

# Magnetic fields in the ISM



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# Outline

## 1 Introduction

## 2 Observational overview

- Faraday rotation & synchrotron emission
- Dust polarization

## 3 Summary

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# Introduction

- Important **role** played by interstellar magnetic fields
  - structure, dynamics & energetics of the ISM
  - star formation process
  - acceleration & propagation of cosmic rays ...
- Best observational **probes** of interstellar magnetic fields
  - radio waves
  - polarization
- Existing & upcoming **instruments**



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## 1 Introduction

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# Observational methods

- Zeeman splitting

In neutral (molecular & atomic) regions  
→  $B_{\parallel}$  (strength & sign)

- Faraday rotation

In ionized regions  
→  $B_{\parallel}$  (strength & sign)

- Synchrotron emission

In general (CR-filled) ISM  
→  $\vec{B}_{\perp}$  (strength & orientation)

- Dust polarization

In general (dusty) ISM  
→  $\vec{B}_{\perp}$  (orientation only)

# Observational methods

- Zeeman splitting

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→  $B_{\parallel}$  (strength & sign)

- Faraday rotation

In ionized regions  
→  $B_{\parallel}$  (strength & sign)

- Synchrotron emission

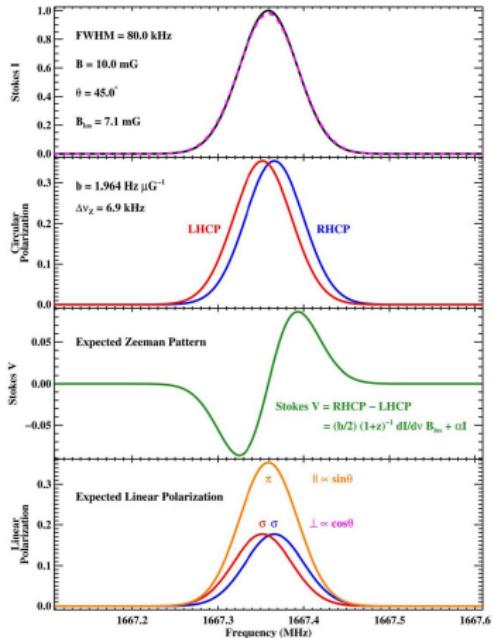
In general (CR-filled) ISM  
→  $\vec{B}_{\perp}$  (strength & orientation)

- Dust polarization

In general (dusty) ISM  
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# Zeeman splitting



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

- In atomic clouds :  
 $B \sim \text{a few } \mu\text{G}$
- In molecular clouds :  
 $B \sim (10 - 3000) \mu\text{G}$

Figure Credit: Robishaw & Heiles

# Outline

## 1 Introduction

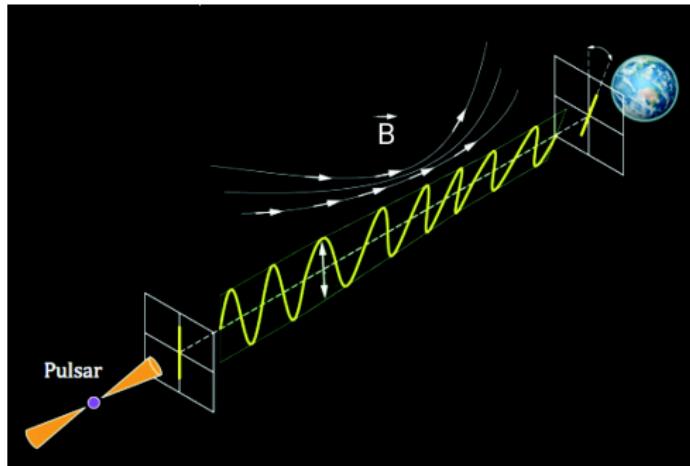
## 2 Observational overview

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# Faraday rotation of point sources

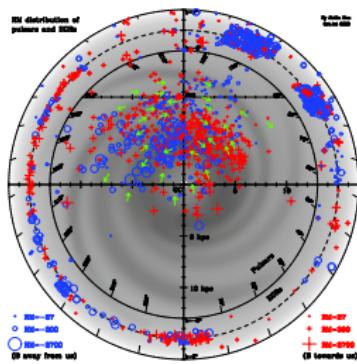
$\Delta\theta = \text{RM} \lambda^2$  where  $\text{RM} = C \int n_e B_{\parallel} dl$   
 $\Rightarrow \text{RM}$  probes  $B_{\parallel}$  in ionized regions



