Magnetic fields in nearby galaxies:

Prospects with future radio telescopes

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Magnetic fields are widely accepted now as important in most astrophysical processes.

Key Science Projects on *Cosmic Magnetism* for LOFAR and SKA
Fundamental questions

• **Structure**
  What is the magnetic power spectrum at small and large scales?

• **Dynamics**
  Do magnetic fields affect gas flows and galaxy evolution?

• **Connection**
  Are galaxies magnetically connected to intergalactic space?

• **Origin**
  When and how were the first magnetic fields generated?

• **Evolution**
  How and how fast were galactic magnetic field amplified?
  (Important for the interpretation of the radio-IR correlation!)
Magnetic field generation and amplification

- **Field seeding**
  Primordial, Weibel instability, ejection by supernovae, stellar winds or jets

- **Field amplification**
  MRI, compressing / shearing flows, turbulent flows, small-scale dynamo

- **Coherent field ordering**
  Mean-field dynamo
Classical mean-field dynamo

- Ionized gas + differential rotation
  + helical turbulence + magnetic diffusion
- Microphysics approximated by the average parameters “alpha-effect” and diffusivity
- → Dynamo equation for the large-scale field
- Generation of large-scale modes
- Field evolution: see talk by Tigran Arshakian
Azimuthal dynamo modes

Dynamo Mode 0 (Axisymmetric Spiral)

Dynamo Mode 1 (Bisymmetric Spiral)

Dynamo Mode 2 (Quadrisymmetric Spiral)

Dynamo Modes 0 + 2
Antisymmetric (dipolar) dynamo mode
Need for realistic models

- **MHD models**: Back-reaction of the field onto turbulence and gas flow
- **Global dynamo models** of galaxies including rotation and gas flows (e.g. spiral arms, bar and galactic outflow)
- **Dynamo action** emerges automatically
- Include **galaxy evolution**
Limitation no 1:

Global 3-D MHD models are limited by huge computing time on present-day computers
Observational tools

- Total and polarized synchrotron emission
- Faraday rotation
- Faraday depolarization
- Zeeman effect
NGC 6946
VLA+Effelsberg 6cm
Total intensity
(Beck 2007)

Typical radio synchrotron disk
Structure analysis:
Wavelet spectra for NGC 6946
- using 2-D isotropic wavelet functions

Three different slopes:
Turbulence – spiral arms – extended disk

Advantages compared to power spectra:

• Wavelet function can be adapted to structures of interest

• Positional information is preserved
Equipartition magnetic field strengths in spiral galaxies

Total field in spiral arms: 20 - 30 $\mu$G
Regular field in interarm regions: 5 - 15 $\mu$G
Total field in circum-nuclear rings: 40 - 100 $\mu$G
Zeeman effect in a distant galaxy

Zeeman effect in the HI absorption line of an intervening galaxy at $z=0.692$ against a bright quasar:

$B_\parallel \approx 84 \, \mu G$

(Wolfe et al. 2008)
Energy densities

Turbulence (cold clouds):
\[ V_{\text{turb}} = 7 \text{ km/s} \]

Ionized gas:
\[ T = 10^4 \text{ K}, f_v = 0.05, h = 1 \text{ kpc} \]

Beck 2007
Limitation no 2:

Understanding the dynamical effects of magnetic fields in galaxies is limited by the insufficient resolution of present-day radio telescopes.
Typical scale lengths in disks of spiral galaxies

- Cold & warm gas: \( \approx 4 \text{ kpc} \)
- Synchrotron: \( \approx 4 \text{ kpc} \)
- Cosmic-ray electrons: \( \leq 8 \text{ kpc} \)
  (upper limit due to energy losses)
- Total magnetic field: \( \geq 16 \text{ kpc} \)
NGC 253
6cm VLA+Effelsberg
Total intensity
+ B-vectors
(Heesen et al. 2009)

Exponential radio halo
Extent is limited by energy losses of the cosmic-ray electrons
NGC 4569
6cm Effelsberg
Polarized intensity
+ B-vectors
(Chyzy et al. 2006)

Past interactions are best visible in the magnetic field!
Limitation no 3:

The observable extent of magnetic fields in galaxies is limited by energy losses of the cosmic-ray electrons.
M 51
6cm VLA+Effelsberg
Total intensity
+ B-vectors
(Fletcher et al. 2009)

Polarization vectors:

Spiral fields
more or less
parallel to the
optical spiral arms
M 51
6cm
VLA+Effelsberg
Total intensity
+ B-vectors
(Fletcher et al. 2009)

Spiral fields parallel to the inner spiral arms:
Density-wave compression
M 51
6cm
VLA+Effelsberg
Total intensity
+ B-vectors
(Fletcher et al. 2009)

Spiral fields between the outer spiral arms (weak density waves):

Dynamo action? Shear?
Spiral fields: coherent or incoherent?

