Interstellar magnetic fields

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Outline

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Early history

- Alfvén (1937)
  ☞ Cosmic-ray confinement implies ”the existence of a magnetic field in interstellar space”
- Fermi (1949)
  ☞ ”The main process of [cosmic-ray] acceleration is due to [interstellar] magnetic fields ... The magnetic field in the dilute matter is $\sim 5\ \mu\mathrm{G}$, while its intensity is probably greater in the heavier clouds”
- Hall; Hiltner (1949) ; Davis & Greenstein (1951)
  ☞ Linear polarization of starlight
  ☞ Due to elongated dust grains aligned by an interstellar magnetic field
- Kiepenheuer (1950)
  ☞ Galactic radio synchrotron emission

(Credit: *Bryan Gaensler*)

Outline

Linear polarization of starlight & dust emission

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

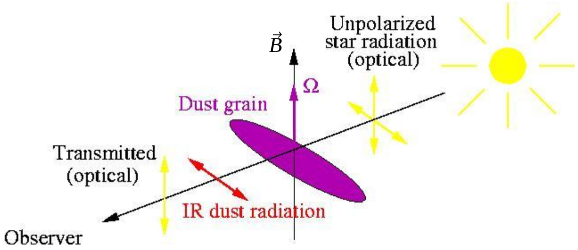
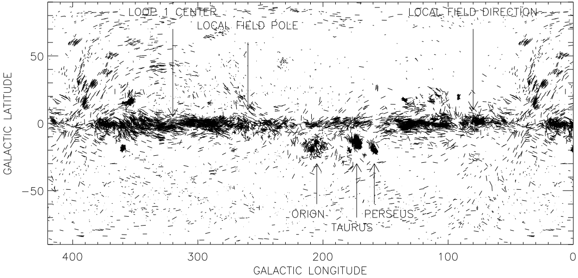


Figure Credit: *Ponthieu & Lagache (2004)*

Linear polarization of starlight & dust emission



Heiles & Crutcher (2005)

☞ - In Galactic Disk : $\vec{B}$ is horizontal

- Near the Sun : $\vec{B}$ is nearly azimutbal $(p \simeq -7°)$

Zeeman splitting

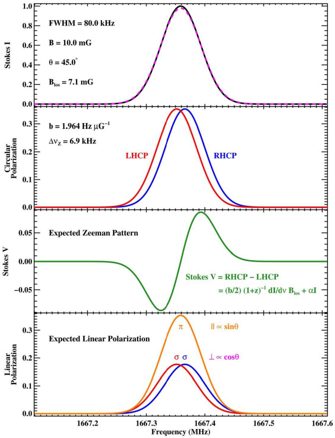


Figure Credit: *Robishaw & Heiles*

Stokes parameter V
gives $B_{\|}$ in neutral regions

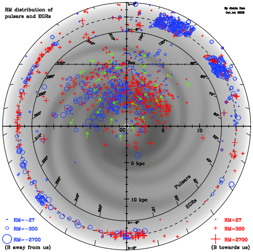
☞ - In atomic clouds :
$B \sim$ a few μG

- In molecular clouds :
$B \sim (10 - 3000)\ \mu$G

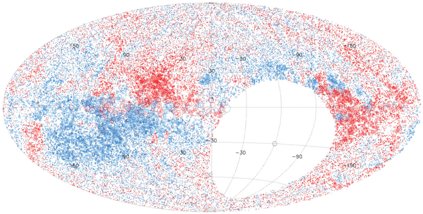
Faraday rotation of point sources

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

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



RMs of pulsars & EGRSs with $|b| < 8^\circ$ *(Han 2009)*



RMs of EGRSs with $\delta > -40^\circ$ *(Taylor et al. 2009)*

Faraday rotation of point sources

In ionized regions

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

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

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

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

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

$\vec{B}_{\rm reg}$ is neither pure ASS nor pure BSS

- In Galactic Halo : $\vec{B}_{\rm reg}$ is CCW at $z > 0$ & CW at $z < 0$ (inner halo)

$\vec{B}_{\rm reg}$ has vertical component

Toward SGP : $(B_{\rm reg})_z \simeq +0.3\ \mu$G

Toward NGP : $(B_{\rm reg})_z \simeq$?

