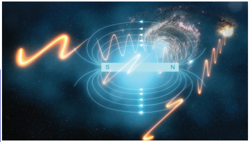

Galactic magnetic fields
I. Observations

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Bad Honnef – 29 January - 3 February, 2023

Outline

Outline

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

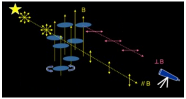
Credit: Bryan Gaensler

Observational tools

- **Polarization of starlight & dust thermal emission**

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

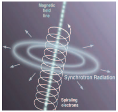
  ☞ $\vec{B}_\perp$ (orientation only)



- **Synchrotron emission**

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

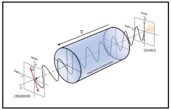
  ☞ $\vec{B}_\perp$ (strength & orientation)



- **Faraday rotation**

  Caused by *thermal electrons* → ionized regions

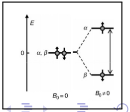
  ☞ $B_\parallel$ (strength & sign)



- **Zeeman splitting**

  Molecular & atomic *spectral lines* → neutral regions

  ☞ $B_\parallel$ (strength & sign)



Outline

1. Introduction
2. Our Galaxy
   - Dust polarization
   - Synchrotron emission
   - Faraday rotation
   - Zeeman splitting
3. External galaxies

Outline

1. Introduction
2. Our Galaxy
   - Dust polarization
   - Synchrotron emission
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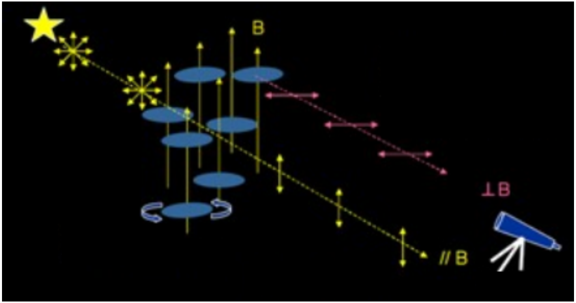
   - Zeeman splitting
3. External galaxies

Physical concept

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

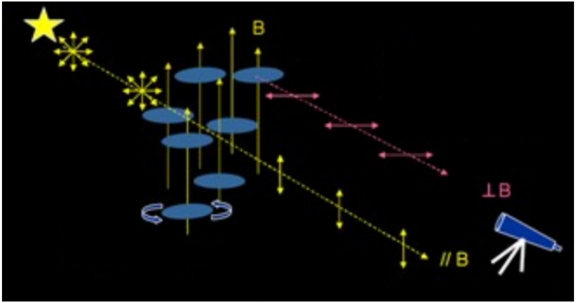
This grain alignement leads to *linear polarization*



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 : $p = p_0 \cos^2 \gamma$

↳ $p_0 = p_{\rm intr} \, F_{\rm align} \, F_{\delta B}$

$\vec{B} \in$ PoS

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

$\Rightarrow p = p_0$

$\vec{B} \perp$ PoS

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

$\Rightarrow p = 0$

Credit: Vincent Guillet

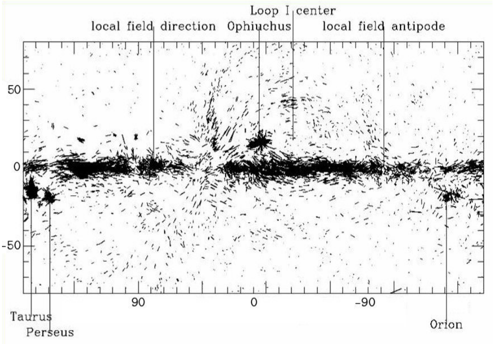
Dust polarization

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 ($\simeq -7°$ from $\hat{e}_\phi$)

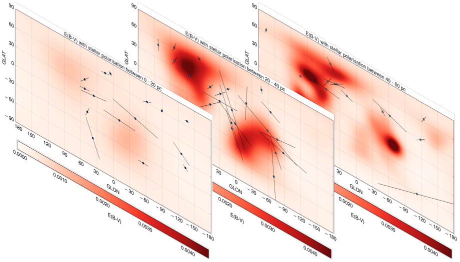
- Toward the halo : $\vec{B}$ has a vertical component

Polarization of starlight

Stars have accurately measured distances (with Gaia)