# Faraday rotation of point sources

$\Delta\theta = \text{RM } \lambda^2$  where  $\text{RM} = C \int n_e B_{\parallel} dl$   
 $\Rightarrow \text{RM probes } B_{\parallel}$  in ionized regions

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



Han (2009)

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

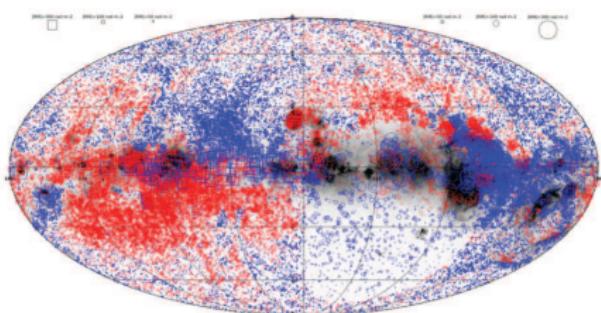


Figure Credit: Dominic Schnitzeler

# Faraday rotation of point sources

## In ionized regions

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

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

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

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

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

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

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

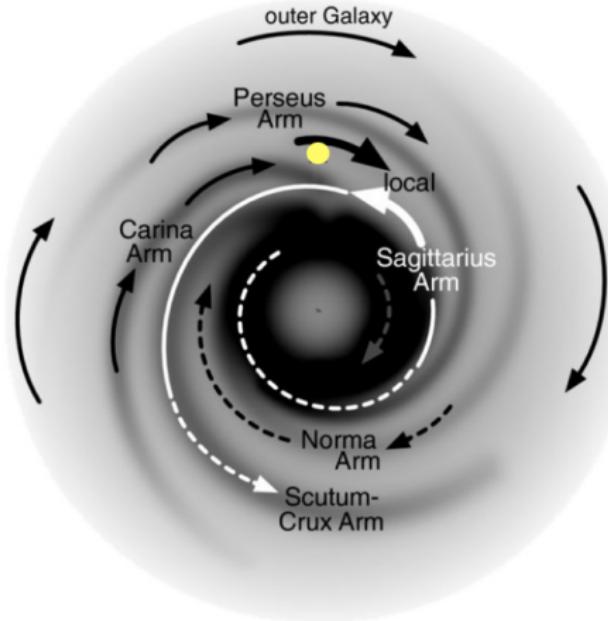
$\vec{B}_{\text{reg}}$  has vertical component

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

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

# Faraday rotation of point sources

Model of the large-scale magnetic field in the Galactic disk

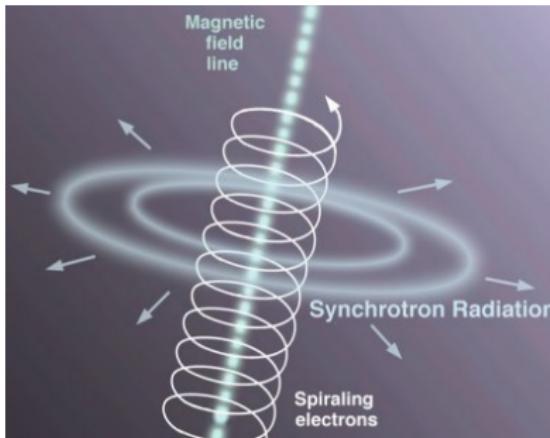


*van Eck et al. (2011)*

# Diffuse synchrotron emission

$$\mathcal{E} = f(\alpha) n_{\text{rel}} B_{\perp}^{\alpha+1} v^{-\alpha} \quad \& \quad \vec{\mathcal{E}} \perp \vec{B}_{\perp}$$

- ⇒ - *Total intensity* probes  $B_{\perp}$  (strength only)  
- *Polarized intensity* probes  $(\vec{B}_{\text{ord}})_{\perp}$  (strength & orientation)