Diffuse synchrotron emission

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

$\Rightarrow$ - *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)

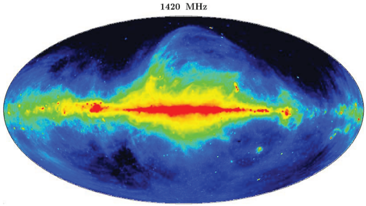
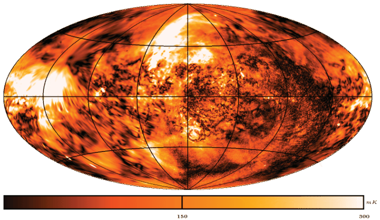


Figure Credit: *Wolfgang Reich*

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



Wolleben et al. (2005)

Diffuse synchrotron emission

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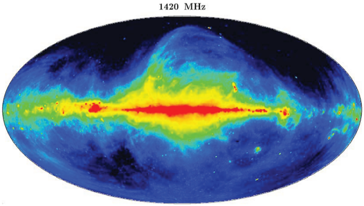
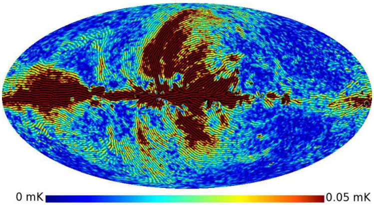


Figure Credit: *Wolfgang Reich*

PI at 23 GHz (WMAP)



Jansson et al. (2009)

Diffuse synchrotron emission

In general ISM

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

- In Molecular Ring : $B_{\rm tot} \sim 7\ \mu$G

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

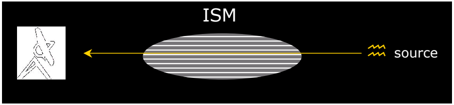
- In Galactic Halo : $\vec{B}_{\rm ord}$ has vertical component

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

Faraday tomography

- Faraday rotation of background point source

$\Delta\theta = \mathrm{RM}\ \lambda^2$ with $\mathrm{RM} = C \int n_e\, B_{||}\, dl$ (rotation measure)

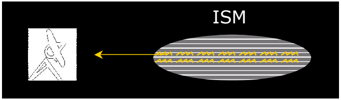


- Faraday rotation of diffuse synchrotron emission

Synchrotron emission & Faraday rotation are *spatially mixed*

$\vec{P}(\lambda^2) = \int \vec{P}(\Phi)\, e^{2i\Phi\lambda^2}\, d\Phi$ with $\Phi = C \int n_e\, B_{||}\, dl$ (Faraday depth)

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



Credit: *Marijke Haverkorn*

Faraday tomography

Also known as rotation measure synthesis

(Burn 1966; Brentjens & de Bruyn 2005)

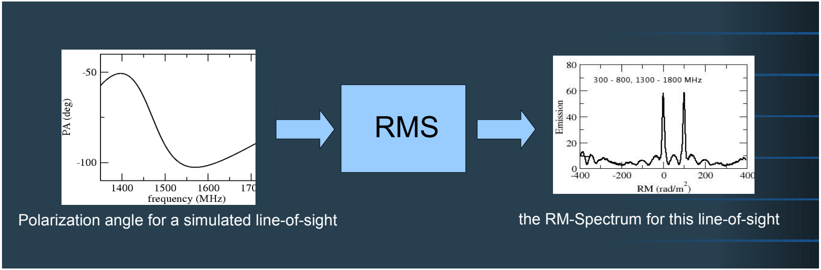


Figure Credit: *Maik Wolleben*

Summary of observational results

- Near the Sun
  - $B_{\rm reg} \simeq 1.5\ \mu$G , $B_{\rm ord} \sim 3\ \mu$G , $B_{\rm tot} \sim 5\ \mu$G
  - $\vec{B}_{\rm reg}$ is horizontal & nearly azimuthal $(p \simeq -7^\circ, -8^\circ)$

- In Galactic Disk
  - $\vec{B}_{\rm reg}$ is horizontal & mostly azimuthal
  - $\vec{B}_{\rm reg}$ reverses direction with decreasing radius
  - $\vec{B}_{\rm reg}$ is symmetric in z
  - $\vec{B}_{\rm reg}$ is neither pure ASS nor pure BSS

- In Galactic Halo
  - $\vec{B}_{\rm reg}$ has horizontal & vertical components
  - $\vec{B}_{\rm reg}$ is anti-symmetric in z