☞ Possible to probe $\vec{B}_\perp$ in 3D

Stellar polarization cube of nearby ISM



3 layers at

0 – 20 pc

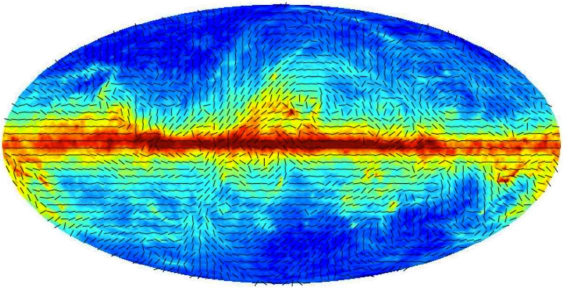
20 – 40 pc

40 – 60 pc

Credit: Marta Alves

Polarization of dust thermal emission

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



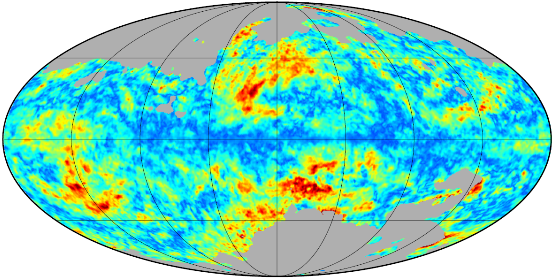
Planck collaboration (2015)

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

- Toward the halo : $\vec{B}$ has a vertical component

Polarization of dust thermal emission

Polarization fraction at 353 GHz (*Planck*)



Planck collaboration (2015)

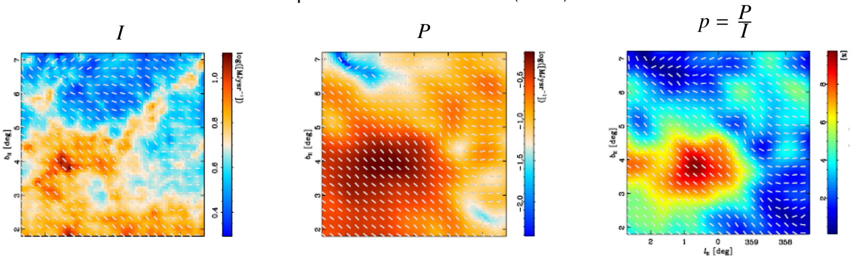
☞ Info on - Inclination of $\vec{B}_{\rm ord}$ to PoS : $\cos^2 \gamma$

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

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

Polarization of dust thermal emission

Pipe Nebula at 353 GHz (*Planck*)

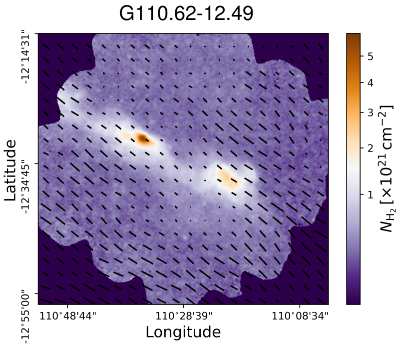


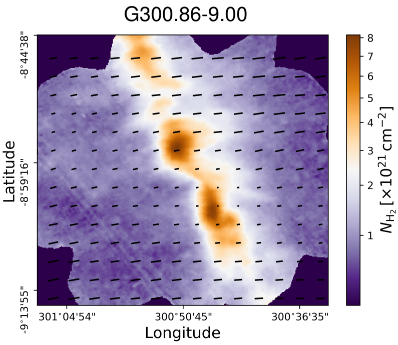
Planck collaboration (2015)

☞ 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)



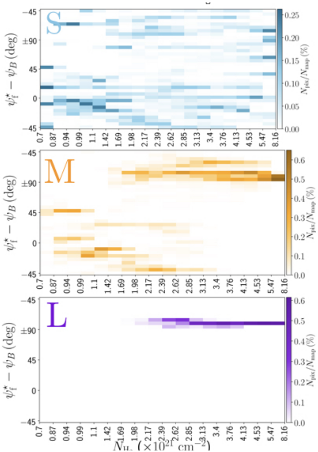


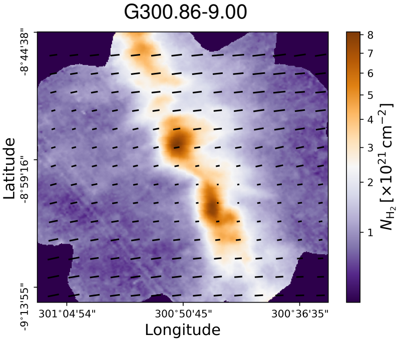
☞ Low-N_H filament $\sim$ $\parallel \vec{B}_\perp$ ☞ High-N_H filament $\sim$ $\perp \vec{B}_\perp$

