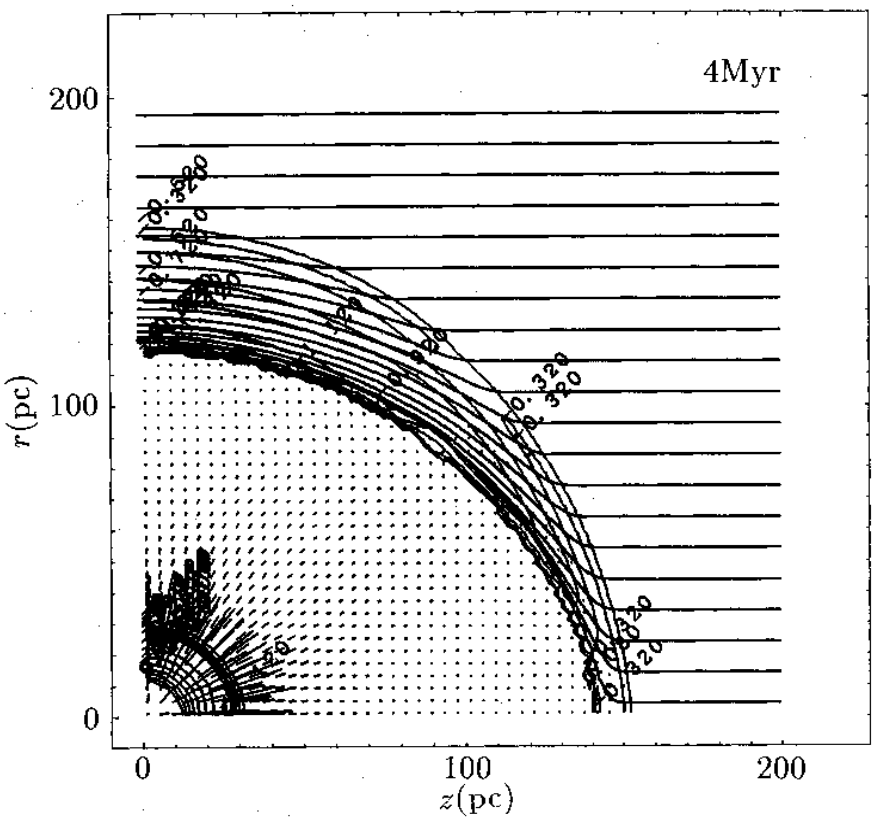
1420 MHz Stokes U

The Galactic Neigbourhood



The Galactic Neigbourhood

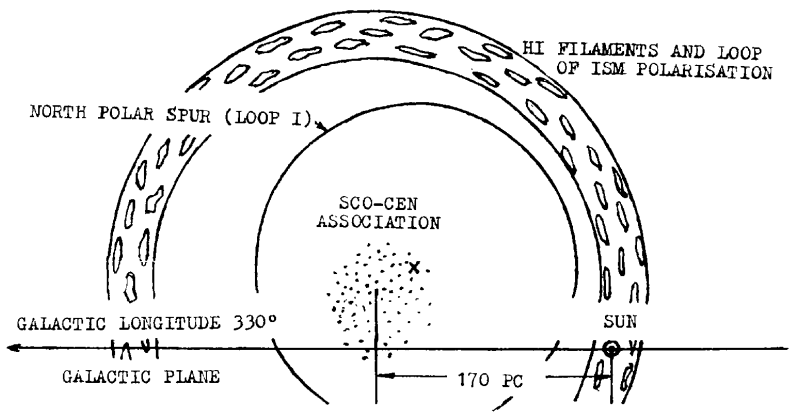
B-Field of an Expanding Shell



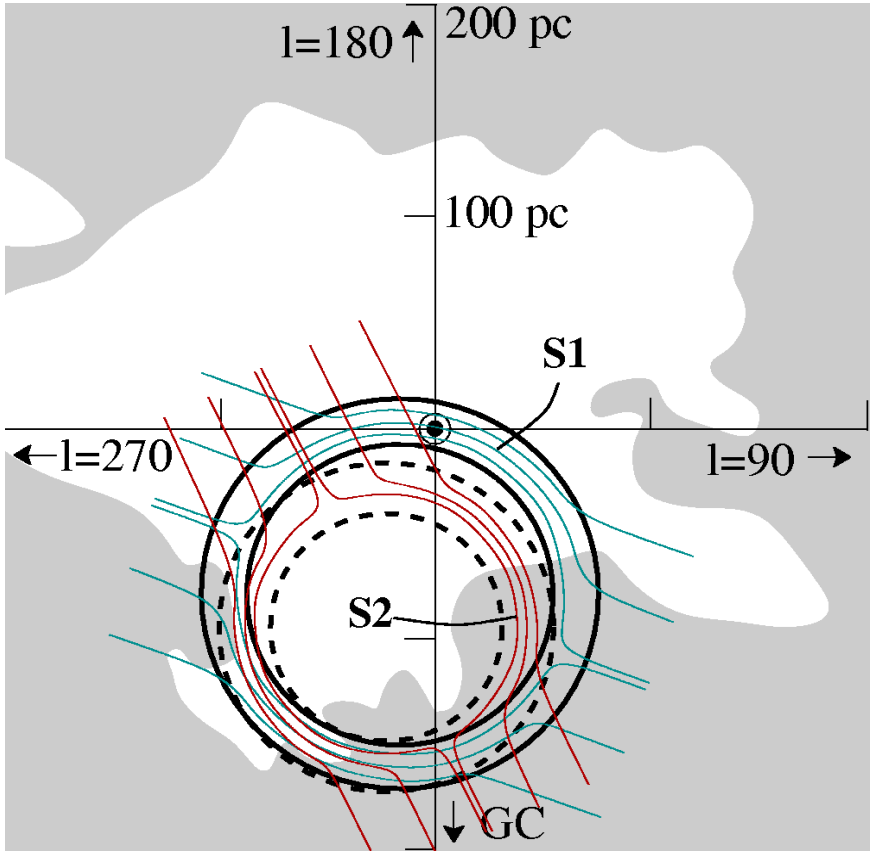
Tomisaka, 1992

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

