Interstellar magnetic fields

Katia FERRIÈRE

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

Cosmic rays and their interstellar medium environment
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Outline

1. Early history
2. Magnetic fields in our Galaxy
    - Observational methods
    - Summary of observational results
    - Magnetic fields near the Galactic center
3. Magnetic fields in external galaxies
    - Spiral galaxies
    - Elliptical galaxies
4. Predictions from dynamo theory
    - Linear solutions
    - Nonlinear solutions

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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*)

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Linear polarization of starlight & dust emission

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

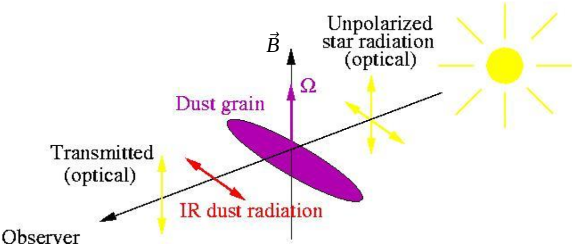
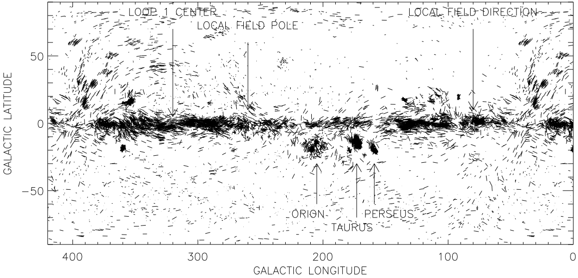


Figure Credit: *Ponthieu & Lagache (2004)*

Linear polarization of starlight & dust emission



Heiles & Crutcher (2005)

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

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

Zeeman splitting

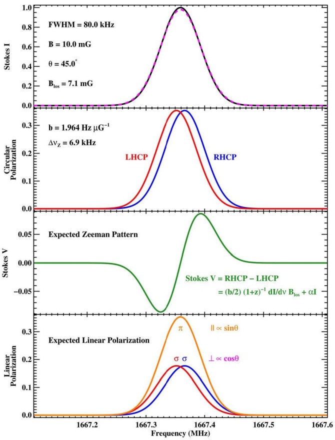


Figure Credit: *Robishaw & Heiles*

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

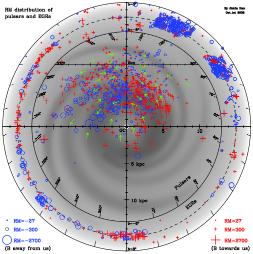
☞ - In atomic clouds : $B \sim$ a few μG

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

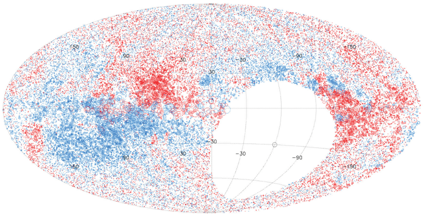
Faraday rotation of point sources

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

$\Rightarrow$ 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 : $p \simeq -8^\circ$

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

CW in local arm, CCW in Sagittarius arm, ...

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

Toward SGP : $(B_{\rm reg})_z \simeq +0.30~\mu$G or $+0.31~\mu$G

Toward NGP : $(B_{\rm reg})_z \simeq -0.14~\mu$G or $0.00~\mu$G

(Taylor et al. 2009) *(Mao et al. 2009)*

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)

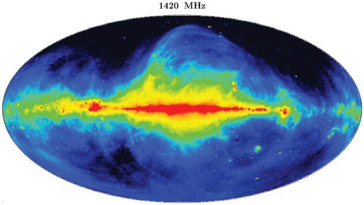
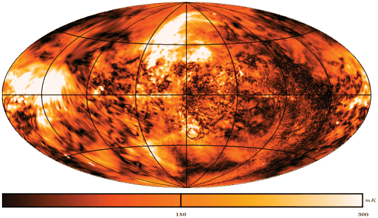


Figure Credit: *Wolfgang Reich*

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



Wolleben et al. (2005)

Diffuse synchrotron emission

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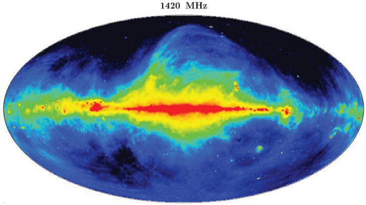
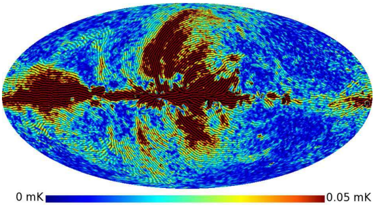