Credit: Jonathan Oers

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)



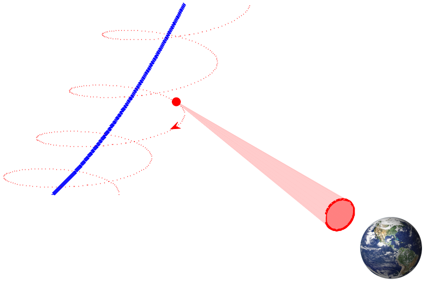


Carrière et al. (2022)

Outline

Physical concept

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

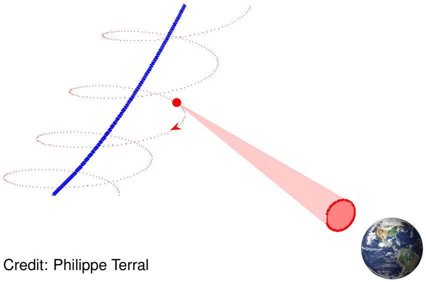


Credit: Philippe Terral

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



Credit: Philippe Terral

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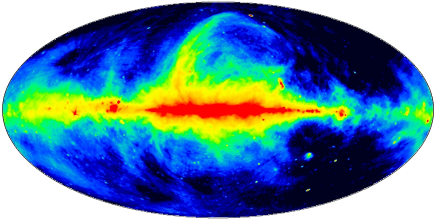
- Polarized intensity : $\overleftrightarrow{P} = \int \overleftrightarrow{\mathcal{E}}_{\rm pol}\, ds$ ☞ $(\overleftrightarrow{B}_\perp)_{\rm ord}$

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

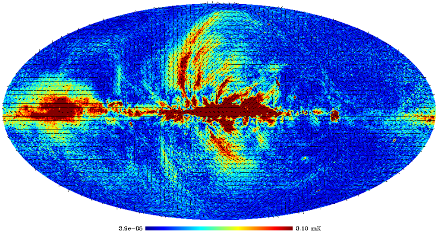
Total & polarized intensities

TI at 408 MHz (76 m Jodrell-Bank + 100 m Effelsberg)



Credit: MPIfR/Patricia Reich

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



Credit: Tess Jaffe

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

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

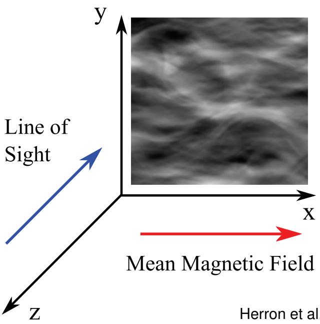
- Toward the halo : $\vec{B}$ has a vertical component

Fluctuations in synchrotron intensity

Theoretical developments (Lazarian & Pogosyan 2012)
& numerical simulations (Herron et al. 2016)

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

Synchrotron total intensity map

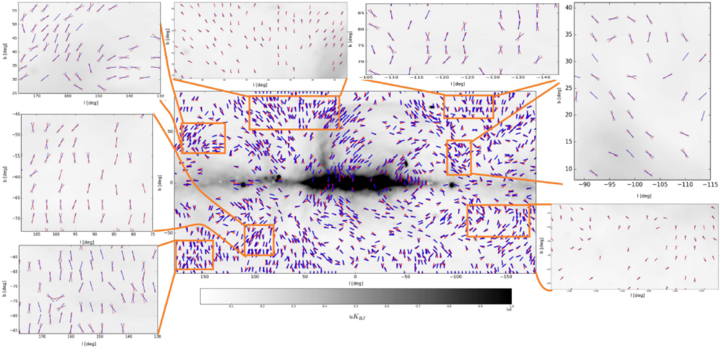


Herron et al. (2016)

Fluctuations in synchrotron intensity

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

Synchrotron intensity gradients & polarization half-vectors (*Planck*)

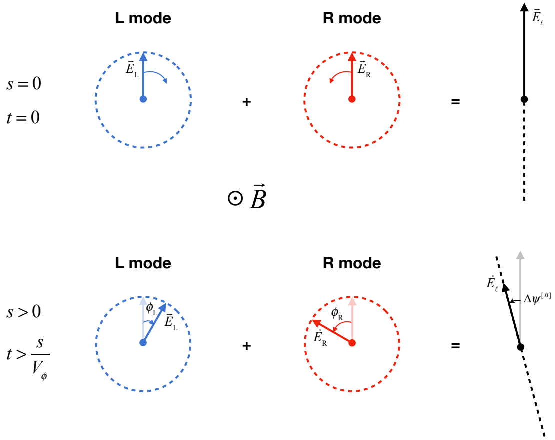


Lazarian et al. (2017)

