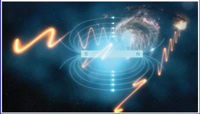
Observations and models of interstellar magnetic fields from large to small scales



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PCMI Symposium 2022

ENS Paris – 24-28 October, 2022

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

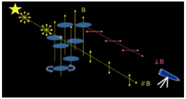
Credit: *Bryan Gaensler*

Observational tools

- Polarization of starlight & dust thermal emission

  Due to *dust grains* $\rightarrow$ general (dusty) ISM

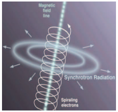
  ☞ $\vec{B}_\perp$ (orientation only)



- Synchrotron emission

  Produced by *CR electrons* $\rightarrow$ general (CR-filled) ISM

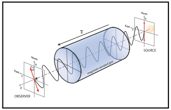
  ☞ $\vec{B}_\perp$ (strength & orientation)



- Faraday rotation

  Caused by *thermal electrons* $\rightarrow$ ionized regions

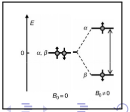
  ☞ $B_\parallel$ (strength & sign)



- Zeeman splitting

  Molecular & atomic *spectral lines* $\rightarrow$ neutral regions

  ☞ $B_\parallel$ (strength & sign)



Outline

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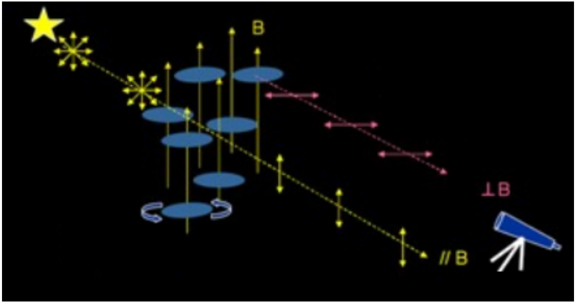
1. Introduction
2. Observations
   - Dust polarization
   - Synchrotron emission
   - Faraday rotation
   - Zeeman splitting
3. Models

Physical concept

Dust grains tend to spin about their short axes
& to align their spin axes with $\vec{B}$

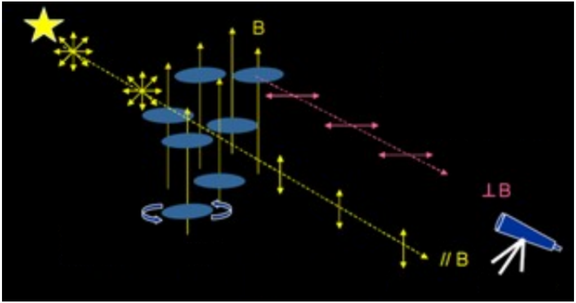
This grain alignement leads to *linear polarization*



Credit: Wen-Ping Chen

Polarization orientation

- Starlight attenuated by dust *(optical)* is polarized $\parallel \vec{B}_\perp$
- Dust thermal emission *(infrared)* is polarized $\perp \vec{B}_\perp$



Credit: Wen-Ping Chen

Polarization fraction

$$p \equiv \frac{P}{I}$$

- Starlight attenuated by dust : $p \simeq \tau\, p_0 \cos^2\gamma$
- Dust thermal emission : $p = p_0 \cos^2\gamma$

↳ $p_0 = p_{\max}\, F_{\mathrm{align}}\, F_{\delta B}$

$\vec{B} \in \mathrm{PoS}$

$\left(\cos^2\gamma = 1\right)$

$\Rightarrow p = p_0$

$\vec{B} \perp \mathrm{PoS}$

$\left(\cos^2\gamma = 0\right)$

$\Rightarrow p = 0$

Credit: Vincent Guillet

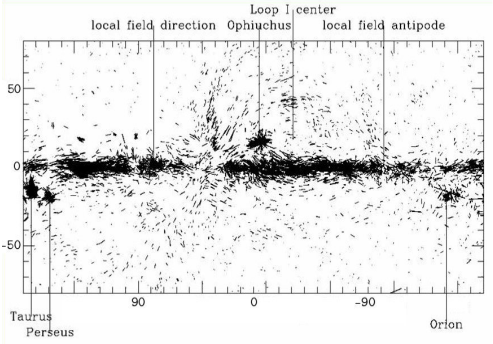
Dust polarization

Altogether

- Polarization *orientation* ☞ *orientation* of $\vec{B}$ *in* PoS
- Polarization *fraction* ☞ *inclination* of $\vec{B}$ *to* PoS (for ideal conditions)