- Fletcher 2004
  - Regular field (coherent)
  - Anisotropic field (incoherent)

Polarization: strong
Faraday rotation: high

- Regular field:
  - Strong polarization
  - High Faraday rotation
- Anisotropic field:
  - Strong polarization
  - Low Faraday rotation
M51
VLA+Effelsberg
RM 3/6cm
(Fletcher et al. 2009)

Complicated & noisy
RM pattern:

Two weak
dynamo modes
(m=0+2),
plus strong
anisotropic fields
Limitation no 4:

The distinction between regular and anisotropic fields is limited by the low signal-to-noise and the low resolution of present-day polarization observations.
High S/N:
RM s from background sources

**LMC**
RM 18-20cm ATCA
(Gaensler et al. 2005)

Axisymmetric
dynamo field?
Limitation no 5:

Detection of large-scale field structures is limited by the small number density of polarized background sources.
Four-frequency analysis in M51

Field reversal between northern disk to inner halo – similar to that found for the Milky Way (Sun et al. 2008)

Fletcher et al. 2009

Broadband RM 3/6cm
Disk: ASS (m=0) + m=2 modes

Broadband RM 18/20cm
Upper layer: BSS (m=1) mode
Limitation no 6:

Field patterns in the disk and the halo are hard to distinguish by broadband polarimetry

(but see next talk by George Heald)
Radio halos:
Edge-on galaxies
NGC 891
3cm Effelsberg
Total intensity
+ B-vectors
(Krause 2007)

Bright radio halo with vertical field components:

Driven by a disk wind?
NGC 4631
Effelsberg 3.6cm
Total intensity
+ B-vectors
(Krause & Dumke)

Huge halo:
X-shaped field, *not* consistent
with standard
dynamo modes

Noisy RM pattern
Limitation no 7:

Present-day radio telescopes do not allow to resolve the structure of radio halos
Pulsar RM\(s\) in the Milky Way: Many reversals?

Han et al. 2001
Limitation no 8:

Detection of large-scale field structures in the Milky Way is limited by the small number of pulsar RMs.
Polarization in the Milky Way

Canadian Galactic Plane Survey (CGPS)
(21cm, DRAO+Effelsberg)

Landecker, Kothes, Reich, et al.

Magnetic filaments or Faraday screens?
Limitation no 9:

*Observation of the small-scale field structure in the Milky Way is limited by Faraday depolarization*
Breaking the limits

- **Higher resolution** (resolving gas-field interaction, resolving dynamo modes, less depolarization)
- **Larger sensitivity** ($A_{\text{eff}}/T_{\text{sys}}$) (high S/N at high resolution, more polarized background sources, more pulsars, more Zeeman sources)
- **Low frequencies** (extended halos, interactions, IGM fields, detection of very low RMs)
- **Spectro-polarimetry** (resolve RM structures along the line-of-sight, reduce Faraday depolarization)
- **Global 3-D MHD models** (understand dynamo action)
Polarization Pathfinders

- GALFACTS (Arecibo, 2008)
- LOFAR → (Europe, 2009)
- ATA (Hat Creek, 2008)
- SKAMP → (Bungendore, 2009)
- EVLA (New Mexico, 2012)
- ASKAP → ( Boolardy, 2012)
- MeerKAT (Karoo, 2012)
- APERTIF → (Westerbork, 2012)
The future I:

Low-frequency radio emission will allow to observe weak magnetic fields
LOw Frequency ARray

30-80 MHz
110-240 MHz

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Low-frequency radio observations

- Frequency of synchrotron emission: $\nu \sim E^2 B$
  → low frequencies trace cosmic-ray electrons in weak magnetic fields

- Lifetime of electrons due to synchrotron loss:
  $t \sim \nu^{-0.5} B^{-1.5}$
  → low frequencies trace old cosmic-ray electrons

- Faraday rotation: $\Delta \psi \sim \nu^{-2} \text{RM}$
  → low frequencies allow to measure small rotation measures
Faraday rotation errors

Detection of low RM needs:

- high signal-to-noise in polarization ($S_p/\sigma_p$) and/or
- wide frequency span ($\Delta \lambda^2$):

$$\Delta RM \approx \sqrt{3} \left( \frac{S_p}{\sigma_p} \Delta \lambda^2 \right)^{-1}$$

