Magnetic fields in the Galactic halo

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Magnetic Fields in the Universe V

From Laboratory and Stars to primordial Structures

Cargèse – 5 - 9 October, 2015

Outline

1. Observational overview
   - The Milky Way
   - External spiral galaxies
2. Physical origin of X-shape magnetic fields
3. Mathematical description of X-shape magnetic fields
4. X-shape magnetic field in the Galactic halo?
   - Our 4 halo field models
   - Our preferred (disk + halo) field model

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Observational tools

- Linear polarization of starlight & dust thermal emission
  Due to *dust grains* → general (dusty) ISM
  ☞ $\vec{B}_\perp$ (orientation only)

- Zeeman splitting
  Molecular & atomic *spectral lines* → neutral regions
  ☞ $B_\parallel$ (strength & sign)

- Faraday rotation
  Caused by *thermal electrons* → ionized regions
  ☞ $B_\parallel$ (strength & sign)

- Synchrotron polarized emission
  Produced by *CR electrons* → general (CR-filled) ISM
  ☞ $\vec{B}_\perp$ (strength & orientation)

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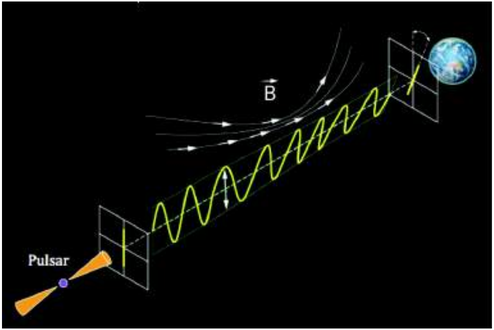
Faraday rotation of point sources

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

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



Faraday rotation of point sources

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

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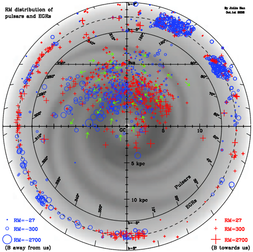
RMs of pulsars & EGRSs with $|b| < 8°$



Han (2009)

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

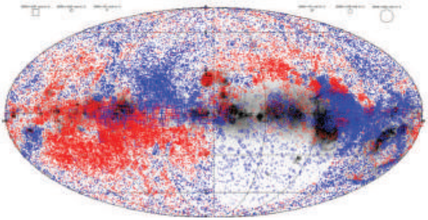


Figure Credit: *Dominic Schnitzeler*

Faraday rotation of point sources

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

$\vec{B}_{\rm reg}$ 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

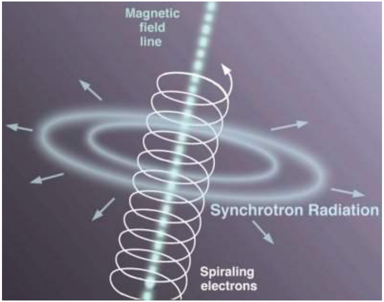
$\rightarrow$ possibly consistent with sym disk & anti-sym halo

Diffuse synchrotron emission

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

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

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



Astronomy Online

Diffuse synchrotron emission

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

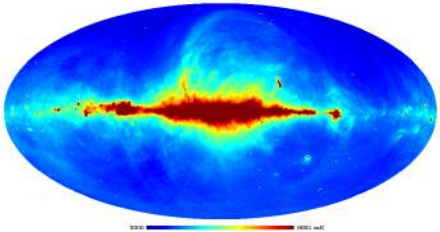

Figure Credit: *Tess Jaffe*

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

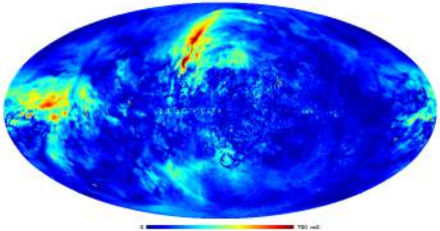

Figure Credit: *Tess Jaffe*

Diffuse synchrotron emission

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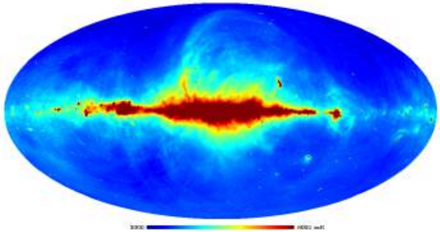