Outline

Physical concept

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



Physical concept

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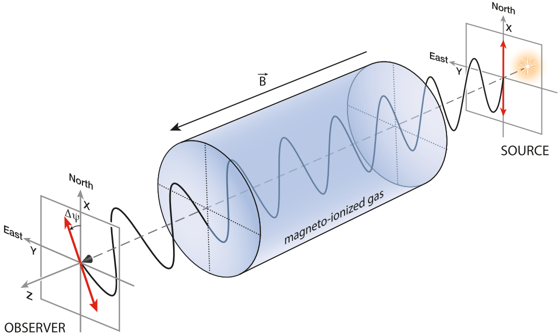
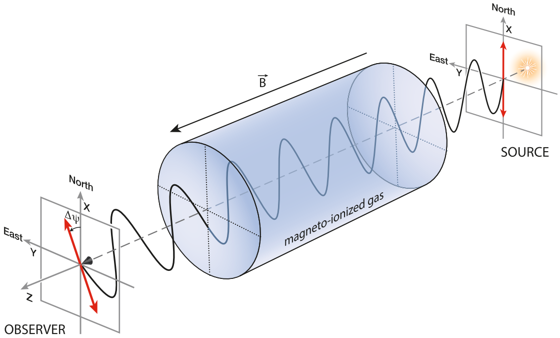


Credit: Theophilus Britt Griswold (NASA Goddard)

Rotation angle & rotation measure

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

Rotation measure : $\mathrm{RM} = C \int n_\mathrm{e}\ B_\| \ ds$ ☞ $B_\|$



Credit: Theophilus Britt Griswold (NASA Goddard)

Rotation angle & rotation measure

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

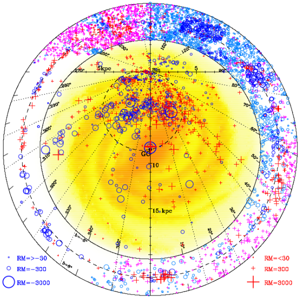
Rotation measure : $\mathrm{RM} = C \int n_\mathrm{e}\, B_\parallel\, ds$ ☞ $B_\parallel$

For Galactic pulsars : $\mathrm{DM} = \int n_\mathrm{e}\, ds \Rightarrow \langle B_\parallel \rangle = \dfrac{\mathrm{RM}}{C\,\mathrm{DM}}$

For extragalactic sources : Need a model of n_e

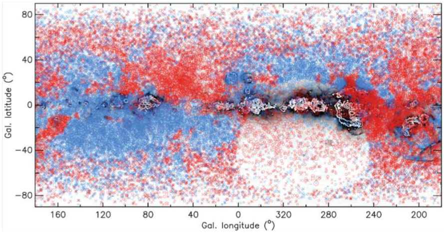
Rotation measures

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



Han et al. (2018)

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

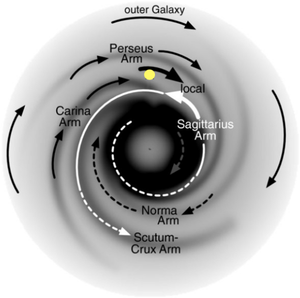
$\vec{B}_{\rm reg}$ probably has a spiral shape

- 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

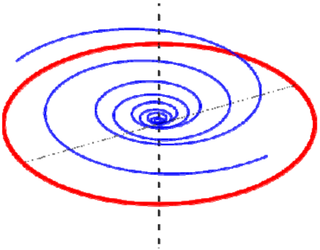
Rotation measures

In the disk



van Eck et al. (2011)

In the halo



Terral & Ferrière (2017)

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Outline

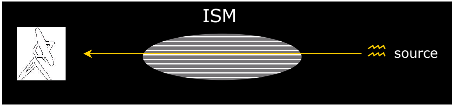
General concept

- Underlying processes
  - Galactic synchrotron emission : linearly polarized
  - Faraday rotation : λ-dependent
- General idea
  - Measure synchrotron polarized intensity at many different λ
  - Convert λ-dependence into s-dependence
- Output
  Faraday cube = 3D map of synchrotron polarized emission as fc(α, δ, Φ)

General method

- Faraday rotation of background source

$$\Delta\psi = \mathrm{RM}\,\lambda^2 \quad \text{with} \quad \mathrm{RM} = C\int_0^L n_e\, B_{\|}\, ds \quad \text{(rotation measure)}$$



