Cosmic magnetism

Katia FERRIÈRE

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

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Outline

1. Introduction

2. Present observational status
   - Radio observations
   - The Milky Way
   - External galaxies
   - Clusters of galaxies

3. Observations with LOFAR and SKA
   - LOFAR
   - SKA
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Cosmic magnetic fields play an important role in the structure, dynamics, energetics & evolution of most astrophysical objects.

The best probes of cosmic magnetic fields are radio waves.

Cosmic magnetism is key science for the new and upcoming large radio telescopes.

- Magnetism KSP
- Cosmic Magnetism SWG
Introduction
Present observational status
Observations with LOFAR and SKA

LOFAR Key Science Project

Cosmic magnetism in the nearby universe

- Management team
  Rainer Beck (PI), George Heald, Anna Scaife

- 32 full members
  Germany [14], Netherlands [11], United Kingdom [3], Poland [2], Italy [1], Sweden [1]

- 60 associated members
  Germany [25], United Kingdom [10], Netherlands [5], Poland [5], Sweden [4],
  Australia [2], France [2], Japan [2], Canada [1], India [1], Italy [1], Korea [1], USA [1]
The origin and evolution of cosmic magnetism

- 2 co-chairs
  Federica Govoni, Melanie Johnston-Hollitt

- 23 members
  Italy [4], Australia [3], Germany [3], Netherlands [3], Canada [2], USA [2], France [1], Japan [1], South Africa [1], United Kingdom [1], SKA [2]
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Present radio observations

- **Zeeman splitting**
  In neutral (molecular & atomic) regions
  \[ \rightarrow B_{||} \text{ (strength & sign)} \]

- **Faraday rotation**
  In ionized regions
  \[ \rightarrow B_{||} \text{ (strength & sign)} \]

- **Synchrotron emission**
  In general ISM
  \[ \rightarrow \vec{B}_{\perp} \text{ (strength & orientation)} \]

- **Faraday tomography**
  Combines synchrotron emission & Faraday rotation
Faraday rotation of point sources

\[ \Delta \theta = \text{RM} \, \lambda^2 \quad \text{where} \quad \text{RM} = C \int n_e \, B_{||} \, dl \]

⇒ \text{RM} \text{ probes } B_{||} \text{ in ionized regions}
The Milky Way

Diffuse synchrotron emission

\[ \mathcal{E} = f(\alpha) \, n_{\text{rel}} \, B_{\perp}^{\alpha+1} \, \nu^{-\alpha} \quad \& \quad \mathcal{E} \perp \mathbf{B}_{\perp} \]

\[ \Rightarrow \quad \text{- Total intensity probes } B_{\perp} \quad \text{(strength only)} \]
\[ \text{- Polarized intensity probes } (\mathbf{B}_{\text{ord}})_\perp \quad \text{(strength & orientation)} \]
**Faraday tomography**

- **Faraday rotation of background source**
  \[ \Delta \theta = RM \lambda^2 \]  
  with  
  \[ RM = C \int n_e B_{\parallel} \, dl \]  
  (rotation measure)

![Diagram showing ISM and source with Faraday rotation](image)

- **Faraday rotation of diffuse synchrotron emission**
  Synchrotron emission & Faraday rotation are *spatially mixed*
  \[ \tilde{P}(\lambda^2) = \int \tilde{P}(\Phi) \, e^{2i\Phi \lambda^2} \, d\Phi \]  
  with  
  \[ \Phi = C \int n_e B_{\parallel} \, dl \]  
  (Faraday depth)

  *Fourier transform* of polarized intensity:  
  \[ \tilde{P}(\lambda^2) \rightarrow \tilde{P}(\Phi) \]

![Diagram showing ISM and source with Fourier transform](image)

Credit: Marijke Haverkorn
Faraday tomography

Also known as rotation measure synthesis

(Burn 1966; Brentjens & de Bruyn 2005)