Figure Credit: *Tess Jaffe*

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

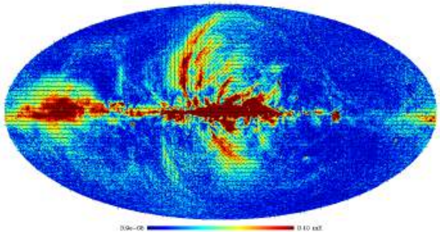

Figure Credit: *Tess Jaffe*

Diffuse 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

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External spiral galaxies

- In galactic disks
  - $B_{\rm ord} \sim (1-5)\ \mu$G & $B_{\rm tot} \sim (5-20)\ \mu$G
  - $\vec{B}_{\rm ord}$ is horizontal
    has spiral structure
- In galactic halos
  - $B_{\rm tot} \lesssim 10\ \mu$G
  - $\vec{B}_{\rm ord}$ has horizontal & vertical components
    is X-shaped

Face-on spiral galaxy: M 51

Total intensity contours
+ apparent $\vec{B}$ vectors
at λ 6 cm (5.0 GHz)
(100 m Effelsberg + VLA)

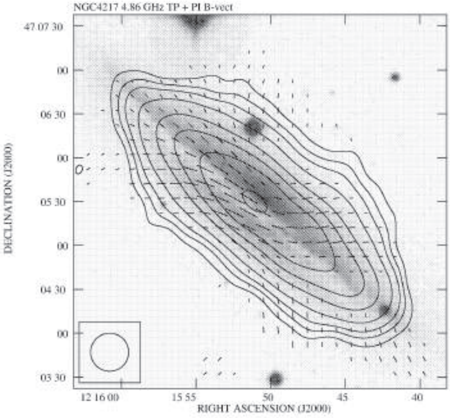
Optical image
(HST)

Fletcher et al. (2009)

NGC 4217

Total intensity contours
+ apparent $\vec{B}$ vectors
at λ 6.2 cm (4.86 GHz)
(VLA)

Optical image
(DSS)

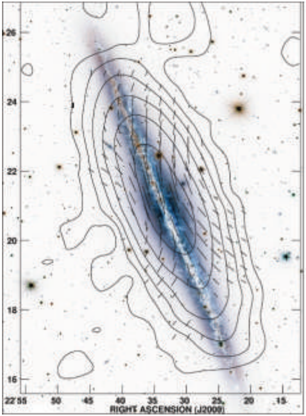


Soida (2004)

NGC 891

Total intensity contours
+ apparent $\vec{B}$ vectors
at λ 3.6 cm (8.35 GHz)
(100 m Effelsberg)

Optical image
(CFHT)



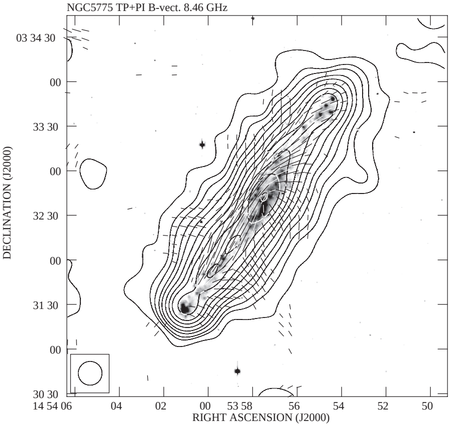
Krause (2009). © MPIfR Bonn & CFHT/Coelum

NGC 5775

Total intensity contours
+ apparent $\vec{B}$ vectors
at λ 3.5 cm (8.46 GHz)
(VLA + 100 m Effelsberg)

Hα image
(VLT)

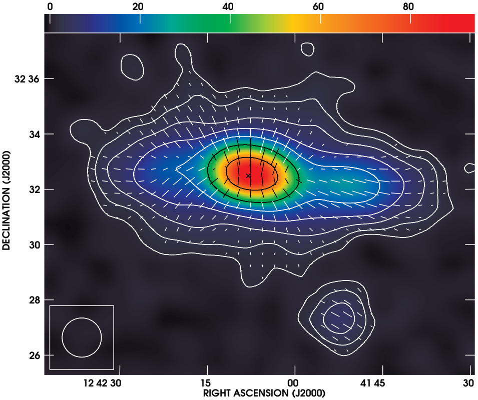
Tüllmann et al. (2000)



Soida et al. (2011)

NGC 4631

Total intensity contours
+ apparent $\vec{B}$ vectors
at λ 3.6 cm (8.35 GHz)
(100 m Effelsberg)

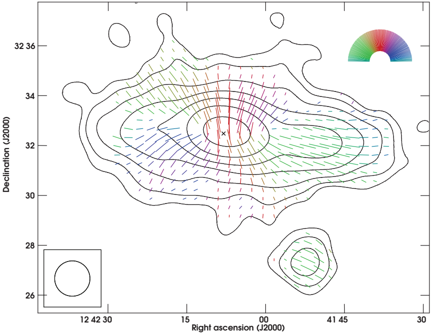


Mora & Krause (2013)