Figure Credit: *Wolfgang Reich*

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

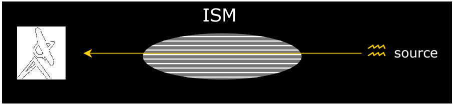
- In Galactic Halo : $\vec{B}_{\rm ord}$ has vertical component

- 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)

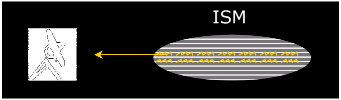


- Faraday rotation of diffuse synchrotron emission

  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)

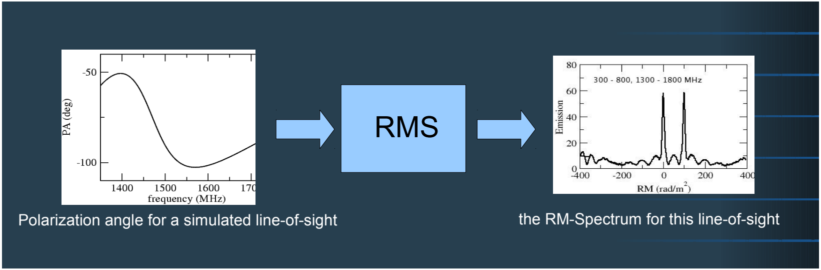


Figure Credit: *Maik Wolleben*

Summary of observational results

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

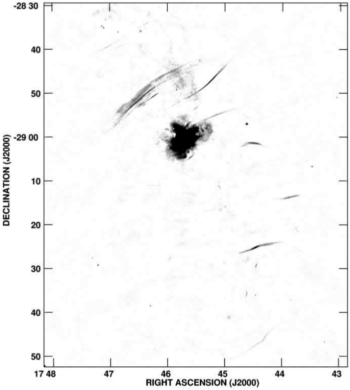
- In Galactic Disk
  - $\vec{B}_{\rm reg}$ is horizontal & mostly azimuthal
  - $\vec{B}_{\rm reg}$ reverses direction with decreasing radius

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

- Global field configuration
  - Azimuthal structure: neither pure ASS nor pure BSS
  - Vertical symmetry : probably sym in disk & antisym in halo

Magnetic fields near the Galactic center

Detection of *non-thermal radio filaments* *(Yusef-Zadeh & Morris 1987 ...)*



(Nord et al. 2004)

Magnetic fields near the Galactic center

- Non-thermal radio filaments
  - ∗ *Morphology & radio (synchrotron) polarization*
    $\vec{B}$ || filaments ⇒ $\vec{B} \perp$ GP
  - ∗ *Dynamical argument*
    No distortion ⇒ $B \gtrsim 1$ mG
  - ∗ *Radio (synchrotron) intensity*
    $B_{\rm equip} \sim (50 - 200)\ \mu$G
- In diffuse ISM
  - ∗ *Pressure-balance argument*
    $B_{\rm in} \sim B_{\rm out}$ ⇒ $B \sim 1$ mG
  - ∗ *Diffuse synchrotron intensity*
    $B_{\rm equip} \sim 10\ \mu$G
- In dense molecular clouds
  - ∗ *FIR/submm (dust thermal emission) polarization*
    $\vec{B}$ is nearly || GP

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Spiral galaxies

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

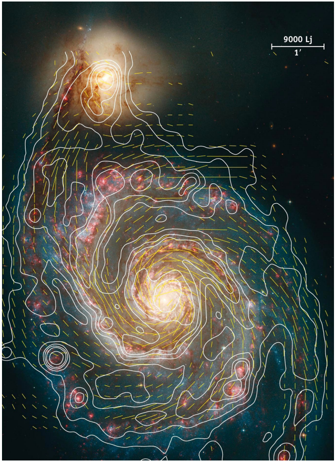
- Observational results
  - All spirals have large-scale, regular / ordered $\vec{B}$
  - In disk : $B_{\rm ord} \sim (1-5)\ \mu$G & $B_{\rm tot} \sim (5-15)\ \mu$G
    In halo : $B_{\rm tot} \lesssim 10\ \mu$G
  - Edge-on spirals $\rightarrow$ In disk : $\vec{B}_{\rm ord}$ is horizontal
    In halo : $\vec{B}_{\rm ord}$ 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)

