Structure, dynamical impact and origin of magnetic fields in nearby galaxies

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and

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Fundamental questions on magnetic fields in galaxies

Structure

• How are magnetic fields related to gas and star formation regions?

Dynamics

• What are the effects on gas flows and cosmic-ray propagation?
• What was the role of magnetic fields for galaxy evolution?

Origin

• How are magnetic fields generated, amplified and ordered?
• Are small-scale fields generated by tangling or by turbulence?
SKA:

High spatial resolution

+ high sensitivity for extended emission

+ excellent polarization performance
Structure:

How are magnetic fields related to gas and star formation regions?
The radio-infrared correlation in M 51

Radio: VLA + Effelsberg 6 cm
IR: Spitzer 8 μm

- Magnetic fields amplified in star-forming regions?
- Magnetic fields coupled to gas clouds?
Synchrotron-IR correlations in NGC 6946

- Correlation between the turbulent field and the star-formation rate SFR ($B_{\text{turb}} \sim \Sigma_{\text{SFR}}^{0.16}$)

- The ordered field is **not** correlated with the SFR
M51: Radio continuum
(VLA 20 cm, 1.4" resolution)

Molecular gas (CO(1-0))
(IRAM PdBI+30m, 1" resolution)

Schinnerer et al. 2013

- Excellent radio-CO correlation on small scales (≈60 pc)
  → Coupling between magnetic fields and gas clouds?
  Or secondary CREs from molecular clouds?

- **Aim: High resolution mapping with SKA and ALMA**
Synchrotron polarization:

Ordered magnetic fields
M 31: The nearest external spiral galaxy
Polarized intensity Effelsberg 3.6 cm

Resolution 90"
(≈300 pc):

- Highly ordered field in the gas "ring"
- Spiral field in the central region

Gießübel, PhD 2012
M 31: The nearest external spiral galaxy
Brighest segment of the northern spiral arm
Polarized intensity VLA 6 cm

Resolution 25"
(≈100 pc):
- Parker loops ?
- Helical field ?
Ordered magnetic fields and molecular gas

Polarized intensity (Effelsberg+VLA 6 cm) and BIMA CO data (Regan et al. 2001)

Two types of ordered fields:
- Density-wave compression (fast MHD wave ?)
- "Magnetic arm" between gas arms
NGC 6946: The mystery of the "magnetic arms"

Total and polarized synchrotron intensity
VLA+Effelsberg 6 cm

Beck & Hoernes 1996
Magnetic arms in NGC 6946: Ordered fields concentrated in interarm regions

Beck 2007
Two types of ordered fields:

- Density-wave compression
- Magnetic arm
M 83: The nearest galaxy with a large bar
Polarized intensity VLA+Effelsberg 6 cm

Three types of ordered fields:

- Bar compression
- Magnetic arm
- Along outer spiral arms

Frick et al. 2014
IC 342: The nearest spiral galaxy after M31 and M33

Polarized intensity Effelsberg 6 cm

Large-scale ordered field:

almost perfectly spiral

→ dynamo-generated?
Three types of ordered fields:

- Spiral arm compression
- Magnetic arm
- Along outer HI spiral arms (MHD wave?)
Proposed origins of "magnetic arms"

1) Reduced turbulence in interarm regions

2) Shearing gas flow

3) Magnetic reconnection (Zimmer, Lesch & Birk 1997)

4) Slow MHD wave (Lou & Fan 1998)

5) Spiral arm forcing (Kotarba et al. 2009)

6) m=2 mode of the mean-field dynamo (Rohde et al. 1999)

7) Coupling between density wave and dynamo wave (Chamandy et al. 2012, 2013)

8) Injection of small-scale fields in spiral arms (Moss et al. 2013)
Spiral arm forcing
SPH model + induction equation

- Field mostly follows the gas
- **No** magnetic arms
- Frequent field reversals

Magnetic field vectors + gas density (colour)
Are ordered fields *regular* or *anisotropic*?