NGC 4631

Total intensity contours
at λ 3.6 cm (8.35 GHz)
(100 m Effelsberg)

+ intrinsic $\vec{B}$ vectors
from λ 3.6 cm & λ 6.2 cm
(VLA + 100 m Effelsberg)



Mora & Krause (2013)

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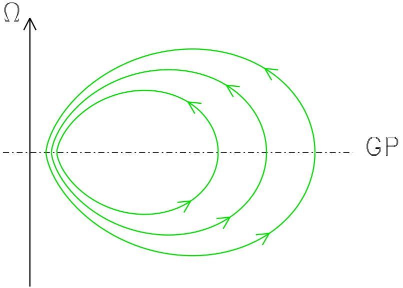
Possible scenarios

- Large-scale regular magnetic field
  - ★ *Conventional dynamo* in the halo
  - ★ *Dynamo* in the halo + *large-scale wind* from the disk
    or *outflow* from the central region
  - ★ *Dynamo* in the disk + *large-scale wind* from the disk
    or *outflow* from the central region

- Small-scale anisotropic random magnetic field
  - ★ *Spiky wind* ☞ extremely elongated magnetic loops

Conventional dynamo in the halo

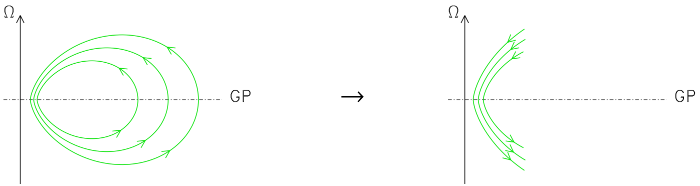
☞ Dipole-like magnetic field sheared out in the azimuthal direction



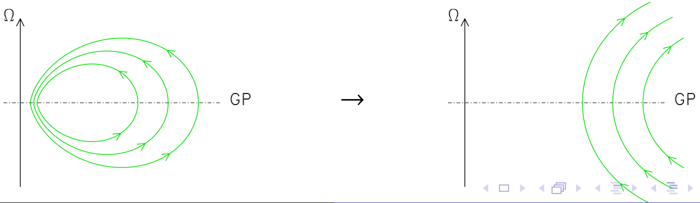
☞ Very different from an X-shape magnetic field

Halo dynamo + wind

- Oblique wind from the disk



- Champagne flow from the central region



Disk dynamo + wind

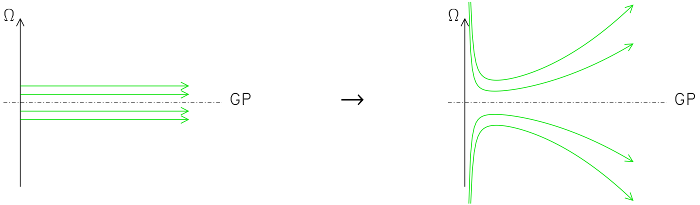
- Oblique wind from the disk

☞ Unphysical, because all field lines converge to the rotation axis
Mathematically, $B_r \to \infty$

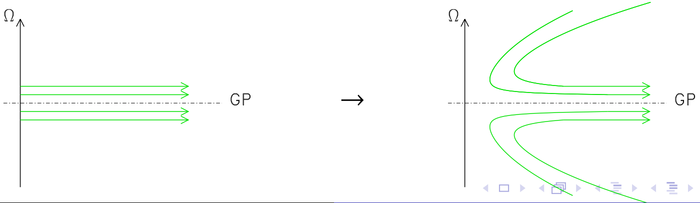
☞ Must prevent field lines from reaching the rotation axis

Disk dynamo + wind

- Oblique wind from the disk + bipolar jet from the galactic center

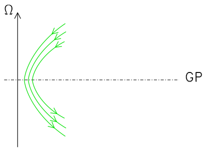


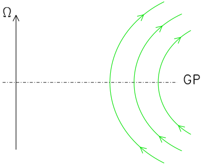
- Champagne flow from the central region



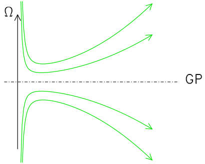
Vertical symmetry

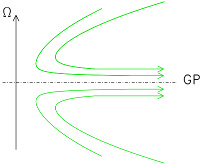
- Halo dynamo + wind
  - ☞ $\vec{B}$ is necessarily anti-symmetric in z





- Disk dynamo + wind
  - ☞ $\vec{B}$ is more likely symmetric in z (but could also be anti-symmetric)





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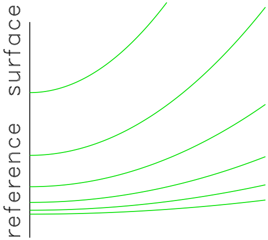
How to model X-shape magnetic fields ?