Astronomy Online

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

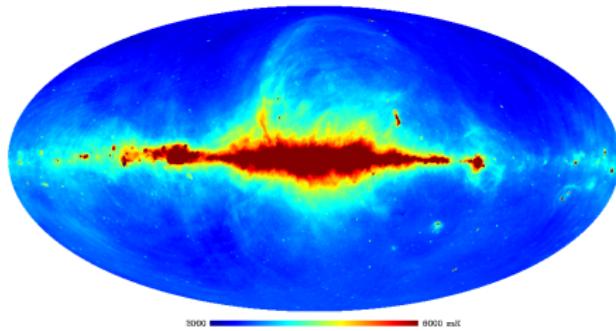


Figure Credit: Tess Jaffe

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

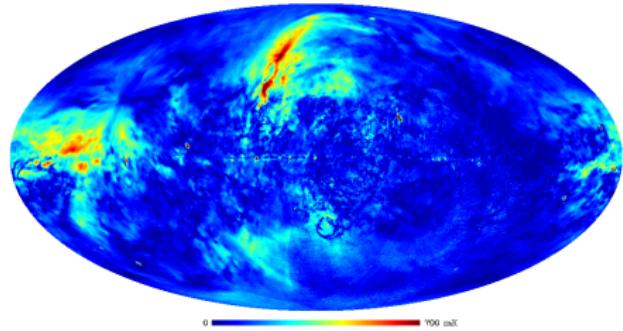


Figure Credit: Tess Jaffe

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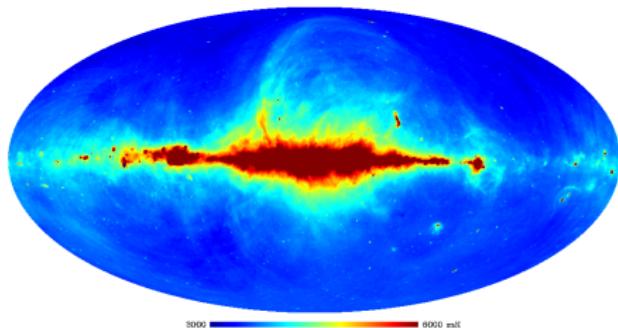


Figure Credit: Tess Jaffe

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

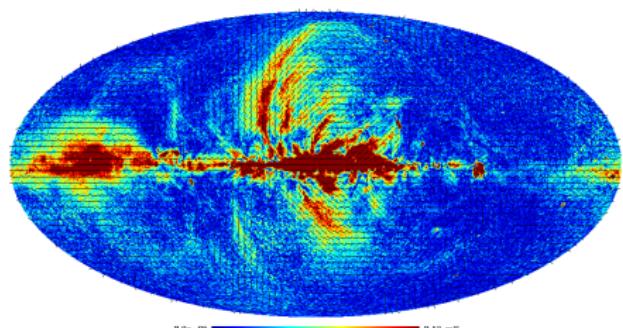


Figure Credit: Tess Jaffe

# Diffuse synchrotron emission

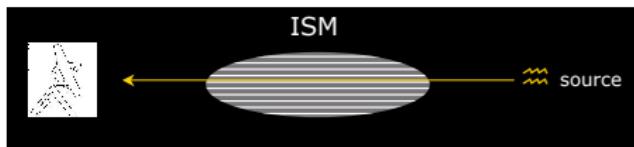
In general ISM

- ☞ -  $\vec{B}$  has *ordered* & *fluctuating* components
  - Near the Sun :  $B_{\text{ord}} \sim 3 \mu\text{G}$  &  $B_{\text{tot}} \sim 5 \mu\text{G}$
  - In Molecular Ring :  $B_{\text{tot}} \sim 7 \mu\text{G}$
  - Global spatial distribution :  $L_B \sim 12 \text{ kpc}$  &  $H_B \sim 4.5 \text{ kpc}$
  - In Galactic disk :  $\vec{B}_{\text{ord}}$  is horizontal
  - In Galactic halo :  $\vec{B}_{\text{ord}}$  has vertical component

# Faraday tomography

- Faraday rotation of background source

$$\Delta\theta = \text{RM } \lambda^2 \quad \text{with} \quad \text{RM} = C \int n_e B_{\parallel} dl \quad (\text{rotation measure})$$

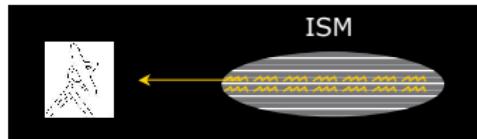


- Faraday rotation of diffuse synchrotron emission

Synchrotron emission & Faraday rotation are *spatially mixed*

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

☞ *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*)