Increasing $\Delta \lambda^2$ is less expensive than increasing $S_p/\sigma_p$!
Polarization surveys with LOFAR

Plans:

- **All-sky shallow surveys at 30, 60, 120, 200 MHz:**
  Search for polarized sources, determine RMs

- **Deeper survey of \( \approx 60 \) nearby galaxies:** RM grid

- **Very deep survey of \( \approx 20 \) nearby galaxies:**
  Diffuse pol + RM maps, RM grid

Issues:

- Instrumental & ionospheric calibration

- Accuracy of Galactic foreground subtraction

- Intrinsic depolarization within background sources:
  Background source density may be low
The future II:

Recognition of large-scale field structures via RM grids
Faraday rotation grids at ≈1.4 GHz with SKA pathfinders

- **ATA:** $A/T \approx 25$, $\Delta \nu \approx 0.2$ GHz,
  $\sigma \approx 20$ $\mu$Jy/beam at 1.4 GHz in 12h
  $\rightarrow \approx 30$ sources per deg$^2$

- **ASKAP, APERTIF:** $A/T \approx 80$, $\Delta \nu \approx 0.3$ GHz,
  $\sigma \approx 10$ $\mu$Jy/beam at 1.4 GHz in 12h
  $\rightarrow \approx 50$ sources per deg$^2$

- **MeerKAT:** $A/T \approx 200$, $\Delta \nu \approx 0.5$ GHz,
  $\sigma \approx 2$ $\mu$Jy/beam at 1.4 GHz in 12h
  $\rightarrow \approx 200$ sources per deg$^2$

- **EVLA:** $A/T \approx 400$, $\Delta \nu \approx 1$ GHz,
  $\sigma \approx 1$ $\mu$Jy/beam at 1.4 GHz in 12h
  $\rightarrow \approx 400$ sources per deg$^2$
POSSUM: Polarisation Survey of the Universe’s Magnetism

- POSSUM wide (all sky): ≈ 50 sources per deg$^2$
  - can recognize large-scale fields in LMC+SMC
- POSSUM deep (one field): ≈ 400 sources per deg$^2$
  - can measure integrated pol from distant galaxies

(see talk by Jeroen Stil)

BROLGA: Broadband Radio Observations of Local Groups with ASKAP

(including RM grids)
(see talk by Tobias Westmeier)
Faraday rotation through spiral galaxies

Recognition of large-scale field structures needs $\geq 10$ RMss from background sources

Bisymmetric regular field

Turbulent field

Sum

Stepanov et al. 2008
The future III:

Resolving magnetic field details with the SKA
SKA core station
Faraday rotation grids with the SKA

- A/T ≈ 2000, Δν ≈ 0.5 GHz
- σ ≈ 20 nJy/beam at 1.4 GHz in 12h
- → ≈ 5000 sources per deg²
SKA RM survey
(simulation by Bryan Gaensler)

≈10000 polarized sources shining through M31
Deep RM grids with the SKA

Recognition of simple field patterns:
- Can be applied to galaxies out to ≈ 100 Mpc distance
  (≈ 60000 galaxies)

3-D reconstruction of field patterns:
- Can be applied to galaxies out to ≈ 10 Mpc distance
  (≈ 50 galaxies)

Stepanov et al. 2008
Future rotation measures of pulsars in the Milky Way

Known pulsars and pulsars to be detected with the SKA

Cordes 2001
Resolving diffuse emission with the SKA

- Intensity of diffuse emission scales as \((\text{beamsize})^2\)
- Observation time scales as \((\text{S/N})^2 \times (\text{beamsize})^{-4}\)

\[\rightarrow\] Resolving diffuse polarized emission requires very high sensitivity and hence the SKA

- Note: Short antenna spacings needed to detect the largest scales
Summary: Future observations

**Diffuse radio polarization:**
- Polarization survey of **distant galaxies**: Effelsberg, GALFACTS, ASKAP, APERTIF
- Magnetic fields in outer disks and halos, intergalactic fields: LOFAR
- Detailed magnetic field structure in nearby galaxies: EVLA, SKA

**RM grids of background sources:**
- Field patterns in nearby galaxies & Milky Way: EVLA, ASKAP, APERTIF
- Field patterns in distant galaxies: EVLA, MeerKAT, SKA
- Evolution of galactic magnetic fields: SKA

**Pulsar RMs:**
- Detailed structure of the **Milky Way’s field**: ASKAP, APERTIF, SKA