Polarization of starlight

$\vec{B}_\perp$ half-vectors from 8 662 stars



Heiles (2000)

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

$\vec{B}_{\rm ord}$ is nearly azimuthal ($\simeq -7^\circ$ from $\hat{e}_\phi$)

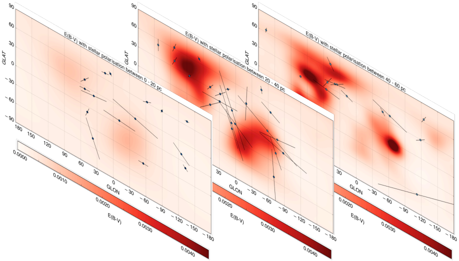
- In the halo : $\vec{B}_{\rm ord}$ has a vertical component

Polarization of starlight

Stars have accurately measured distances (with Gaia)

☞ Possible to probe $\vec{B}$ in 3D

Stellar polarization cube of nearby ISM



3 layers at

0 – 20 pc

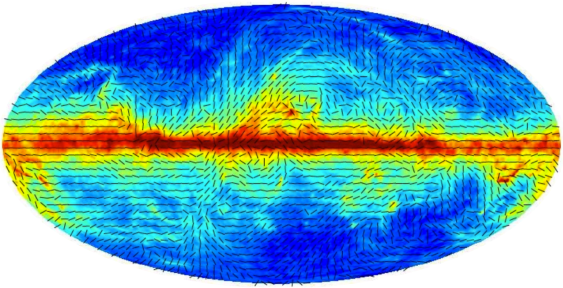
20 – 40 pc

40 – 60 pc

Credit: Marta Alves

Polarization of dust thermal emission

Total intensity & $\vec{B}_\perp$ half-vectors at 353 GHz (Planck)



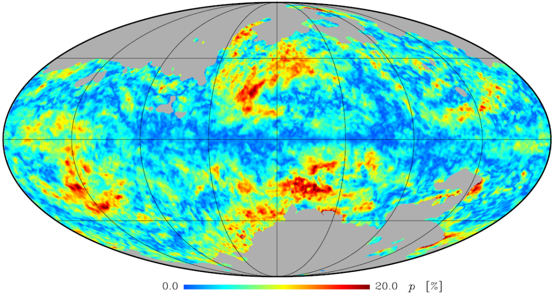
Planck collaboration (2015)

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

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

Polarization of dust thermal emission

Polarization fraction at 353 GHz (Planck)



Planck collaboration (2015)

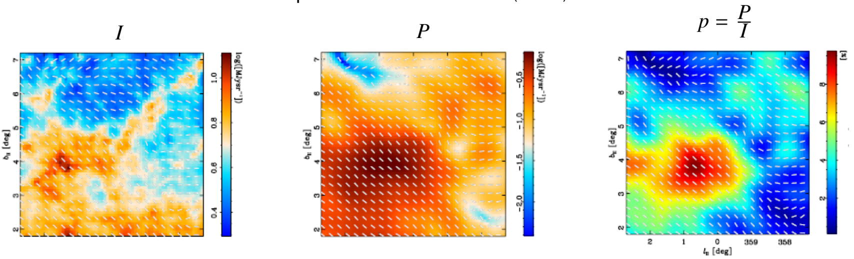
☞ Info on - Inclination of $\vec{B}_{\rm ord}$ to PoS : $\cos^2\gamma$