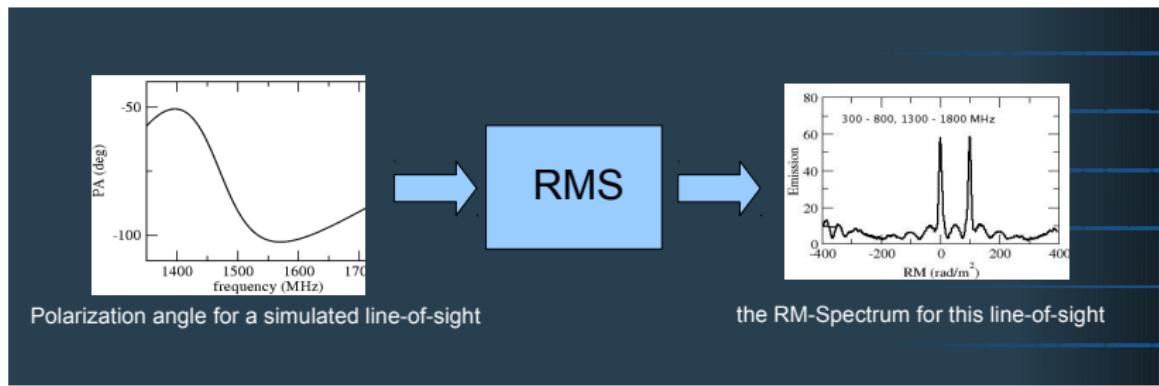


Figure Credit: Maik Wolleben



# Low-Frequency Array

- Largest existing network of radio telescopes

- Centered in the Netherlands & rolled out across Europe
- ~ 25 000 omni-directional dipole antennas, concentrated in 47 stations (24+14 [Netherlands] + 6 [Germany] + 1 [France] + 1 [UK] + 1 [Sweden])
- Signals are digitized, transmitted to a central supercomputer, & combined to produce radio images in real time

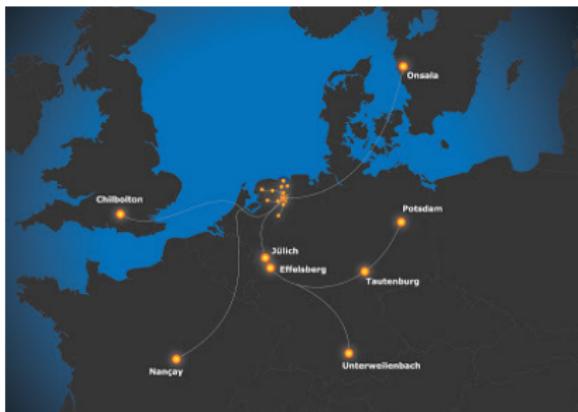


Figure Credit: ASTRON



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- Characteristics

- Frequency range: (10 – 250) MHz
- Wavelength range: (30 – 1.2) m
- Field of view: (660 – 1.3) deg<sup>2</sup>
- Resolution: (5 – 0.2) arcsec @  $L = 1\,000$  km
- Sensitivity: 0.16 mJy @ 150 MHz & for 8 hr

- Pathfinder for SKA



# Low-frequency radio observations

## ● Faraday rotation

- $\Delta\theta = \text{RM } \lambda^2$  with  $\text{RM} \propto \int n_e B_{\parallel} dl$   
⇒ Can probe small RM's → regions with *low*  $n_e$  and *weak*  $B$

## ● Diffuse synchrotron emission

- Emission is *almost purely synchrotron* (no contamination by thermal emission)
- $\mathcal{E} \propto n_{\text{rel}} B_{\perp}^{\alpha+1} \nu^{-\alpha}$   
⇒ Can probe regions with *low*  $n_{\text{rel}}$  and *weak*  $B$
- $\nu \propto E^2 B_{\perp}$  &  $t_{\text{syn}} \propto E^{-1} B_{\perp}^{-2}$   
⇒ Can probe *low-energy* CR electrons  
which live *longer* and propagate *further* from their sources

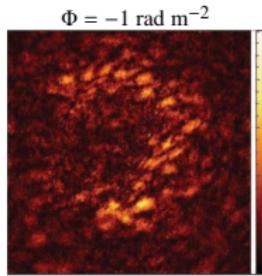
## ● Faraday tomography

- *High-resolution* Faraday-depth spectra
- Strong *Faraday depolarization* (differential Faraday rotation & internal Faraday dispersion)