Figure Credit: Maik Wolleben
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Faraday rotation of point sources

\[ \Delta \theta = \text{RM} \lambda^2 \quad \text{where} \quad \text{RM} = C \int n_e B_\parallel dl \]

\[ \Rightarrow \text{RM} \quad \text{probes} \quad B_\parallel \quad \text{in ionized regions} \]

RM of pulsars & EGRSs with |b| < 8°

RM of EGRSs with \( \delta > -40° \)

Han (2009)

Taylor et al. (2009)
Faraday rotation of point sources

In ionized regions

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

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

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

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

  $\vec{B}_{\text{reg}}$ 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
**Diffuse synchrotron emission**

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

\[ \Rightarrow \quad \text{- Total intensity probes } B_{\perp} \quad (\text{strength only}) \]

\[ \quad \text{- Polarized intensity probes } (\vec{B}_{\text{ord}})_{\perp} \quad (\text{strength & orientation}) \]

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

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

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Figure Credit: **Tess Jaffe**
**Diffuse synchrotron emission**

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

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

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

PI at 23 GHz (WMAP)

Figure Credit: Tess Jaffe
In general ISM

- Near the Sun: $B_{\text{ord}} \sim 3 \, \mu G$ & $B_{\text{tot}} \sim 5 \, \mu G$
- In Molecular Ring: $B_{\text{tot}} \sim 7 \, \mu G$
- In Galactic disk: $\mathbf{B}_{\text{ord}}$ is horizontal
- In Galactic halo: $\mathbf{B}_{\text{ord}}$ has vertical component
- Global spatial distribution: $L_B \sim 12 \, \text{kpc}$ & $H_B \sim 4.5 \, \text{kpc}$
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Observations with LOFAR and SKA

- LOFAR
- SKA
Magnetic fields in external galaxies

- **Spiral galaxies**
  - All spirals have large-scale, regular / ordered $\vec{B}$
  - In disk: $B_{\text{ord}} \sim (1 - 5) \mu G$ & $B_{\text{tot}} \sim (5 - 20) \mu G$
    - In halo: $B_{\text{tot}} \lesssim 10 \mu G$
  - Edge-on spirals $\rightarrow$ In disk: $\vec{B}_{\text{ord}}$ is horizontal
    - In halo: $\vec{B}_{\text{ord}}$ is X-shaped
  - Face-on spirals $\rightarrow$ $\vec{B}_{\text{ord}}$ follows spiral arms

- **Elliptical galaxies**
  - No large-scale, regular / ordered $\vec{B}$
    - Only small-scale, fluctuating $\vec{B}$
  - $B_{\text{tot}} \sim$ a few $\mu G$
**Edge-on spiral galaxy: NGC 891**

- Total intensity contours
- $\vec{B}$ vectors
- at $\lambda$ 3.6 cm
  
  (100m Effelsberg)

- Optical image
  
  (CFHT)

© MPIfR Bonn (Krause 2009)
Face-on spiral galaxy: M 51

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

Optical image
(HST)

Fletcher et al. (2009)
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Magnetic fields in clusters of galaxies

- Clusters have an **intergalactic** magnetic field

- No large-scale, regular / ordered $\vec{B}$
  Only small-scale, fluctuating $\vec{B}$

- **Faraday rotation** $\leftarrow B \sim $ a few $\mu G$ & $\ell_{\text{cor}} \sim $ a few 10 kpc

- **Synchrotron emission** $\rightarrow B_{\text{tot}} \sim (0.1 - 1) \mu G$
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Low-frequency radio observations

- **Faraday rotation**
  \[ \Delta \theta = \text{RM} \lambda^2 \]
  with \( \text{RM} \propto \int n_e B_{||} \, dl \)
  \( \Rightarrow \) Can probe small RMs \( \rightarrow \) regions with low \( n_e \) and weak \( B \)

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

- **Faraday tomography**
  - *High-resolution* Faraday-depth spectra
  - Strong *Faraday depolarization* (differential Faraday rotation & internal Faraday dispersion)
Low-frequency radio observations

