Magnetic fields in the Milky Way

Katia FERRIÈRE

Institut de Recherche en Astrophysique et Planétologie,
Observatoire Midi-Pyrénées, Toulouse, France

Cosmic Ray Anisotropy Workshop 2017

Guadalajara – October 10 - 13, 2017

Outline

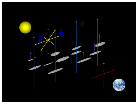
Outline

Observational methods

- Polarization of starlight & dust thermal emission

  Due to *dust grains* → general (dusty) ISM

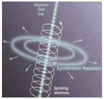
  ☞ $\vec{B}_\perp$ (orientation only)



- Synchrotron emission

  Produced by *CR electrons* → general (CR-filled) ISM

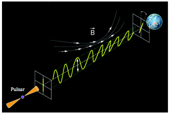
  ☞ $\vec{B}_\perp$ (strength & orientation)



- Faraday rotation

  Caused by *thermal electrons* → ionized regions

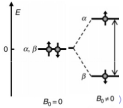
  ☞ $B_\parallel$ (strength & sign)



- Zeeman splitting

  Molecular & atomic *spectral lines* → neutral regions

  ☞ $B_\parallel$ (strength & sign)



Main limitations

Except for Zeeman splitting, the classical methods are

- Indirect
  They also depend on dust, CR electrons, or thermal electrons
- Incomplete
  They do not lead to full $\vec{B}$
- Only 2D
  They provide only LOS-integrated quantities

To overcome the LOS-integration problem
& *gain access to the LOS dimension* :

☞ Faraday tomography

Outline

Dust polarization

- *Optical starlight* is polarized $\parallel \vec{B}_\perp$
- *Infrared dust thermal emission* is polarized $\perp \vec{B}_\perp$

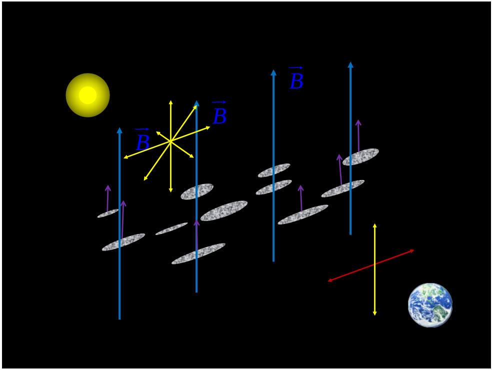
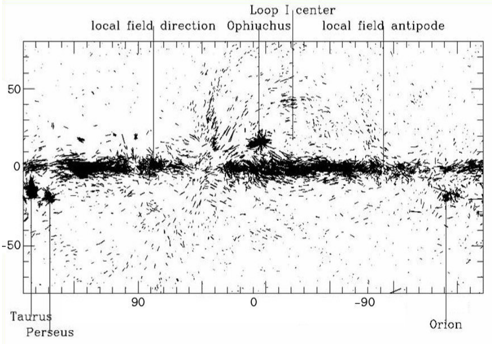


Figure Credit: *Philippe Terral*

Dust polarization: starlight

$\vec{B}$ vectors from 8 662 stars



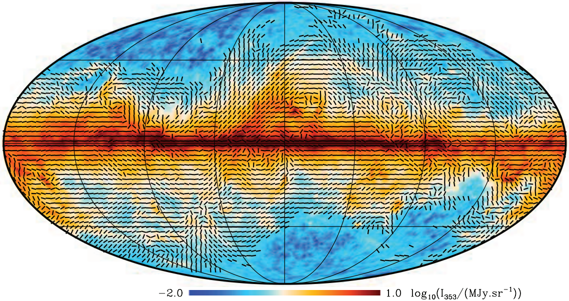
Heiles (2000)

☞ - In Galactic disk : $\vec{B}_{\rm ord}$ is horizontal

- Near the Sun : $\vec{B}_{\rm ord}$ is nearly azimuthal $(p \simeq -7^\circ)$

Dust polarization: dust thermal emission

Total intensity & $\vec{B}$ vectors at 353 GHz



Credit: *Planck* collaboration (ESA)

☞ - In Galactic disk : $\vec{B}_{\rm ord}$ is horizontal

- In Galactic halo : $\vec{B}_{\rm ord}$ has vertical component

Synchrotron emission

$\mathcal{E} = f(\alpha)\, n_{\rm CRe}\, B_\perp^{\,\alpha+1}\, \nu^{-\alpha}$ & $\vec{\mathcal{E}} \perp \vec{B}_\perp$

$\Rightarrow$ - *Total intensity* probes $B_\perp$ (strength only)