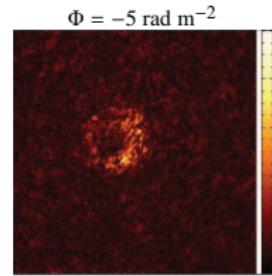
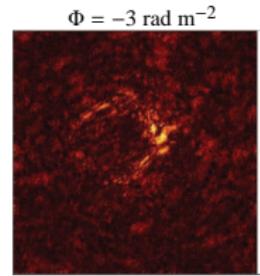
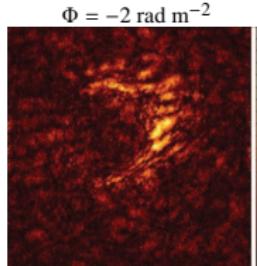


# Faraday tomography of the Fan region

- LOFAR HBA
- Stokes U at 4 different Faraday depths



Iacobelli et al. (2013)





# Square Kilometer Array

- Largest network of radio telescopes in development

- Cores in Australia (SKA-low & SKA-survey) & South Africa (SKA-mid)
- 250 000<sup>+</sup> antennas + 2 500<sup>+</sup> dishes (SKA2), spread over 3 000<sup>+</sup> km
- Total collecting area: 0.1 km<sup>2</sup> (SKA1) → 1 km<sup>2</sup> (SKA2)
- Ultra-fast data transmission to central super-supercomputer

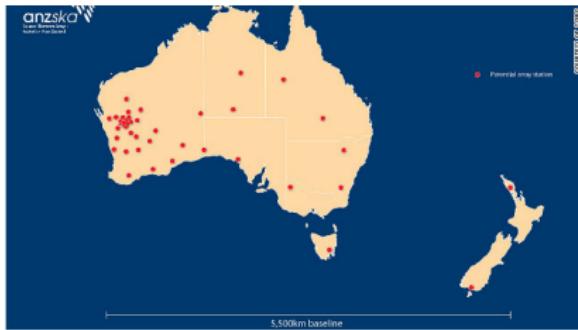


Figure Credit: CNN.com





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- Total collecting area: 0.1 km<sup>2</sup> (SKA1) → 1 km<sup>2</sup> (SKA2)
- Ultra-fast data transmission to central super-supercomputer

## ● Characteristics

- Frequency range: 50 MHz – 3 GHz (SKA1) → 14 GHz (SKA2)
- Wavelength range: 6 m – 10 cm (SKA1) → 2.1 cm (SKA2)
- Field of view: ~ 200 deg<sup>2</sup> @ < 1 GHz &  $\gtrsim$  1 deg<sup>2</sup> @ > 1 GHz
- Resolution: 0.4 arcsec – 7 mas (SKA1) → 3 mas (SKA2) @  $L = 3\,000$  km
- Sensitivity: 10<sup>+</sup>× LOFAR (SKA1) & 100<sup>+</sup>× LOFAR (SKA2)

## ● Timeline

- 2018: Construction begins
- 2020: Phase 1
- 2025: Phase 2

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# Dust polarization

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

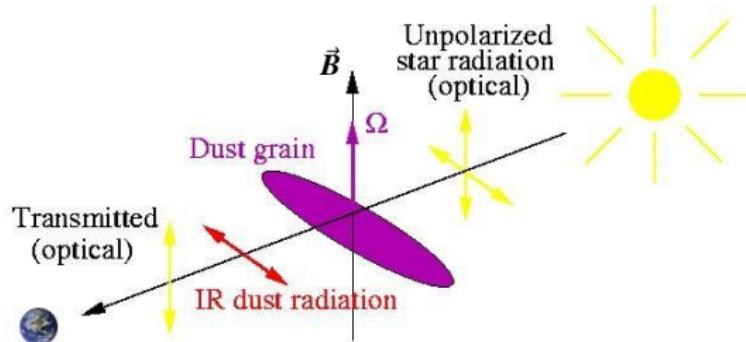
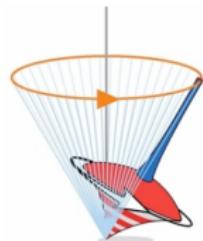
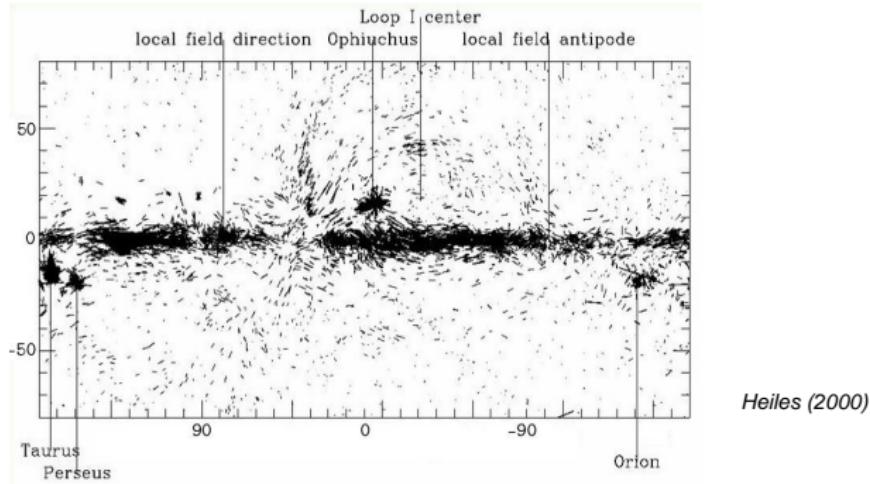