- Magnetic fluctuations : $\frac{B_{\rm fluct}}{B_{\rm ord}}$

- Grain properties & alignment efficiency : $p_{\rm max}$ & $F_{\rm align}$

Polarization of dust thermal emission

Pipe Nebula at 353 GHz (Planck)

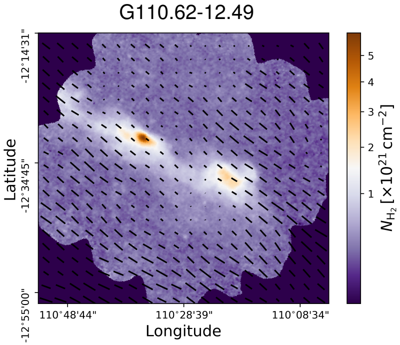


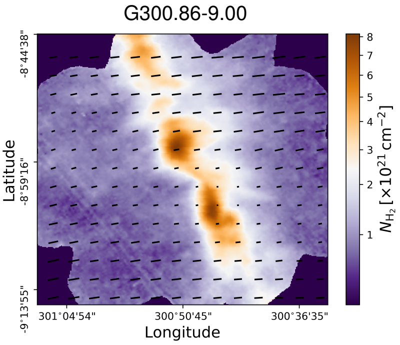
Planck collaboration (2015)

☞ Anti-correlation between $p = \frac{P}{I}$ & $S = \sqrt{\langle(\Delta\psi)^2\rangle}$

Magnetic field orientation in dust filaments

Galactic fields from the Herschel Galactic cold core (GCC) key-program with $\vec{B}_\perp$ half-vectors from Planck (353 GHz)





☞ Low-$N_{\rm H}$ filament $\sim \parallel \vec{B}_\perp$

☞ High-$N_{\rm H}$ filament $\sim \perp \vec{B}_\perp$

Credit: Jonathan Oers (PhD student of Isabelle Ristorcelli & Katia Ferrière)

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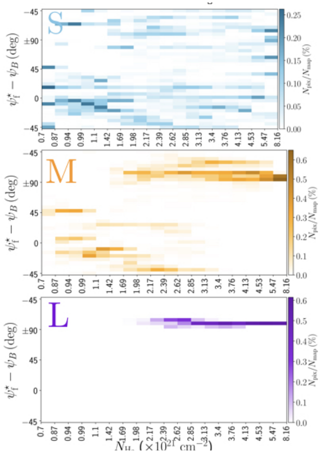
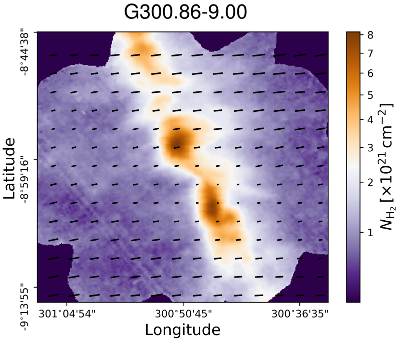


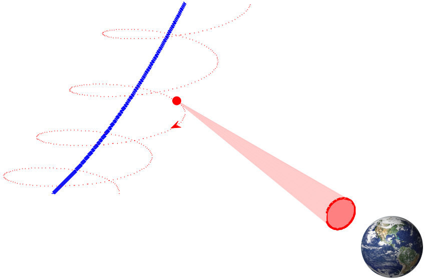


Carrière et al. (2022)

Outline

Physical concept

Relativistic electrons gyrating about magnetic field lines emit *synchrotron radiation*

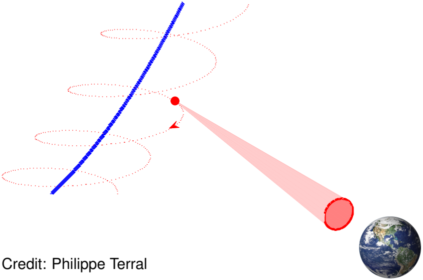


Credit: Philippe Terral

Total & polarized intensities

Emissivity : $\mathcal{E} = f(\alpha)\, n_{\rm CRe}\, B_\perp^{\;\alpha+1}\, \nu^{-\alpha}$ & $\mathcal{E}_{\rm pol} = p_{\rm syn}\, \mathcal{E}$ & $\overleftrightarrow{\mathcal{E}}_{\rm pol} \perp \vec{B}_\perp$