The Galactic Neigbourhood

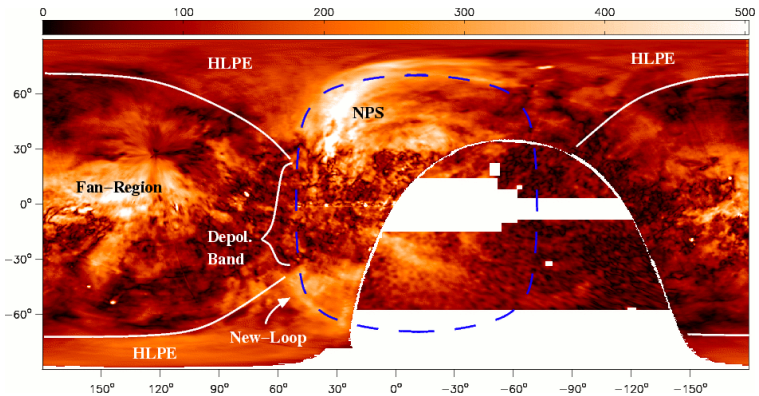


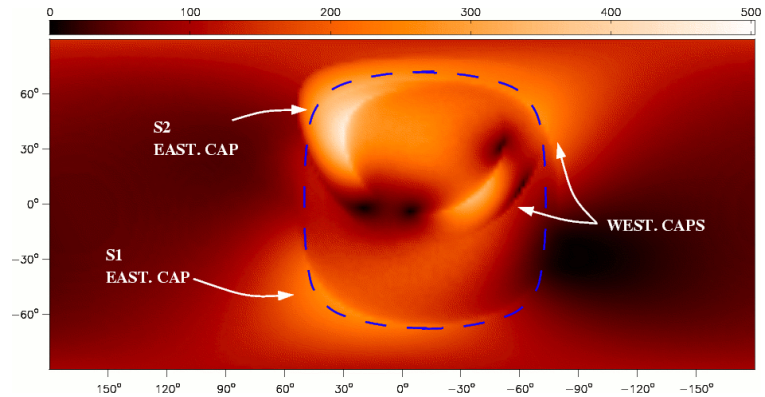
Weaver, 1979



- HI shell, radio loop
- shells produced by stellar winds or supernova activity
- refined model: 2 synchrotron emitting shells (Wolleben, 2007)