Figure Credit: Ponthieu & Lagache (2004)

# Dust polarization: starlight

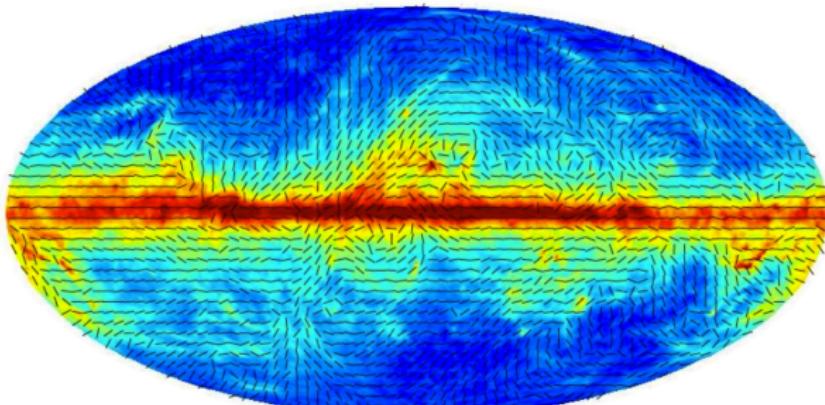
$\vec{B}$  vectors from 8 662 stars



- In Galactic disk :  $\vec{B}$  is horizontal
- Near the Sun :  $\vec{B}$  is nearly azimuthal ( $p \simeq -7^\circ$ )

## Dust polarization: dust thermal emission

## Total intensity & $\vec{B}$ vectors at 353 GHz (Planck)



Jean-Philippe Bernard, Planck collaboration (ESLAB 2013)

The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada



product of  
from more  
id Canada

- In Galactic disk :  $\vec{B}_{\text{ord}}$  is horizontal
  - In Galactic halo :  $\vec{B}_{\text{ord}}$  has vertical component

# Planck

- **Microwave space surveyor**

- At Earth-Sun L2 point
- Observed the whole sky in T1 & P1
- Designed to measure CMB anisotropies
- Also measured Galactic foreground emission

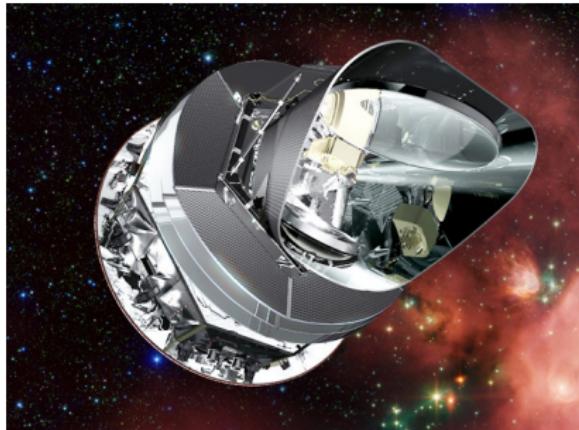


Image Credit: *ESA/AOES Medialab*

# Planck

## ● Microwave space surveyor

- At Earth-Sun L2 point
- Observed the whole sky in TI & PI
- Designed to measure CMB anisotropies
- Also measured Galactic foreground emission