- *Polarized intensity* probes $(\vec{B}_{\rm ord})_\perp$ (strength & orientation)

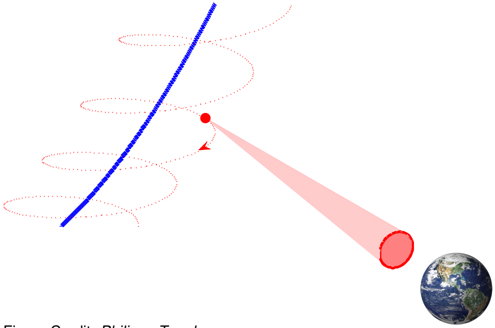


Figure Credit: *Philippe Terral*

Synchrotron emission

$\mathcal{E} = f(\alpha)\, n_{\rm CRe}\, B_\perp^{\alpha+1}\, \nu^{-\alpha}$ & $\vec{\mathcal{E}} \perp \vec{B}_\perp$

$\Rightarrow$ - *Total intensity* probes $B_\perp$ (strength only)

- *Polarized intensity* probes $(\vec{B}_{\rm ord})_\perp$ (strength & orientation)

TI at 1.4 GHz (25m Stockert + 30m Villa Elisa)

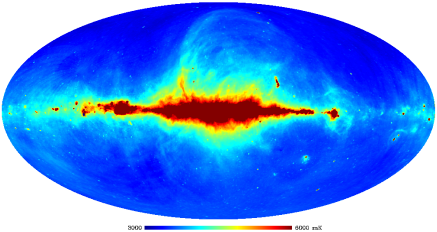


Figure Credit: *Tess Jaffe*

PI at 1.4 GHz (26m DRAO + 30m Villa Elisa)

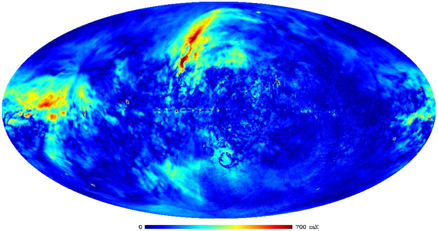


Figure Credit: *Tess Jaffe*

Synchrotron emission

$\mathcal{E} = f(\alpha)\, n_{\rm CRe}\, B_\perp^{\alpha+1}\, \nu^{-\alpha}$ & $\vec{\mathcal{E}} \perp \vec{B}_\perp$

$\Rightarrow$ - *Total intensity* probes $B_\perp$ (strength only)

- *Polarized intensity* probes $(\vec{B}_{\rm ord})_\perp$ (strength & orientation)

TI at 1.4 GHz (25m Stockert + 30m Villa Elisa)

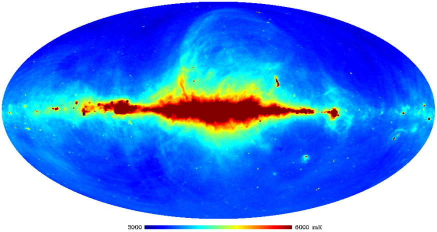


Figure Credit: *Tess Jaffe*

PI & $\vec{B}$ vectors at 23 GHz (WMAP)

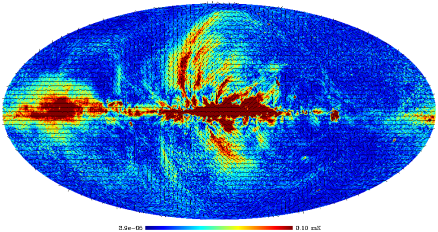


Figure Credit: *Tess Jaffe*

Synchrotron emission

In general (CR-filled) ISM

☞ - $\vec{B}$ has *ordered* & *fluctuating* components

- Near the Sun : $B_{\rm ord} \sim 3\ \mu$G & $B_{\rm tot} \sim 5\ \mu$G

- Global spatial distribution : $L_{\rm B} \sim 12$ kpc & $H_{\rm B} \sim 4.5$ kpc

- In disk : $\vec{B}_{\rm ord}$ is horizontal
- In halo : $\vec{B}_{\rm ord}$ has horizontal & vertical components

Faraday rotation

$\Delta\theta = \mathrm{RM}\ \lambda^2$ where $\mathrm{RM} = C \int n_e B_{\parallel}\, dl$