- Total intensity : $I = \int \mathcal{E}\, ds$ ☞ $B_\perp$
- Polarized intensity : $\overleftrightarrow{P} = \int \overleftrightarrow{\mathcal{E}}_{\rm pol}\, ds$ ☞ $(\overleftrightarrow{B}_\perp)_{\rm ord}$



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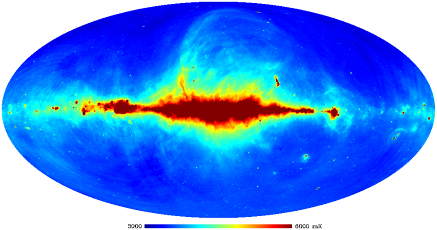
- Polarized intensity : $\overleftrightarrow{P} = \int \overleftrightarrow{\mathcal{E}}_{\rm pol}\, ds$ ☞ $(\overleftrightarrow{B}_\perp)_{\rm ord}$

↳ $Q + i\,U = \int \mathcal{E}_{\rm pol}\, e^{2i\psi}\, ds$

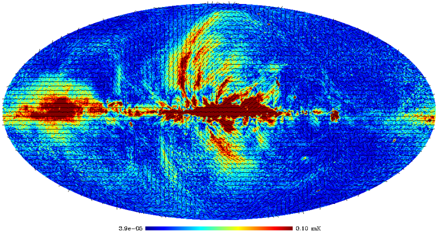
Total & polarized intensities

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



Credit: Tess Jaffe

PI & $\vec{B}_\perp$ half-vectors at 23 GHz (WMAP)



Credit: Tess Jaffe

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

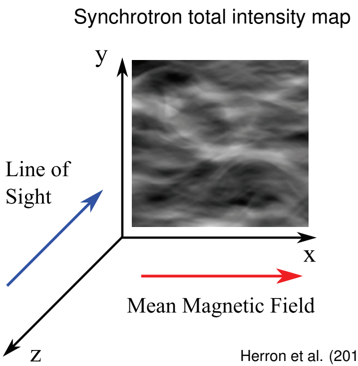
- In the disk : $\vec{B}_{\rm ord}$ is horizontal
- In the halo : $\vec{B}_{\rm ord}$ has a vertical component

Fluctuations in synchrotron intensity

Theoretical developments (Lazarian & Pogosyan 2012)

& numerical simulations (Herron et al. 2016)

☞ Synchrotron intensity fluctuations are anisotropic, forming filaments || $\vec{B}_{\perp}$

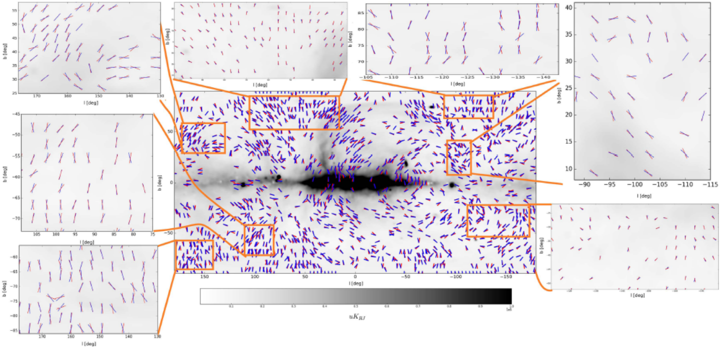


Herron et al. (2016)

Fluctuations in synchrotron intensity

Synchrotron intensity gradients ☞ orientation of $\vec{B}_\perp$

Synchrotron intensity gradients & polarization half-vectors (Planck)



Lazarian et al. (2017)