- Faraday rotation of Galactic synchrotron emission

Synchrotron emission & Faraday rotation are *spatially mixed*

$$\vec{P}(\lambda^2) = \int \vec{F}(\Phi)\, e^{2i\Phi\lambda^2}\, d\Phi \quad \text{with} \quad \Phi(z) = C\int_0^z n_e\, B_{\|}\, ds \quad \text{(Faraday depth)}$$

Fourier transform $\Rightarrow$ $\vec{F}(\Phi) = \frac{1}{\pi}\int \vec{P}(\lambda^2)\, e^{-2i\Phi\lambda^2}\, d\lambda^2$

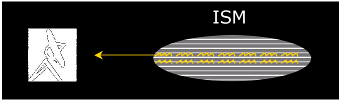


Figure Credit: Marijke Haverkorn

Faraday spectrum

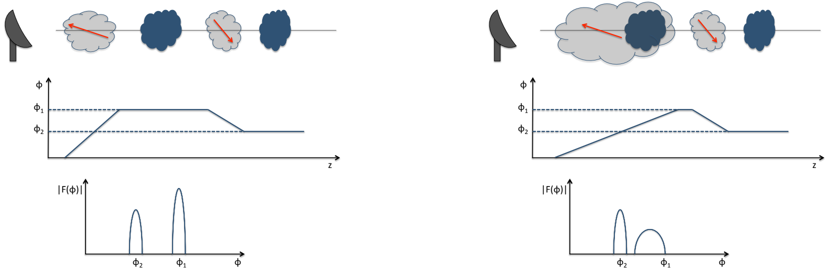
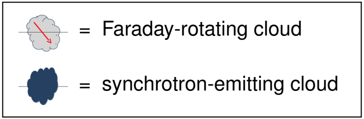


Figure Credit: Marta Alves



Faraday cube

For a given sky area

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

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

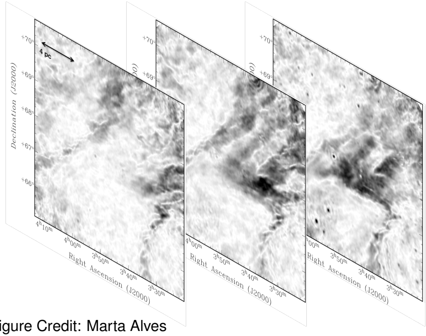


Figure Credit: Marta Alves

3 slices at

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

Expected results

- From synchrotron polarized intensity map to Faraday cube
  - Measure $\vec{P}(\lambda^2)$ at many different λ
  - Fourier transform $\vec{P}(\lambda^2)$ to obtain $\vec{F}(\Phi)$
- From Faraday cube to physical space
  - Uncover synchrotron-emitting & Faraday-rotating features in Faraday cube
  - Identify these features with interstellar matter structures
- For synchrotron-emitting regions

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

  $\Delta\Phi$ ☞ $B_\parallel$

Outline

Physical concept

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

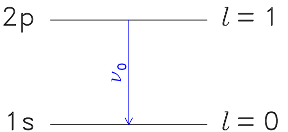
Coupling between magnetic moment & external magnetic field splits energy levels with $j \neq 0$ into $2j+1$ sublevels $(m = -j, ..., +j)$
$\Rightarrow$ leads to *splitting* of spectral lines

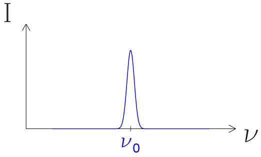
Splitting: $\Delta\nu = \frac{1}{4\pi}\,\Omega_\mathrm{e} = \frac{e\,B}{4\pi\,m_\mathrm{e}\,c}$