The Galactic Neigbourhood





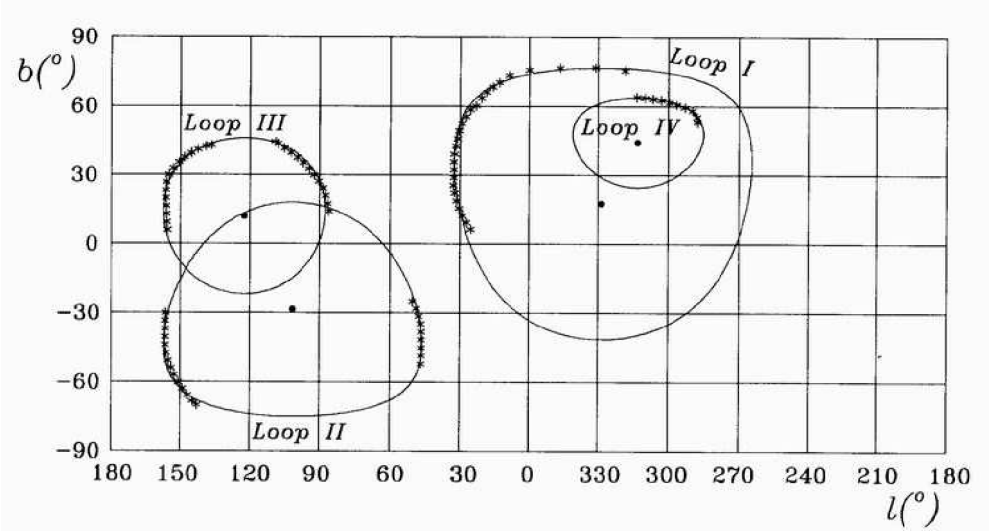
- a previous large-scale B-field has probably been tangled up by the complex evolution of the Local Bubble / Loop-I region

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

The Galactic Neigbourhood

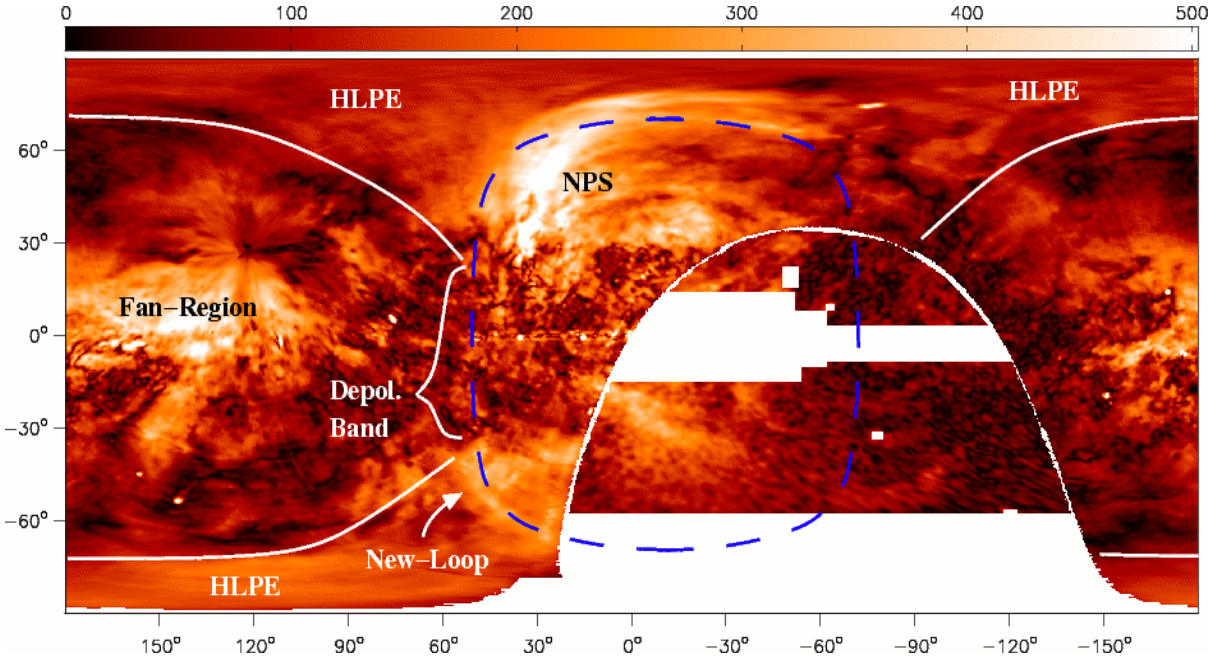
Other Radio Loops

- 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

Summary: The Polarized Sky

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

Modeling Total Intensity

A Model of Diffuse Galactic Radio Emission from 10 MHz to 100 GHz

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[2] *School of Physics A29, The University of Sydney, NSW 2006, Australia*
[3] *Department of Physics & Electronics, Rhodes University, Grahamstown 6140, South Africa*
[4] *Dominion Radio Astrophysical Observatory, National Research Council, P.O. Box 248, Penticton, B.C., Canad*
[5] *Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany*