$\Rightarrow$ RM probes $B_{\parallel}$ in ionized regions

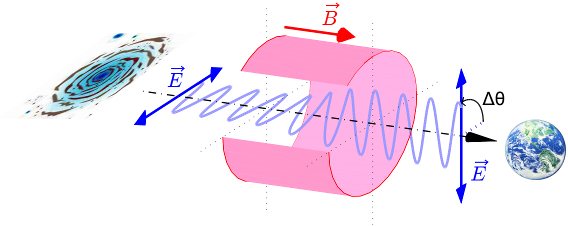


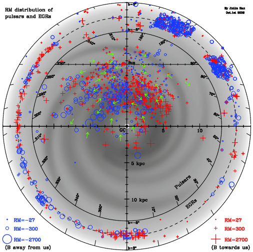
Figure Credit: *Philippe Terral*

Faraday rotation

$\Delta\theta = \mathrm{RM}\ \lambda^2$ where $\mathrm{RM} = C \int n_e\, B_{\parallel}\, dl$

$\Rightarrow$ RM probes $B_{\parallel}$ in ionized regions

RMs of pulsars & EGRSs with $|b| < 8°$



Han (2009)

RMs of EGRSs [NVSS ($\delta > -40°$) + S-PASS ($\delta < 0°$)]

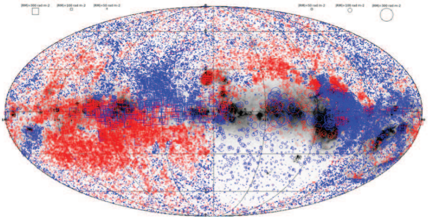


Figure Credit: *Dominic Schnitzeler*

Faraday rotation

In ionized regions

☞ - $\vec{B}$ has *regular* & *fluctuating* components

Near the Sun : $B_{\rm reg} \simeq 1.5\ \mu$G & $B_{\rm fluct} \sim 5\ \mu$G

- In disk : $\vec{B}_{\rm reg}$ is horizontal & mostly azimuthal

Near the Sun : $\vec{B}_{\rm reg}$ is CW $(p \simeq -8^\circ)$

$\vec{B}_{\rm reg}$ reverses direction with decreasing radius

$\vec{B}_{\rm reg}$ is symmetric in z

- In halo : $\vec{B}_{\rm reg}$ has horizontal & vertical components

$\vec{B}_{\rm reg}$ is CCW at $z > 0$ & CW at $z < 0$

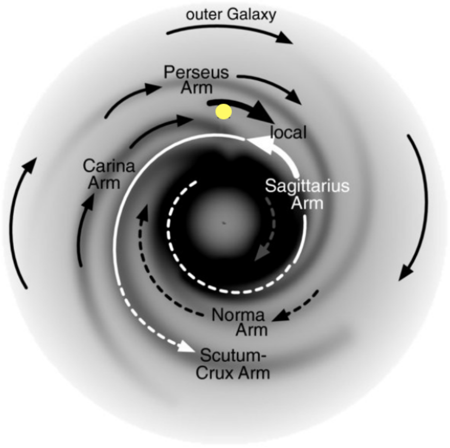
$\rightarrow$ anti-symmetric in z

$(B_{\rm reg})_z \simeq +0.3\ \mu$G toward SGP & $\simeq 0\ \mu$G (?) toward NGP

$\rightarrow$ possibly consistent with sym disk & anti-sym halo

Faraday rotation

Model of the large-scale magnetic field in the Galactic disk



van Eck et al. (2011)

Outline

General concept

- Underlying processes

  - Galactic synchrotron emission : polarized

  - Faraday rotation : λ-dependent

- General idea

  - Measure synchrotron polarized intensity at many different λ

  - Convert λ-dependence into LOS-dependence

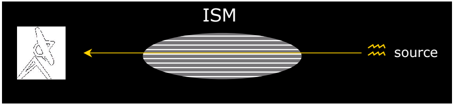
- Output

  Faraday cube = 3D cube of synchrotron polarized emission as fc(α, δ, Φ)

More precisely

- Faraday rotation of background source

  $\Delta\theta = \mathrm{RM}\ \lambda^2$ with $\mathrm{RM} = C\ \int_0^L n_\mathrm{e}\ B_\parallel\ dl$ (rotation measure)



- Faraday rotation of Galactic synchrotron emission

  Synchrotron emission & Faraday rotation are *spatially mixed*

  $P(\lambda^2) = \int F(\Phi)\ e^{2i\Phi\lambda^2}\ d\Phi$ with $\Phi(z) = C\ \int_0^z n_\mathrm{e}\ B_\parallel\ dl$ (Faraday depth)

  ☞ *Fourier transform* of polarized intensity : $P(\lambda^2)\ \rightarrow\ F(\Phi)$