## ● Characteristics

- Frequencies: 30 GHz → 857 GHz
- Wavelengths: 1 cm → 350 μm
- Sky coverage: 100%
- Resolution: 30 arcmin → 5 arcmin
- Sensitivity: 0.03 MJy sr<sup>-1</sup> s<sup>1/2</sup> @ 857 GHz

## ● Timeline

- May 2009: Spacecraft launched
- Jan 2012: HFI terminated
- Oct 2013: LFI terminated

# PILOT

## ● Sub-millimeter balloon-borne experiment

- *Polarized Instrument for Long wavelength Observation of the Tenuous ISM*
- Designed to measure polarized emission from interstellar dust
  - ☞ - Galactic plane survey ( $|b| \leq 20^\circ$ )
  - Deep field observations ( $|b| > 20^\circ$ )



# PILOT

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- Designed to measure polarized emission from interstellar dust
  - ↳ - Galactic plane survey ( $|b| \leq 20^\circ$ )
  - Deep field observations ( $|b| > 20^\circ$ )

## ● Characteristics

- Frequencies: 545 GHz & 1 250 GHz
- Wavelengths: 550  $\mu\text{m}$  & 240  $\mu\text{m}$
- Sky coverage: 32% – MW coverage: 97%
- Resolution: 3.3 arcmin & 1.4 arcmin
- Sensitivity: (10–50)× Planck

## ● Timeline

- Aug 2015: 1st flight (from Timmins, Ontario, Canada) [only 240  $\mu\text{m}$ ]
- 2016: 2nd flight (from Southern hemisphere)
- 2017: 3d flight (from TBD)

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# Instrument characteristics

	Frequency	Wavelength	Resolution
LOFAR	10 MHz – 250 MHz	30 m – 1.2 m	5'' – 0.2''
SKA	50 MHz – 14 GHz	6 m – 2.1 cm	0.4'' – 3 mas
Planck	30 GHz – 857 GHz	1 cm – 350 $\mu$ m	30' – 5'
PILOT	545 GHz & 1 250 GHz	550 $\mu$ m & 240 $\mu$ m	3.3' – 1.4'

# Magnetic field strength

- In neutral regions

- In atomic clouds :  $B \sim \text{a few } \mu\text{G}$
- In molecular clouds :  $B \sim (10 - 3\,000) \mu\text{G}$

- In ionized regions

- Near the Sun :  $B_{\text{reg}} \simeq 1.5 \mu\text{G}$  &  $B_{\text{fluct}} \sim 5 \mu\text{G}$

- In general ISM

- Near the Sun :  $B_{\text{ord}} \sim 3 \mu\text{G}$  &  $B_{\text{tot}} \sim 5 \mu\text{G}$
- Global spatial distribution :  $L_B \sim 12 \text{ kpc}$  &  $H_B \sim 4.5 \text{ kpc}$

# Magnetic field direction

- Near the Sun

- $\vec{B}_{\text{reg}}$  is horizontal & nearly azimuthal ( $p \simeq -7^\circ, -8^\circ$ )

- In the Galactic disk

- $\vec{B}_{\text{reg}}$  is horizontal & mostly azimuthal

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

- $\vec{B}_{\text{reg}}$  is symmetric in  $z$

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

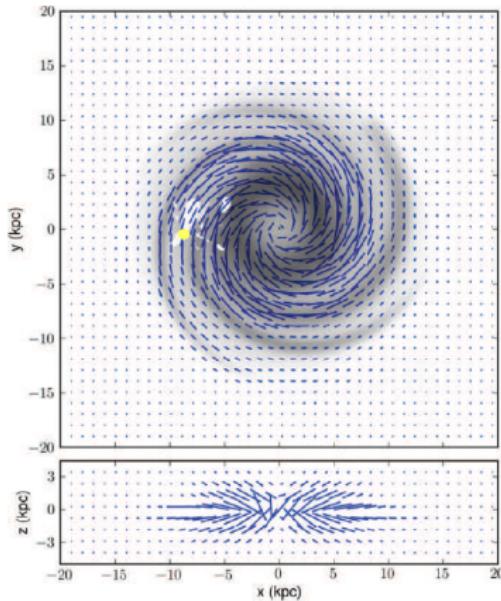
- In the Galactic halo

- $\vec{B}_{\text{reg}}$  has horizontal & vertical components

- $\vec{B}_{\text{reg}}$  is anti-symmetric in  $z$

# Magnetic field direction

Model of the large-scale magnetic field in the Galaxy



Jansson & Farrar (2012)