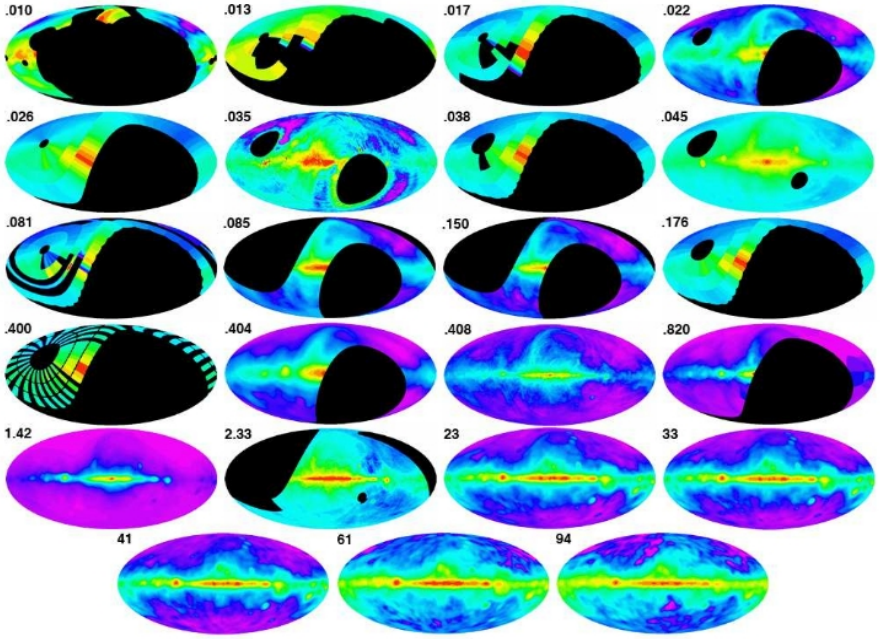
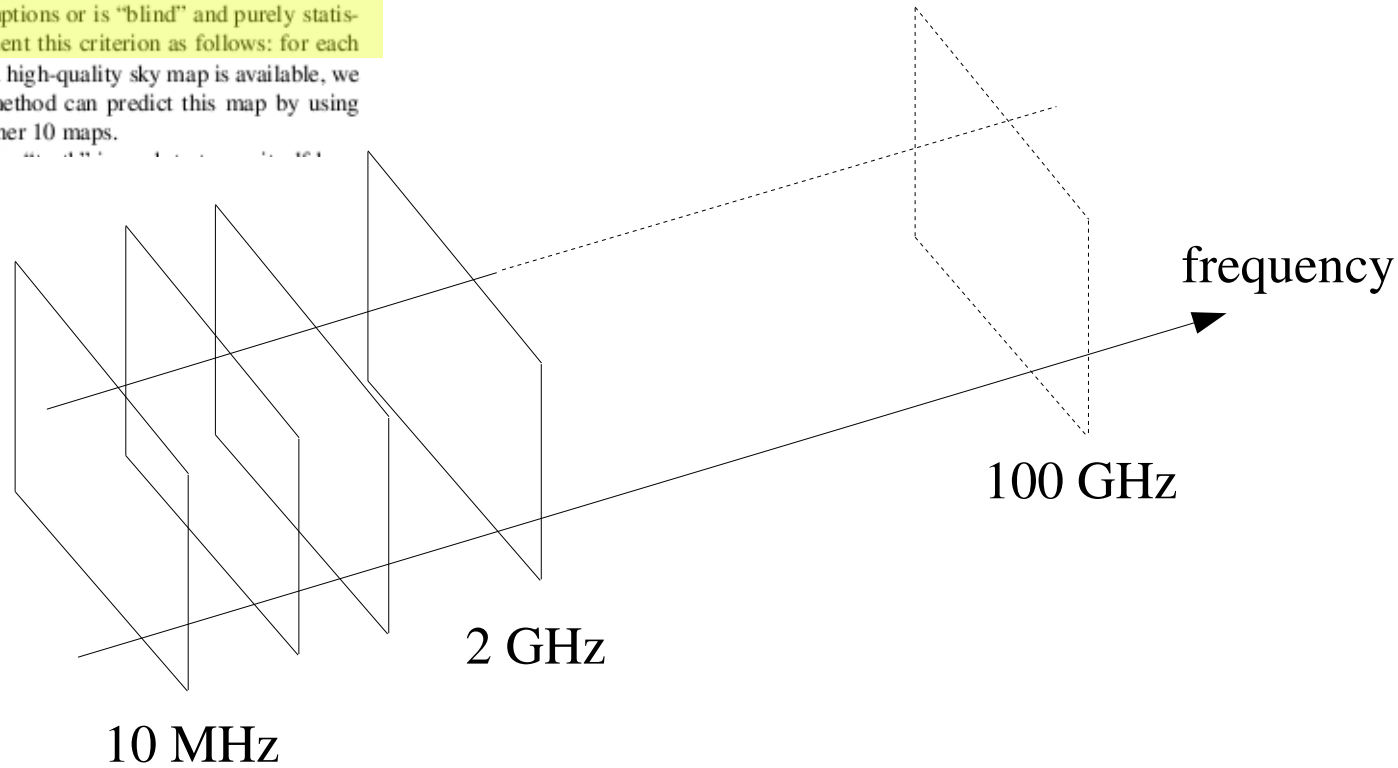