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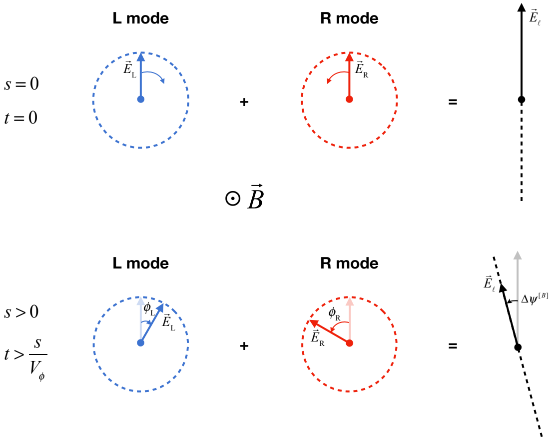
Physical concept

When a linearly polarized radio wave travels through a magneto-ionized medium, the orientation of linear polarization undergoes *Faraday rotation*



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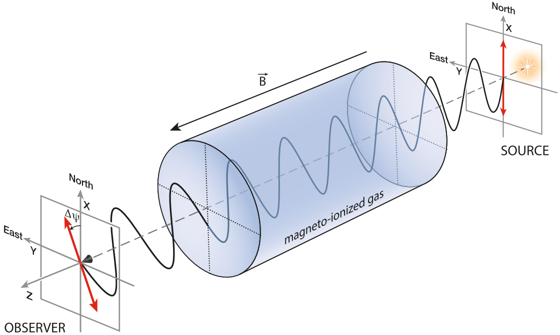
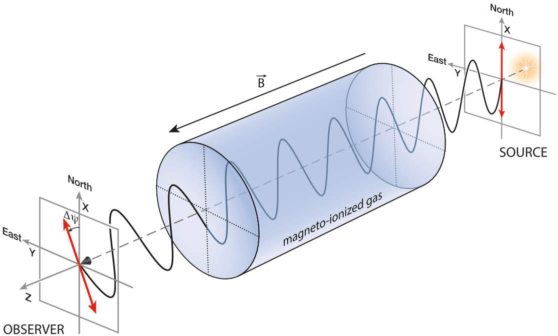


Credit: Theophilus Britt Griswold (NASA Goddard)

Rotation angle & rotation measure

Rotation angle : $\Delta\psi = \mathrm{RM}\ \lambda^2$

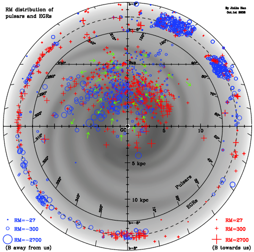
Rotation measure : $\mathrm{RM} = C \int n_e\, B_\parallel\, ds$ ☞ $B_\parallel$



Credit: Theophilus Britt Griswold (NASA Goddard)

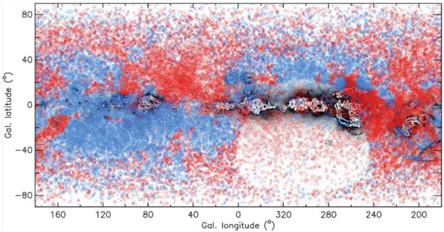
Rotation measures

RMs of pulsars & EGRSs with $|b| < 8^\circ$



Han (2009)

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



Schnitzeler et al. (2019)

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

$\vec{B}_{\rm reg}$ is nearly azimuthal ($\simeq -8^\circ$ from $\hat{e}_\phi$)

- In the disk : $\vec{B}_{\rm reg}$ is horizontal & mostly azimuthal, with *reversals* in B_ϕ

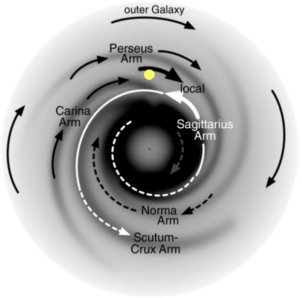
$\vec{B}_{\rm reg}$ probably has a spiral shape