Low frequencies are ideal to study magnetic fields in
- galactic outer disks & halos
- tails of interacting or stripped galaxies
- intergalactic medium
Galactic pulsars
- Strong polarized fluxes $\rightarrow$ good polarization calibrators
- $B_\parallel \propto \frac{\text{RM/DM}}{} \rightarrow$ excellent accuracy on $B_\parallel$
- Expect $\gtrsim 1000$ new pulsars

Extragalactic point sources
- Expect $\approx 7 \times 10^6$ new sources at 200 MHz
- Most sources will be strongly Faraday depolarized
- Altogether, expect few new polarized sources
All-sky images in the 4 Stokes parameters

- Single core station (Effelsberg – 3 August, 2012)
- Single channel at 32 MHz, 200 kHz bandwidth
- 1.3 sec integration time, 11° resolution

Figure Credit: Rainer Beck (from Jana Köhler & James Anderson)
Faraday tomography of the Fan region

- LOFAR HBA
- Stokes U at 4 different Faraday depths

$\Phi = -1 \text{ rad m}^{-2}$
$\Phi = -2 \text{ rad m}^{-2}$
$\Phi = -3 \text{ rad m}^{-2}$
$\Phi = -5 \text{ rad m}^{-2}$

Iacobelli et al. (2013)
Nearby galaxies

16 nearby galaxies have already been observed

- M 33 (HBA & LBA, Cycle 0 DDT)
- M 51 (HBA, commissioning & Cycle 0)
- M 81, M 82 (HBA & LBA, Cycle 0)
- M 101 (HBA, Cycle 0)
- NGC 628 (HBA, Cycle 1)
- NGC 891 (HBA, commissioning)
- NGC 3079 (HBA, Cycle 0)
- NGC 3432 (HBA, Cycle 1)
- NGC 3627, NGC 3628 (HBA, Cycle 0)
- NGC 4631 (HBA, commissioning & Cycle 0)
- NGC 6946 (HBA, Cycle 0)
- IC 10 (HBA & LBA, Cycle 0)
- IC 342 (HBA & LBA, Cycle 0)
- Stefan’s Quintet (HBA, Cycle 0)

Credit: Rainer Beck (Cosmic Magnetism SKA 1 Assessment Workshop, January 2014)
Nearby galaxy M51

- **Total intensity image**
  - LOFAR HBA
  - 170 subbands in [120,180] MHz, 36 MHz total bandwidth
  - 6 h observation time, 20″ resolution

Figure Credit: *David Mulcahy*
Nearby galaxy M 51

- **Polarization image**
  - Diffuse polarized emission from Galactic foreground, not from M 51
  - Diffuse emission from M 51 is strongly *Faraday depolarized*
  - Only 4 resolved background polarized sources (not enough for RM grid)

- **Faraday tomography**
  - Strongest component in Faraday spectra due to instrumental polarization
  - One component due to Galactic foreground (Faraday screen)
  - One component internal to M 51
  - Several unresolved background polarized sources

*Credit: Rainer Beck (Cosmic Magnetism SKA 1 Assessment Workshop, January 2014)*
Nearby galaxies in the LOFAR HBA MSSS

MSSS = Multifrequency Snapshot Sky Survey  (George Heald et al.)

Figure Credit: Rainer Beck (from Chris Chyży & MSSS Team)
Galaxies in the Virgo Cluster

LOFAR HBA

Figure Credit: Rainer Beck (from de Gasperin et al., in prep.)
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Observations with SKA 1

- **Key SKA 1 observations**
  - Polarization all-sky survey at $\sim 1$ GHz
  - Polarization deep field at $\sim 1$ GHz
  - Deep targeted polarization observations of specific objects at lower and higher frequencies