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

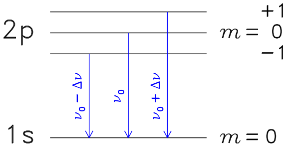
Splitting of spectral line

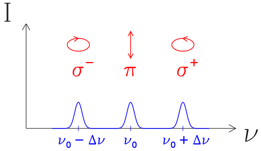
- If $B = 0$





- If $B \neq 0$

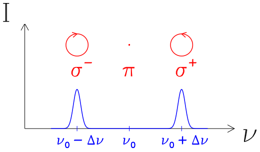




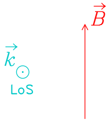
Splitting of spectral line

- If $\vec{B} \parallel$ LoS

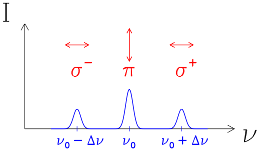
☞ *Circular* polarization



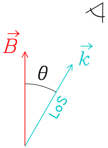
- If $\vec{B} \perp$ LoS



☞ *Linear* polarization



Stokes parameters



- *Total* intensity

$$I = I_\pi + I_{\sigma^+} + I_{\sigma^-}$$
$$= \hat{\mathcal{I}}_\pi \sin^2\theta + \left(\hat{\mathcal{I}}_{\sigma^+} + \hat{\mathcal{I}}_{\sigma^-}\right) \tfrac{1}{2}\left(1 + \cos^2\theta\right)$$

- *Circular* polarization

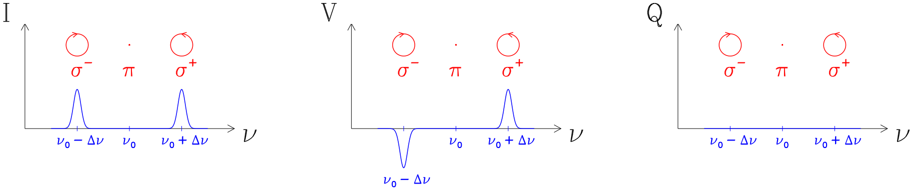
$$V = I_{\circlearrowright} - I_{\circlearrowleft}$$
$$= \left(\hat{\mathcal{I}}_{\sigma^+} - \hat{\mathcal{I}}_{\sigma^-}\right) \cos\theta$$

- *Linear* polarization

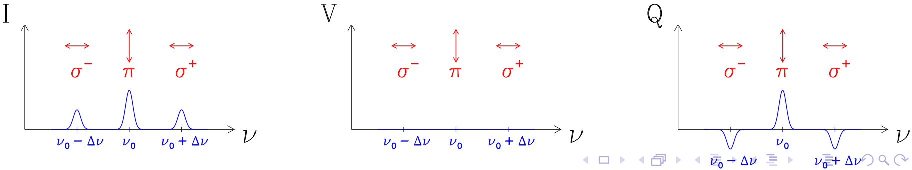
$$Q = I_{\updownarrow} - I_{\leftrightarrow} \quad \& \quad U = I_{\nwarrow\!\searrow} - I_{\swarrow\!\nearrow}$$
$$= \left[\hat{\mathcal{I}}_\pi - \tfrac{1}{2}\left(\hat{\mathcal{I}}_{\sigma^+} + \hat{\mathcal{I}}_{\sigma^-}\right)\right] \sin^2\theta$$

Stokes parameters

- If $\vec{B} \parallel$ LoS $(\theta = 0°)$ ☞ *Circular* polarization

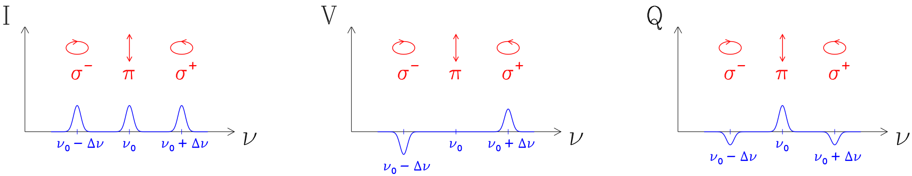


- If $\vec{B} \perp$ LoS $(\theta = 90°)$ ☞ *Linear* polarization



Stokes parameters

- If $\vec{B}$ oblique to LoS ☞ *Elliptical* polarization

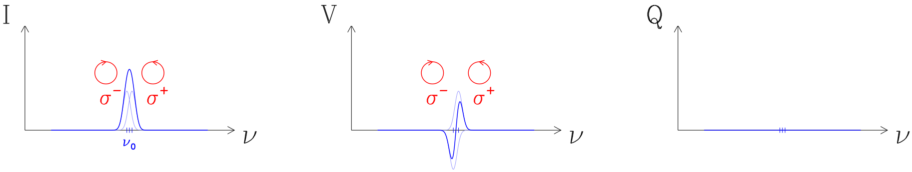


Measure
- $\Delta\nu$ ☞ B (*strength*)
- $\frac{V}{I}$ or $\frac{Q}{I}$ ☞ θ (*angle to LoS*)
- $\frac{U}{Q}$ ☞ χ (*angle in PoS*)