Outline

Spiral galaxies

- Observational methods

  - Synchrotron emission (total & polarized)

  - Faraday rotation

- Observational results

  - All spirals have large-scale, regular / ordered $\vec{B}$

  - In disk : $B_{\rm ord} \sim (1 - 5)\ \mu$G & $B_{\rm tot} \sim (5 - 15)\ \mu$G
    In halo : $B_{\rm tot} \lesssim 10\ \mu$G

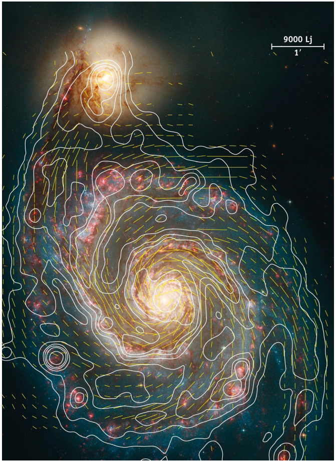
  - Edge-on spirals $\rightarrow$ In disk : $\vec{B}_{\rm ord}$ is horizontal
    In halo : $\vec{B}_{\rm ord}$ has vertical component

    Face-on spirals $\rightarrow$ $\vec{B}_{\rm ord}$ follows spiral arms

Face-on spiral galaxy: M 51

TI contours
+ $\vec{B}$ vectors
at λ 6 cm
(100m Effelsberg
+ VLA)

Optical image
(HST)

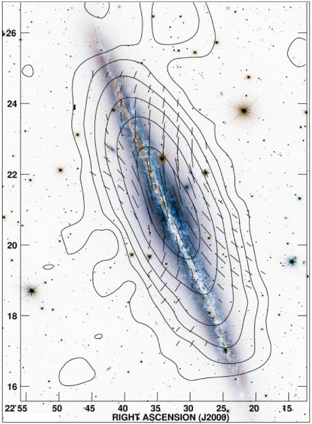


Fletcher et al. (2009)

Edge-on spiral galaxy: NGC 891

TI contours
+ $\vec{B}$ vectors
at λ 3.6 cm
(100m Effelsberg)

Optical image
(CFHT)



© MPIfR Bonn *(Krause 2009)*

Elliptical galaxies

- Observational methods
  - Synchrotron emission (total & polarized)
  - Faraday rotation

- Observational results
  - No large-scale, regular $\vec{B}$
    Only small-scale, turbulent $\vec{B}$
  - $B_{\rm tot} \sim$ a few μG

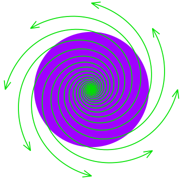
Outline

Field geometry

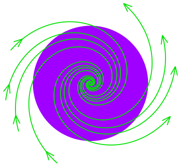
- In the disk
  - B_Φ dominant *because strong differential rotation*
  - $B_R \sim 0.1\ B_\Phi$
  - $B_Z < B_R,\ B_\Phi$ *because disk geometry*
  - Reversals in B_Φ e.g., if strong $\partial\Omega/\partial Z$
- In the halo
  - $B_Z \sim B_R$ *because spherical geometry*
  - B_Φ large if strong differential rotation
  - $B_R,\ B_Z$ large if Galactic wind

Azimuthal structure

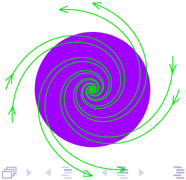
- If underlying galaxy is axisymmetric
  $\Rightarrow$ - ASS $(m = 0)$ is always easiest to amplify
  - Higher-order modes generally decay in time



- If external disturbance
  $\Rightarrow$ Possible to excite BSS $(m = 1)$



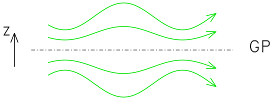
- If underlying spiral or bar
  $\Rightarrow$ Possible to excite QSS $(m = 2)$



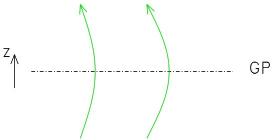
Vertical symmetry (for ASS)

- Under typical galactic conditions
  ⇒ Both S0 & A0 are amplified

- If the disk dominates
  ⇒ S0 grows faster



- If the halo dominates
  ⇒ A0 grows faster



- Possibly mixed S0-A0 configuration
  with S0 dominant in the disk
  A0 dominant in the halo