Figure 1. The maps show (from left to right, top to bottom) the 0.010 GHz (52), 0.0135 GHz (55), 0.0175 GHz (55), 0.022 GHz (57), 0.026 GHz (58), 0.0345 GHz (61), 0.038 GHz (58), 0.045 GHz (63), 0.0815 GHz (55), 0.085 GHz (65), 0.150 GHz (65), 0.176 GHz (58), 0.400 GHz (58), 0.404 GHz (72), 0.408 GHz (50), 0.820 GHz (73), 1.42 GHz (74; 75; 76) and 2.326 GHz (78) surveys, and the CMB-free WMAP foreground maps at 23, 33, 41, 61 and 94 GHz (18; 19; 22; 79).

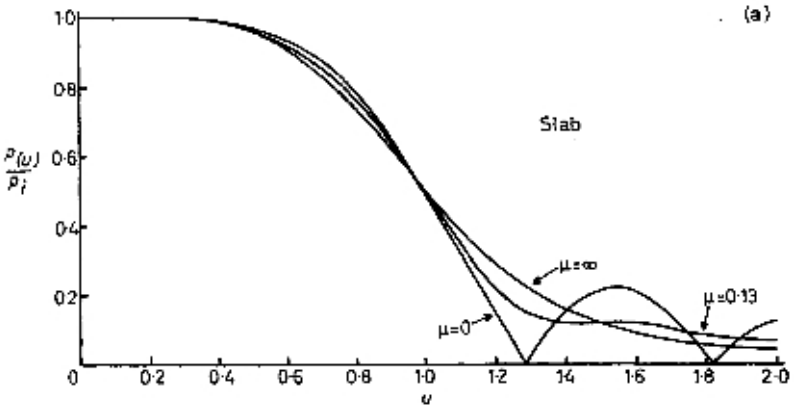
Modeling Total Intensity