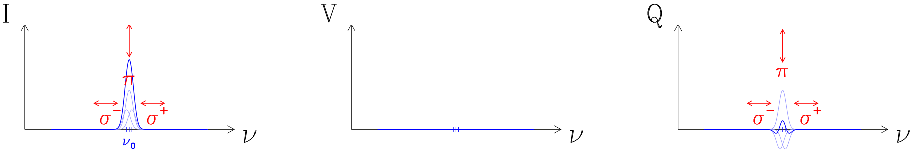
☞ $\vec{B}$

Limit of small splitting ($\Delta\nu \ll$ line width)

- If $\vec{B} \parallel$ LoS ($\theta = 0°$) ☞ *Circular* polarization

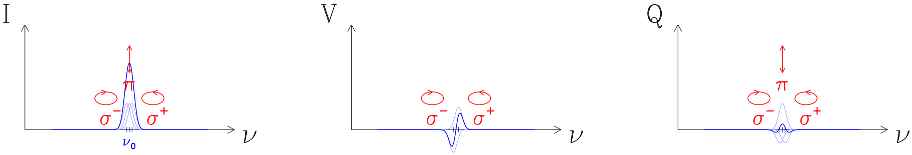


- If $\vec{B} \perp$ LoS ($\theta = 90°$) ☞ *Linear* polarization



Limit of small splitting ($\Delta\nu \ll$ line width)

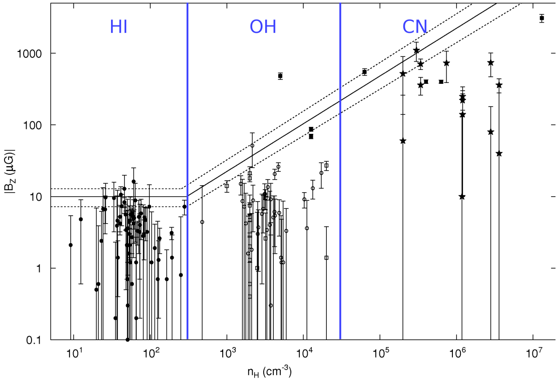
- If $\vec{B}$ oblique to LoS ☞ *Elliptical* polarization



Measure

$$\begin{cases} - \; V = \left(\hat{\mathcal{I}}_{\sigma^+} - \hat{\mathcal{I}}_{\sigma^-}\right)\cos\theta = -\dfrac{dI_\nu}{d\nu}\,\Delta\nu\cos\theta & ☞ \; B_\parallel \\ - \; Q = \left[\hat{\mathcal{I}}_\pi - \tfrac{1}{2}\left(\hat{\mathcal{I}}_{\sigma^+} + \hat{\mathcal{I}}_{\sigma^-}\right)\right]\sin^2\theta = -\tfrac{1}{4}\dfrac{d^2I_\nu}{d\nu^2}\,\Delta\nu^2\sin^2\theta & ☞ \; B_\perp \end{cases}$$

Magnetic field strength



Crutcher et al. (2010)

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

- In molecular clouds :

$$B \lesssim (10\ \mu\text{G}) \left(\frac{n_\text{H}}{300\ \text{cm}^{-3}}\right)^{0.65}$$

Goldreich-Kylafis effect

If anisotropic radiation field

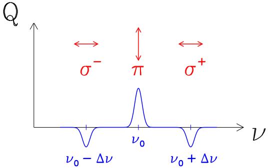
$\Rightarrow$ σ^+, π, σ^- transitions are radiatively excited at different rates

$\Rightarrow$ $m = +1$, $m = 0$, $m = -1$ levels are not equally populated

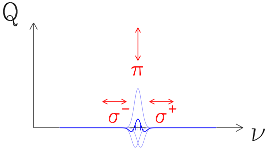
This imbalance can lead to *linear polarization* $\parallel \vec{B}_\perp$ or $\perp \vec{B}_\perp$

Balanced population

$\Delta\nu \gg$ line width



$\Delta\nu \ll$ line width



Goldreich-Kylafis effect

If anisotropic radiation field

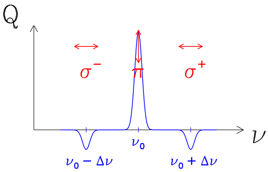
$\Rightarrow$ σ^+, π, σ^- transitions are radiatively excited at different rates

$\Rightarrow$ $m=+1$, $m=0$, $m=-1$ levels are not equally populated

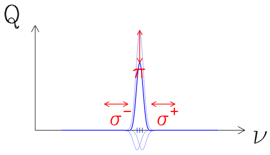
This imbalance can lead to *linear polarization* $\parallel \vec{B}_\perp$ or $\perp \vec{B}_\perp$