- **Input**

  Consider a magnetic configuration

  defined by a *network of field lines*

  ☞ - shape of field lines
  - distribution of B_n on a reference surface

- **Purpose**

  Derive an analytical expression

  for the associated $\vec{B}(r, \varphi, z)$

- **Method**

  Use the Euler potentials, α and β,

  defined such that $\vec{B} = \vec{\nabla}\alpha \times \vec{\nabla}\beta$

Euler potentials

- Definition

  2 scalar functions, α and β, such that $\boxed{\vec{B} = \vec{\nabla}\alpha \times \vec{\nabla}\beta}$

- Advantages

  ★ $\vec{B}$ is automatically *divergence-free*

  $$\vec{\nabla} \cdot \vec{B} = 0$$

  ★ α and β are *constant along field lines*

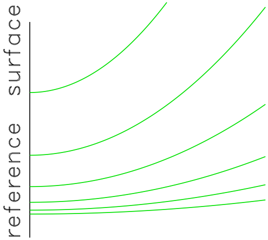
  $$\vec{B} \perp \vec{\nabla}\alpha \perp \text{surfaces of c}^{\text{st}}\ \alpha \quad \Rightarrow \quad \vec{B} \text{ tg surfaces of c}^{\text{st}}\ \alpha$$
  $$\vec{B} \perp \vec{\nabla}\beta \perp \text{surfaces of c}^{\text{st}}\ \beta \quad \Rightarrow \quad \vec{B} \text{ tg surfaces of c}^{\text{st}}\ \beta$$

  ★ Direct measure of *magnetic flux*

  $$\vec{B} \cdot d\vec{S} = d\alpha\, d\beta$$

How to use the Euler potentials ?

- **Consider** a *network of field lines*
  - ☞ - shape of field lines
    - distribution of B_n on a reference surface



- **Find** 2 independent functions, α and β,

  with - α and β constant along field lines
  - $d\alpha \; d\beta \; = \; B_n \; dS$ on the reference surface

- **Derive** $\vec{B}(r, \varphi, z)$ using $\vec{B} \; = \; \vec{\nabla}\alpha \times \vec{\nabla}\beta$

Poloidal, X-shape magnetic field

- Poloidal magnetic field

  φ is c^{st} along field lines

  $\Rightarrow$ Take $\beta = \varphi$

- X-shape magnetic field

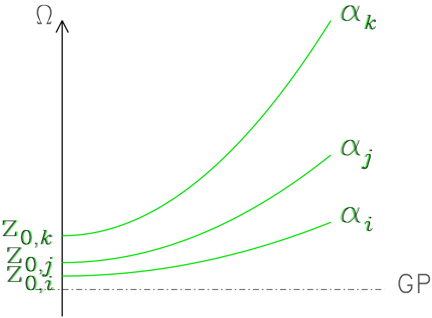
  E.g., $z = z_0 \, (1 + a\, r^2)$

  $\Rightarrow z_0 = \dfrac{z}{1 + a\, r^2}$ is c^{st} along field lines

  $\Rightarrow$ Take $\alpha = \mathrm{fc}(z_0)$

- Exponential decrease with z

  Take $\alpha = \alpha_0 \, \exp\left(-\frac{|z_0|}{H}\right)$



Spiral, X-shape magnetic field

- **Spiral magnetic field**

  E.g., $\varphi = \varphi_0 + f_\varphi(r,z)$

  $\Rightarrow \ \varphi_0 = \varphi - f_\varphi(r,z)$ is c^{st} along field lines

  $\Rightarrow$ Take $\beta = \varphi_0$

- **X-shape magnetic field**

  E.g., $z = z_0\,(1 + a\,r^2)$

  $\Rightarrow \ z_0 = \dfrac{z}{1 + a\,r^2}$ is c^{st} along field lines

  $\Rightarrow$ Take $\alpha = \mathrm{fc}(z_0)$

- **Exponential decrease with z**

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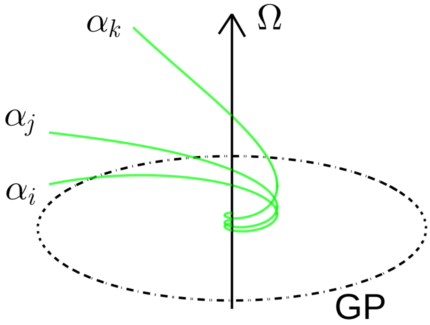