- In the halo : $\vec{B}_{\rm reg}$ is CCW at $z > 0$ & CW at $z < 0$

$\vec{B}_{\rm reg}$ possibly has an upward spiraling shape

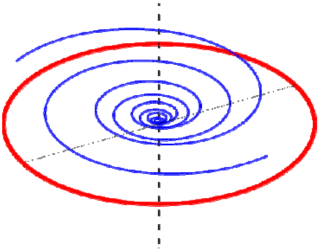
Rotation measures

In the disk



van Eck et al. (2011)

In the halo



Terral & Ferrière (2017)

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Outline

Physical concept

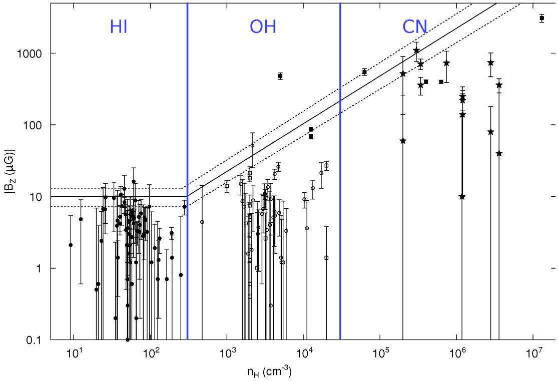
Atom/molecule with nonzero (electronic) angular momentum
has (high) magnetic moment

Coupling between magnetic moment & external magnetic field
splits energy levels with $j \neq 0$ into $2j+1$ sublevels $(m = -j, ..., +j)$
$\Rightarrow$ leads to *splitting* of spectral lines

Splitting: $\Delta\nu = \frac{1}{4\pi}\,\Omega_e = \frac{e\,B}{4\pi\,m_e\,c}$

In principle:
- *splitting* ☞ *strength* of $\vec{B}$
- *polarization* ☞ *direction* of $\vec{B}$

Magnetic field strength



Crutcher et al. (2010)

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

- In molecular clouds : $B \lesssim (10\ \mu\mathrm{G}) \left(\frac{n_\mathrm{H}}{300\ \mathrm{cm}^{-3}}\right)^{0.65}$

Outline

Large-scale models

Very difficult to construct a complete and realistic model of $\langle\vec{B}\rangle$

1. The Galactic magnetic field is inherently complex

- $\vec{B}$ has a significant turbulent component
  ☞ Need a realistic description of $\delta\vec{B}$

- $\vec{B}$ is different in the different ISM phases
  ☞ Must exploit the different tracers

- $\langle\vec{B}\rangle$ varies in space in a non-analytical manner
  ☞ Analytical models don't give a fair description

Large-scale models

Very difficult to construct a complete and realistic model of $\langle\vec{B}\rangle$

2. Observational tracers have important limitations
   They are generally

- Indirect
  They also depend on dust, CR electrons, or thermal electrons

- Incomplete
  They do not lead to the full $\vec{B}$ (only $\vec{B}_\perp$ or $B_\parallel$)

- Two-dimensional
  They provide only LoS-integrated quantities

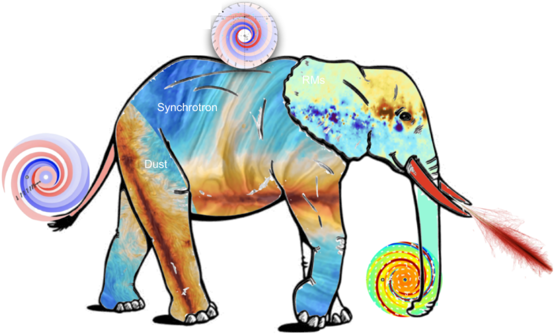
- Affected by
  - turbulent fluctuations
  - our position inside the Local Bubble

Large-scale models

Very difficult to construct a complete and realistic model of $\langle \vec{B} \rangle$