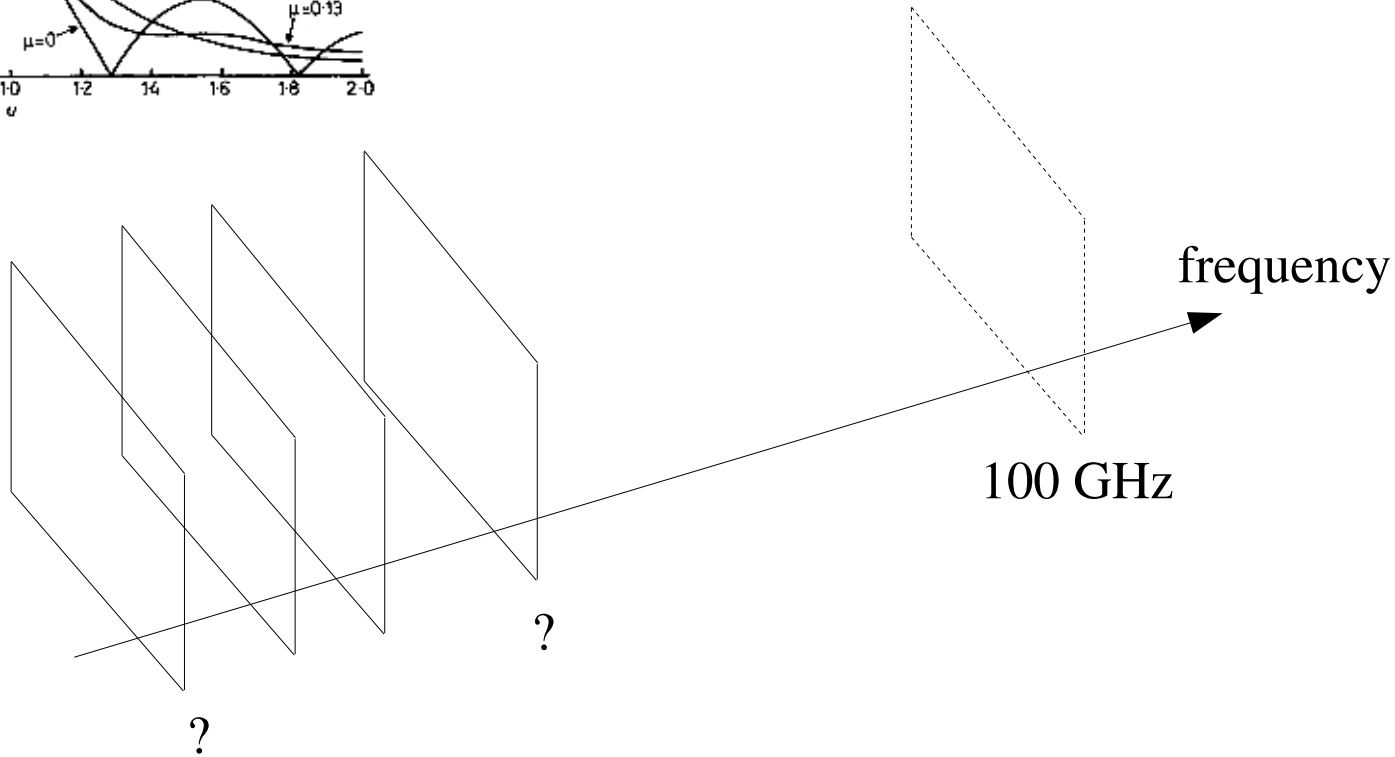
3.1 Criteria: accuracy and simplicity

In this paper, our main criterion for chosing 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





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

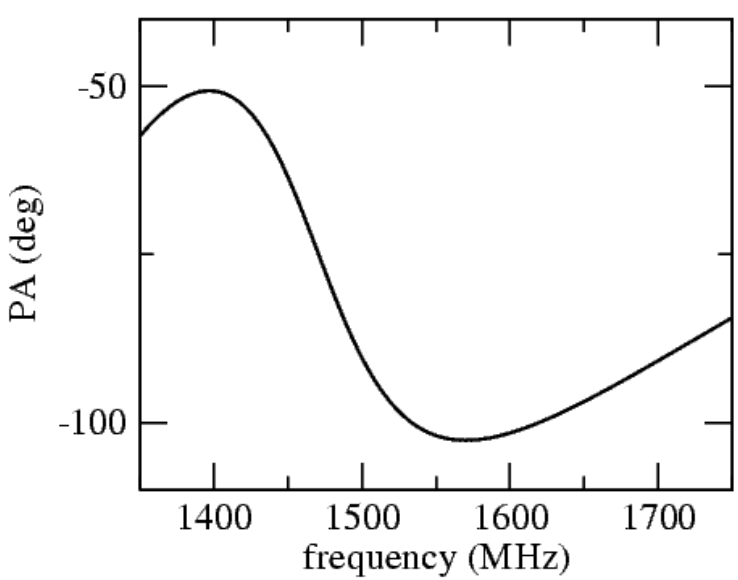
Future Surveys

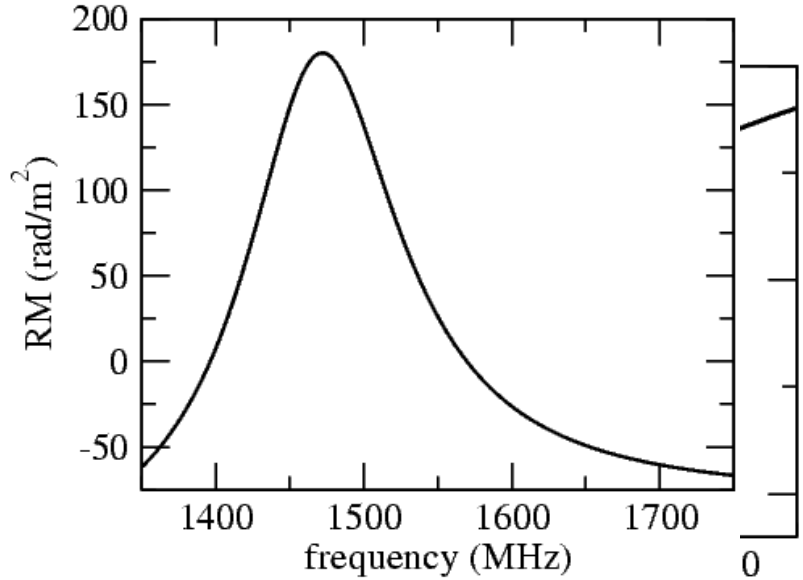
- Recent advances in digital signal processing are bringing us into the era of 3-dimensional imaging of the polarized sky.
- Wide-band data with high spectral resolution (spectro-polarimetry) enable rotation measure synthesis