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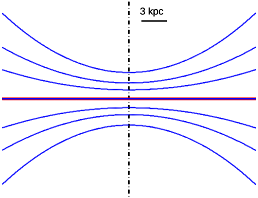
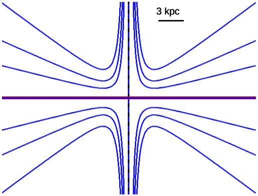
Poloidal field lines

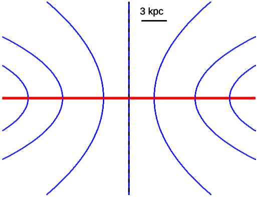
(a) Model A



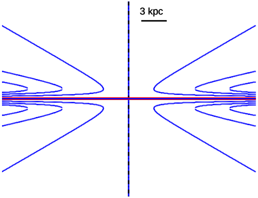
(b) Model B



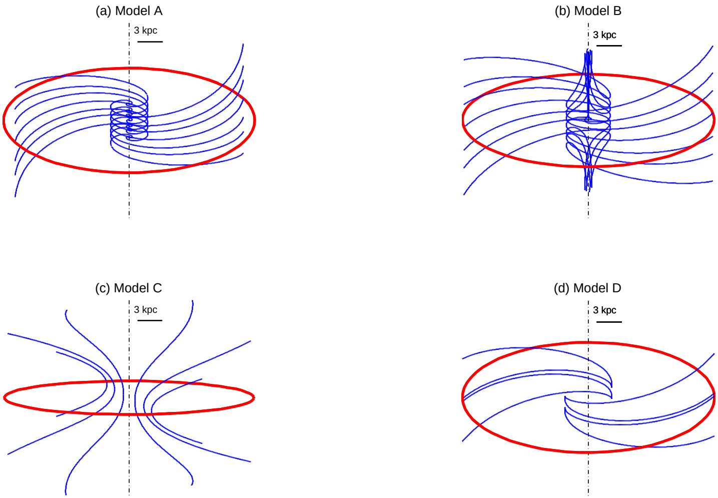
(c) Model C



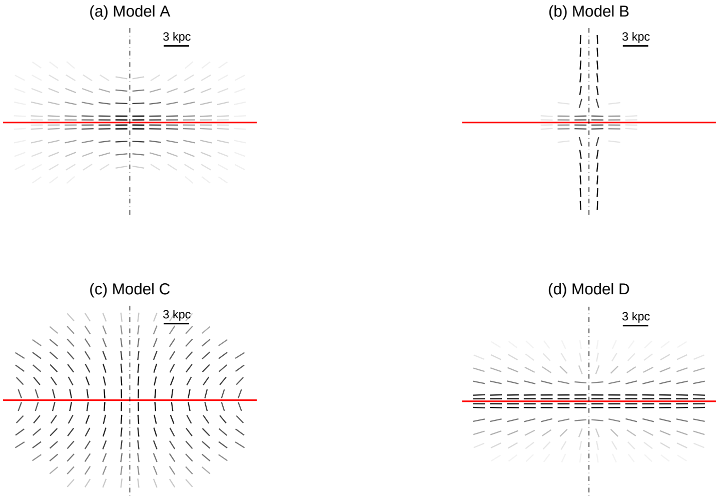
(d) Model D



Full, spiraling field lines



Synchrotron polarization maps



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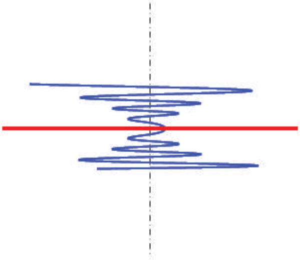
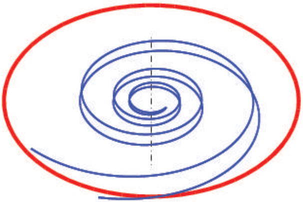
Representative field line

D1 (disk) + C0 (halo)

Edge-on view

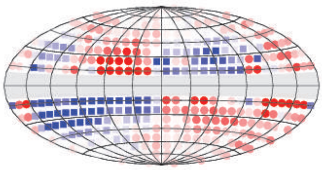


Oblique view

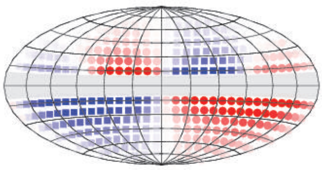


All-sky map of Galactic Faraday depth

Observations



Model



Synchrotron polarization map