2. Observational tracers have important limitations

☞ Difficult to get the full picture

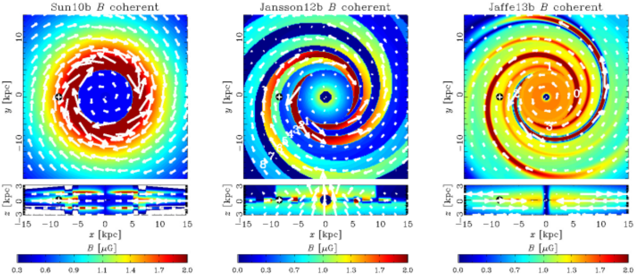


Credit: Tess Jaffe

Existing large-scale models

- Analytical models
  - May include some physically motivated constraints
  - Free parameters fit to observational data (synchrotron emission, Faraday rotation)

3 models of the large-scale magnetic field in the Galactic disk & halo

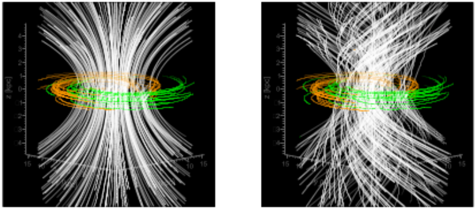


Planck collaboration (2016)

Existing large-scale models

- Analytical models
  - May include some physically motivated constraints
  - Free parameters fit to observational data (synchrotron emission, Faraday rotation)

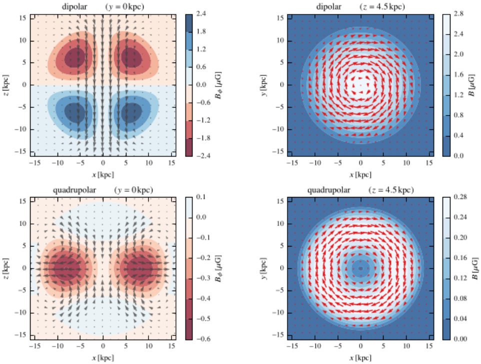
Improved model of the large-scale magnetic field in the Galactic halo:
X-shaped magnetic field wound up by Galactic rotation



Unger & Farrar (2019)

Existing large-scale models

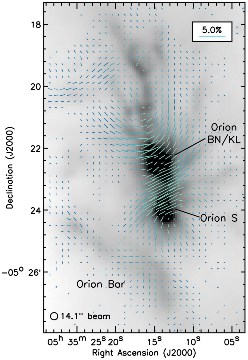
- Physical models
  - Solutions of mean-field dynamo equation
  - Optimized against observational data

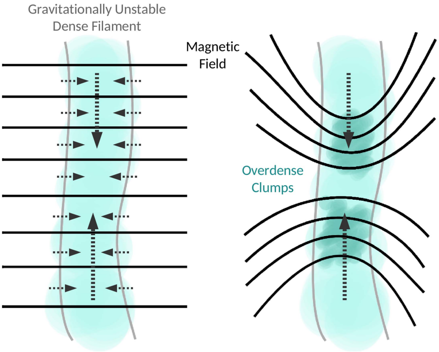


Shukurov et al. (2019)

Small-scale models

Hourglass-shaped magnetic field in the OMC-1 cloud in Orion A

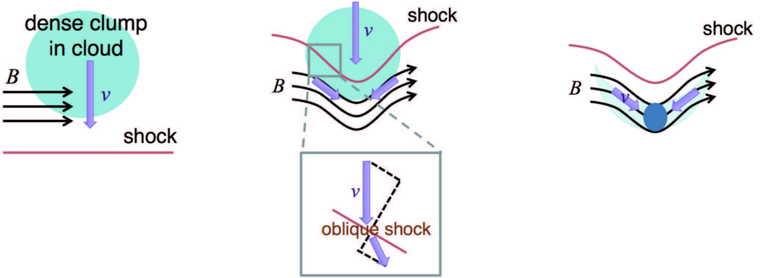




Pattle et al. (2017)

Small-scale models

Shocked magnetic field & filament formation



Inoue et al. (2018)