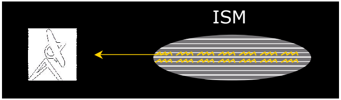


Figure Credit: *Marijke Haverkorn*

Simple illustration

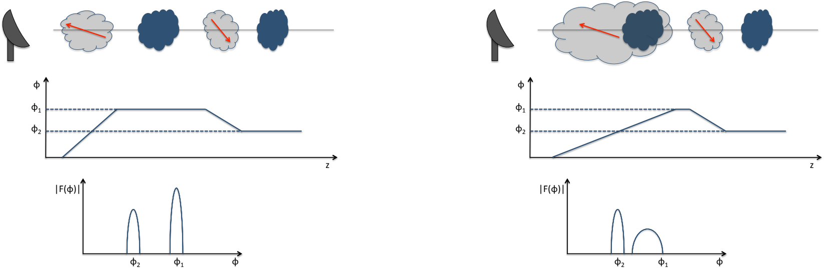
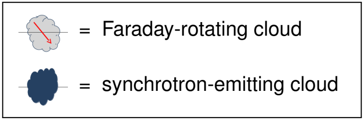


Figure Credit: *Marta Alves*

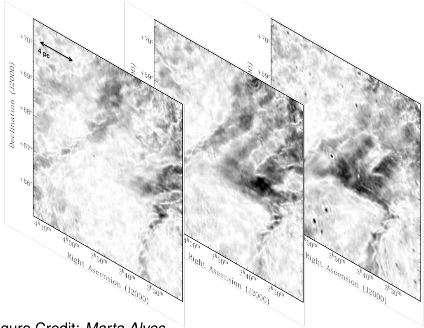


Faraday cube

For given sky area

- Derive *Faraday spectrum*, $F(\Phi)$, in many directions (α, δ)
- Combine all derived Faraday spectra into *Faraday cube* = 3D cube of $F(\alpha, \delta, \Phi)$

Faraday cube toward Fan region, obtained with LOFAR *(van Eck et al. 2017)*



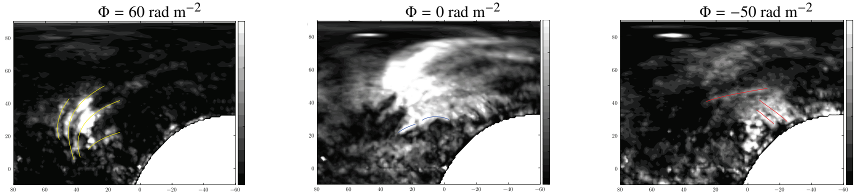
3 slices at

$$\Phi_1 = -2.0 \text{ rad m}^{-2}$$
$$\Phi_2 = -1.5 \text{ rad m}^{-2}$$
$$\Phi_3 = -1.0 \text{ rad m}^{-2}$$

Figure Credit: *Marta Alves*

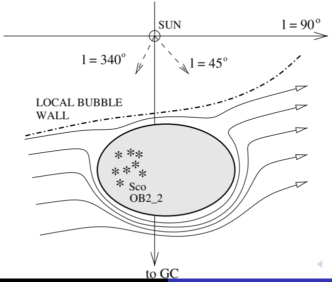
Example of a nearby magnetized bubble

Polarized intensity at 3 different Faraday depths



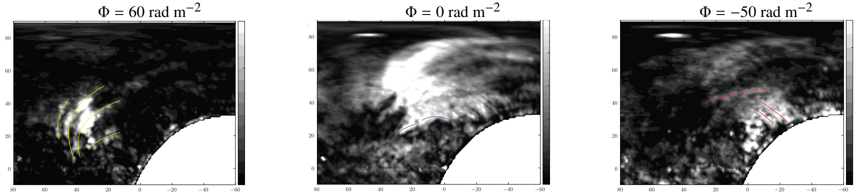
Wolleben et al. (2010)

Interpretation



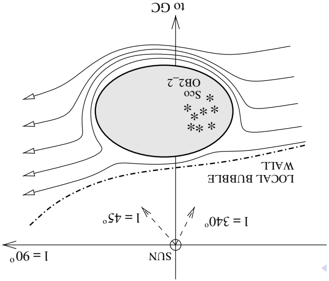
Example of a nearby magnetized bubble

Polarized intensity at 3 different Faraday depths



Wolleben et al. (2010)

Interpretation



General results

- From Faraday space to physical space
  - Uncover synchrotron-emitting & Faraday-rotating features in Faraday cube
  - Identify these features with interstellar matter structures
- For synchrotron-emitting regions

  $\int F(\Phi)\, d\Phi \quad \Rightarrow \quad \vec{B}_\perp$
- For Faraday-rotating regions

  $\Delta\Phi \quad \Rightarrow \quad B_\parallel$