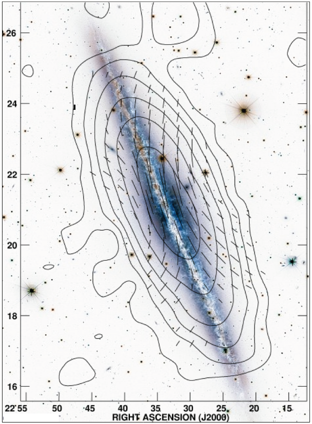


Fletcher et al. (2009)

Edge-on spiral galaxy: NGC 891

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

Optical image
(CFHT)



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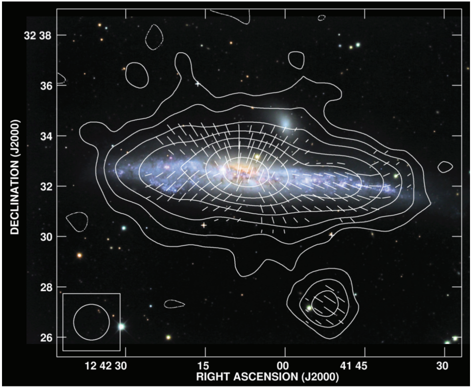
Edge-on spiral galaxy: NGC 4631

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

Optical image
(Misti Mountain)



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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

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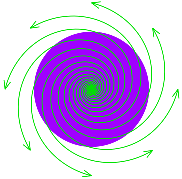
Field geometry

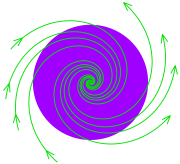
- In the disk
  - B_Φ dominant *because strong differential rotation*
  - $B_R \sim 0.1\ B_\Phi$
  - $B_Z < B_R,\ B_\Phi$ *because disk geometry*
  - Reversals in B_Φ e.g., if strong $\partial\Omega/\partial Z$
- In the halo
  - $B_Z \sim B_R$ *because spherical geometry*
  - B_Φ large if strong differential rotation
  - $B_R,\ B_Z$ large if Galactic wind
- Near the center
  - $B_Z \sim B_R$ *because spherical geometry*
  - $B_R,\ B_\Phi$ large *because strongly sheared noncircular motions*
  - B_Z large if horizontal inflow or vertical outflow

Azimuthal structure

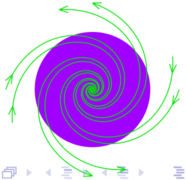
- If underlying galaxy is axisymmetric
  $\Rightarrow$ - ASS $(m = 0)$ is always easiest to amplify
  - Higher-order modes generally decay in time



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



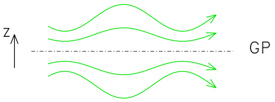
- If underlying spiral or bar
  $\Rightarrow$ Possible to excite QSS $(m = 2)$



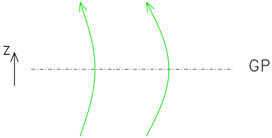
Vertical symmetry (for ASS)

- Under typical galactic conditions
  $\Rightarrow$ Both S0 & A0 are amplified

- If the disk dominates
  $\Rightarrow$ S0 grows faster



- If the halo or the center dominates
  $\Rightarrow$ A0 grows faster



- At early times & in the nonlinear regime
  $\Rightarrow$ Possibly mixed S0-A0 configuration
  with S0 dominant in the disk
  A0 dominant in the halo & near the center

Temporal behavior (for ASS)

- Under typical galactic conditions
  - S0 & A0 grow *monotonically* with time
  - S0 grows faster ($\gamma \sim 1$ Gyr^{-1})
  - A0 gets more easily *oscillatory* ($\omega \sim 1$ Gyr^{-1})
- Factors favoring oscillatory behavior :
  - Spherical geometry (halo, center)
  - α strongly anisotropic
  - Vanishing or weak Galactic wind
  - Ω decreasing away from the midplane

Nonlinear solutions

- Field growth *saturates* when $B \longrightarrow B_{\rm equip}$
  - $B_{\rm final} \lesssim 2\, B_{\rm equip}$
  - $t_{\rm sat} \sim$ several Gyrs

- Final spatial configuration is *smoother* than in linear regime

- *Nonlinear interactions* occur between different modes
  $\Rightarrow$ Possible to amplify modes that would decay in linear regime
  $\Rightarrow$ Possible to maintain mixed S0-A0 configuration