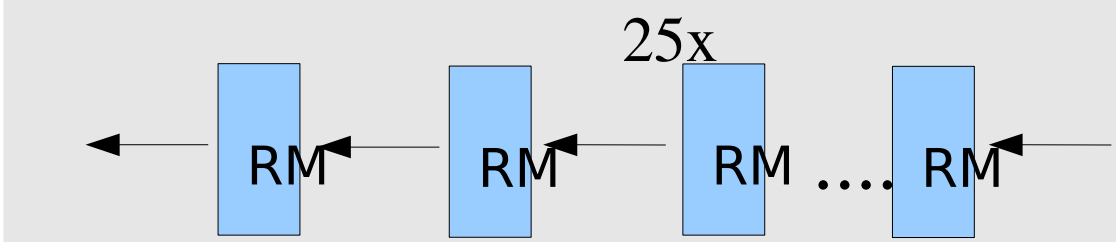
Spectro-Polarimetry

$$RM\ [rad/m^2] = 0.81 * l\ [pc] * B_{||}\ [\mu G] * n_e\ [cm^{-3}]$$

$$\Delta\varphi = RM\,\lambda^2$$







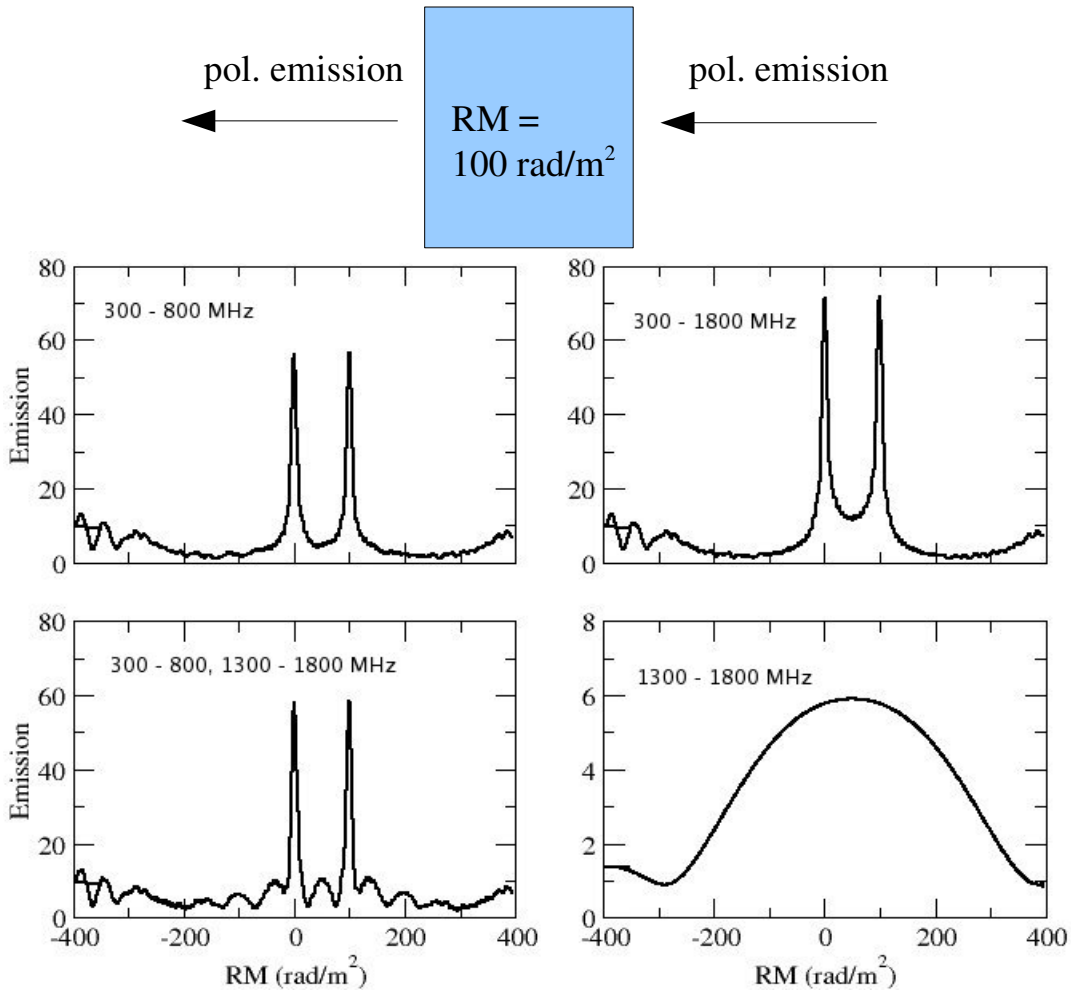
$n_e = 0.05\ cm^{-3}$

$L = 150\ pc$

$B_{||} = -4...4\ \mu G$

$RM = -25...25\ rad/m^2$

Rotation Measure Synthesis



Future / On-going Polarization Surveys

Name	Frequency MHz	Comments
LOFAR	110 – 250	
MWA	80 – 300	
SKAMP	700 – 1400	Final frequency range
GMIMS	300 – 1800	
GALFACTS	1225 – 1525	Arecibo sky
EMLS	1450	Galactic plane survey
CGPS	1420	Galactic plane survey
SGPS	1420	Galactic plane survey
STAPS	1300 – 1800	PI Haverkorn
SPASS	2300	
GEMS	5000, 10000	
C-BASS	5000, 10000	
Sino-German	4850	

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

Ettore Carretti	Istituto di Radioastronomia, Bologna, Italy