Unbalanced population

$\Delta\nu \gg$ line width



$\Delta\nu \ll$ line width



Outline

Observational tools

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

- Faraday rotation
  ☞ $B_\parallel$ (strength & sign)

- Polarization of dust thermal emission
  ☞ $\vec{B}_\perp$ (orientation only)

Synchrotron emission

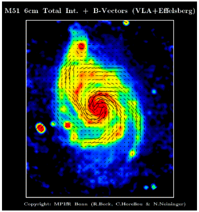
Spiral galaxies

- $B_{\text{tot}} \sim$ a few μG
- $\vec{B}$ has an ordered component
- ∗ *Face on*
  - Disk : $\vec{B}_{\text{ord}}$ follows the spiral arms

  ∗ *Edge on*
  - Disk : $\vec{B}_{\text{ord}}$ is horizontal
  - Halo : $\vec{B}_{\text{ord}}$ has an X shape

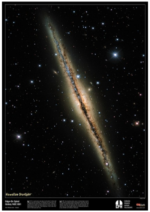
M 51

HST

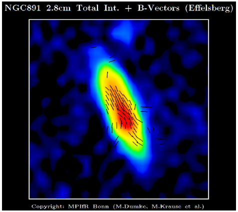


Effelsberg + VLA (6.2 cm)

NGC 891



CFHT



Effelsberg (2.8 cm)

Synchrotron emission

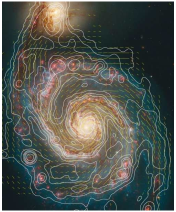
Spiral galaxies

- $B_{\rm tot} \sim$ a few μG
- $\vec{B}$ has an ordered component
- $*$ *Face on*
  - Disk : $\vec{B}_{\rm ord}$ follows the spiral arms

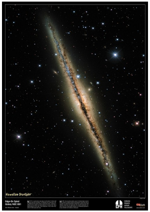
  $*$ *Edge on*
  - Disk : $\vec{B}_{\rm ord}$ is horizontal
  - Halo : $\vec{B}_{\rm ord}$ has an X shape

M 51


HST


Effelsberg + VLA (6.2 cm)

NGC 891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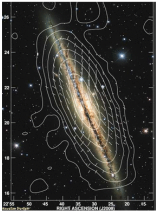


Effelsberg (3.6 cm)

Synchrotron emission

Elliptical galaxies

- Most are radio quiet
  - ☞ Low level of star formation
  - $\Rightarrow$ Lack of relativistic electrons
  - $\Rightarrow$ Undetectable $\vec{B}$

  Dynamo models
  - ☞ $B_{\rm tot} \sim$ a few μG ??

- $\vec{B}$ has only a fluctuating component

Faraday rotation

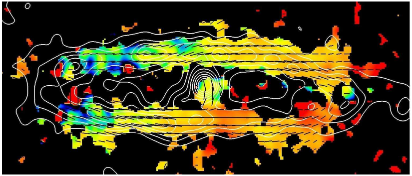
Spiral galaxies

- $\vec{B}$ has a regular component

- Azimuthal structure
  Variety of behaviors :
  $\vec{B}_{\rm reg}$ axisymmetric, bisymmetric ..., or mixed

- Vertical structure
  More difficult to establish
  Indications of even-symmetry $\vec{B}_{\rm reg}$

RM map of M 31 (Effelsberg 6 cm & 11 cm)



Beck (2015). Copyright: MPIfR/Bonn

Polarization of dust thermal emission

Spiral galaxies

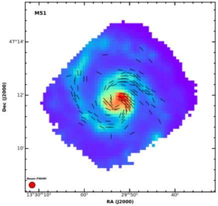
- $\vec{B}$ has an ordered component

- $*$ *Face on*
  - Disk : $\vec{B}_{\rm ord}$ follows the spiral arms

  $*$ *Edge on*
  - Disk : $\vec{B}_{\rm ord}$ is horizontal
  - Off disk : $\vec{B}_{\rm ord}$ has a vertical component

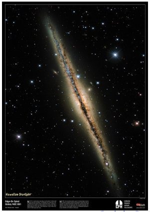
M 51

HST



SOFIA/HAWC+ ($154\,\mu$m)

NGC 891



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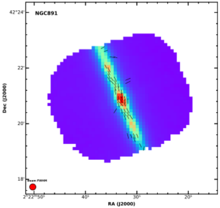

SOFIA/HAWC+ ($154\,\mu$m)