- **Key science drivers**
  - Cosmic evolution of magnetic fields in galaxies and clusters
  - Detailed structure of magnetic fields in galaxies and clusters
  - Properties of magnetic fields in AGNs
    - Relation between supermassive black holes and their environment
  - Detection of magnetic fields in the Cosmic Web
    - Properties and relation to the large-scale structure

Credit: Federica Govoni (Cosmic Magnetism SKA 1 Assessment Workshop, January 2014)
Rotation measure grid

- High sensitivity, high resolution, whole sky coverage
  → All-sky, closely-spaced grid of RMs

- Observations at $\gtrsim 1$ GHz to reduce Faraday depolarization

- Expect $\approx 20\,000$ RMs of Galactic pulsars [$\approx 6 \text{ deg}^{-2}$ in GD], i.e., all Galactic pulsars beaming towards us  
  (Smits et al. 2009)

- Expect $\approx (1 - 4) \times 10^7$ RMs of background polarized sources
  [$\approx (300 - 1\,000) \text{ deg}^{-2}$] with SKA 1  
  (Larry Rudnick, SKA1 Assessment Workshop)

☞ Powerful tool to study cosmic magnetic fields at all redshifts
The Milky Way

- **Pulsar RMs** + distance estimates (from parallax or DMs)
  - 3D structure of large-scale \( \gtrsim 100 \text{ pc} \) magnetic field in GD
    - number & location of field reversals
    - magnetic spiral vs optical spiral

- **RM grid of extragalactic point sources**
  - structure of large-scale magnetic field in GH & outer GD
  - magnetic fields in SNRs & H\text{II} regions
  - power spectrum of magneto-ionic turbulence (down to \( \lesssim 1' \))

- **Faraday tomography**
  - high-resolution 3D map of local \( \lesssim 5 \text{ kpc} \) magnetic field
  - small-scale \( \gtrsim 0.1 \text{ pc} \) magnetic features
  - properties of magneto-ionic turbulence
External galaxies

**Low-z galaxies**

- Deep RM grid of background compact sources
- Mapping of diffuse (total + polarized) synchrotron emission
  + Faraday tomography (in the nearest galaxies)

- Nearest galaxies (LMC, SMC, M31)
  \[ \sim 10^5 \text{ RMs} \text{ (deep obs.)} + \text{Faraday tomography} \]
  \[ \rightarrow \text{ very detailed 3D map of magnetic field structure} \]

- Galaxies out to \( \sim 10 \text{ Mpc} \) (\( \sim 100 \) galaxies)
  \[ \geq 100 \text{ RMs} + \text{synchrotron mapping} \]
  \[ \rightarrow \text{3D reconstruction of large-scale magnetic field structure} \]

- Galaxies out to \( \sim 100 \text{ Mpc} \) (\( \sim 60,000 \) galaxies)
  \[ \geq 10 \text{ RMs} \]
  \[ \rightarrow \text{recognition of simple magnetic patterns (ASS, BSS...)} \]
External galaxies

- **Galaxies at** \( z \gtrsim 0.1 \)

  - Detailed study of individual galaxies
    - Too small (\( \lesssim 1' \)) for RM grid of background *compact* sources
    - RMs of background *extended* sources
      → maps of magnetic field structure
      → temporal evolution of galactic magnetic fields

- **RM statistics of (unresolved) Ly\( \alpha \) absorbers**
  → trends of \( \text{RM}_{\text{source}} \text{ vs } z \) & \( \text{RM}_{\text{Ly}\alpha} \text{ vs } z \) separately
  → evolution of magnetic fields in galaxies & protogalaxies
Clusters of galaxies

- **RM grid** of background compact sources
  - ($\sim 1000$ RM behind a typical nearby cluster)
  - $+ \text{RM toward embedded sources}$
  - $\rightarrow \pm$ detailed map of magnetic field structure

- Detection/mapping of diffuse **synchrotron emission** (deep obs.)
  - $\rightarrow$ estimates of magnetic field strength
    - map of magnetic field structure
    - global radial dependence of $B$