John Dickey	University of Tasmania, Australia
Andrew Fletcher	University of Newcastle, UK
Bryan Gaensler	University of Sydney, Australia
Marijke Haverkorn	Jansky Fellow, UC Berkeley
Han JinLin	Chinese Academy of Sciences, Beijing
Tom Landecker (PI)	DRAO
Paddy Leahy	University of Manchester, UK
Naomi McClure-Griffiths	ATNF, CSIRO, Australia
David McConnell	ATNF, CSIRO, Australia
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Russ Taylor	University of Calgary
Maik Wolleben (PI)	DRAO

GMIMS

Scientific objectives:

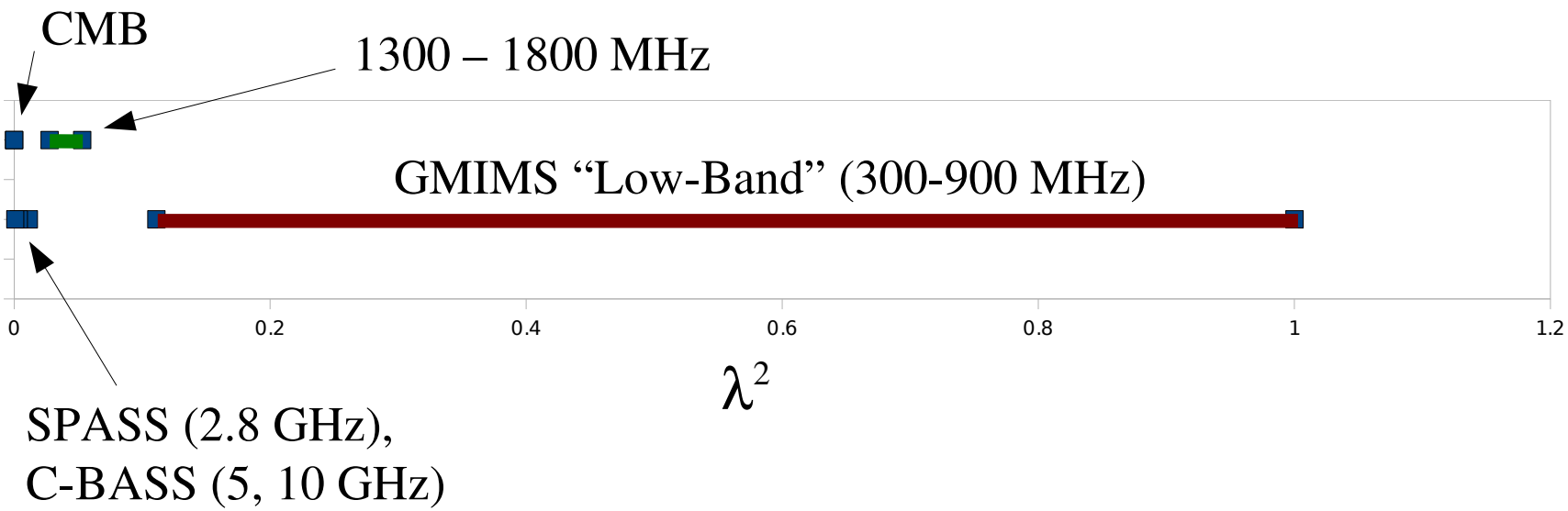
- Study of the Galactic magneto-ionic medium and the role of magnetic fields in the Milky Way
- CMB foregrounds
- (Contributions to SKA pathfinder experiments)

Galactic B-field studies $\Rightarrow$ more physics

CMB foregrounds $\Rightarrow$ less physics

GMIMS

$$\Delta \varphi = RM\ \lambda^2$$



END