**Regular field**
- Polarization: strong
- Faraday rotation: strong

**Anisotropic field**
- Polarization: strong
- Faraday rotation: weak

Fletcher 2004
The fields in the magnetic arms are **regular** and directed inwards

→ dynamo-generated?
There is no satisfying explanation yet for the generation of magnetic arms

- Develop better models
- *High-resolution SKA data needed*
Dynamical impact:

Interaction of magnetic fields

with gas and cosmic rays
Can magnetic fields affect galactic rotation?

- Magnetic forces may explain the rising part of the rotation curve
- Crucial: measure **radial profiles** of the regular+turbulent magnetic fields
Can magnetic fields affect galaxy evolution and the formation of spiral arms?
Spiral arms
(3D MHD simulations)

Spiral arms are smoother for stronger magnetic fields

\( \beta = 10^6 \)  
\( \beta = 10 \)  
\( \beta = 1 \)  
\( \beta = 0.1 \)

Dobbs & Price 2008
MHD model of evolving spiral galaxies

The magnetic field may affect galaxy evolution:

- Spiral structure is more patchy after 2 Gyr
- Star-formation rate is $\approx 30\%$ lower
- Strong vertical outflows
NGC 1097: The largest bar on sky
Total and polarized intensity VLA 6 cm

Strong ordered field in front of the bar:

Affecting the gas flow?
NGC 1097: Circumnuclear ring
Total and polarized intensity VLA 3.6 cm

Strong field in the circumnuclear ring
\( \approx 50 \, \mu G \)
Magnetic fields can drive accretion

(1) Magnetic stress (Balbus & Hawley 1998, Beck et al. 1999, 2005):

\[ \frac{dM}{dt} = -\frac{h}{\Omega} \left( < B_{\text{tot},r} B_{\text{tot},\phi} > + < B_{\text{reg},r} B_{\text{reg},\phi} > \right) \]

NGC 1097:

h=100 pc, v=450 km/s, \( B_{\text{tot},r} \approx B_{\text{tot},\phi} \approx 50 \mu \text{G} \), \( B_{\text{reg},r} \approx B_{\text{reg},\phi} \approx 10 \mu \text{G} \):

\[ \frac{dM}{dt} \approx 1 \, M_\odot/\text{yr} \]

(2) Angular momentum transport by fast MHD waves (Lou et al. 2001):

\[ \frac{dM}{dt} < 10 \, M_\odot/\text{yr} \]
NGC 4631: The largest radio halo
Total and polarized intensity VLA+Effelsberg 6 cm

X-shaped pattern of the ordered field in the halo

Mora & Krause 2013
NGC 4631: the largest radio halo
Total intensity JVLA 5-7 GHz C+D array (project CHANGES)

Resolution 2.7", rms noise 5.5 μJy/beam

- Magnetic spurs
- But no polarization detectable at this resolution

Mora, PhD 2014
NGC 253: The nearest starburst galaxy

- Radio filaments mark the boundaries of the outflow cone
- **Outflow bulk velocity** of the cosmic-ray electrons: $\geq 300$ km/s
- Faraday rotation indicates a helical field in the outflow cone
Radio-bright dwarf galaxy: NGC 1569

Bomans, priv. comm.

Kepley et al. 2010

Magnetic spurs indicate strong outflows
LMC: The nearest external galaxy
Polarized intensity ATCA+Parkes 6 cm

Resolution 3' (≈44 pc): Filamentary structure

Faraday rotation of background sources: large-scale regular field! (dynamo-generated?)
Some basics: Synchrotron intensity

\[ I_{\text{syn}} \approx \langle N_{\text{CRE}} B_\perp^{1+\alpha} \rangle \approx \langle N_{\text{CRE}} B_\perp^2 \rangle \]

(A) Energy equipartition between total cosmic rays and magnetic fields (Stepanov et al. 2014):

\[ I_{\text{syn}} \sim \langle B_\perp^4 \rangle \sim \langle B_\perp \rangle^4 (1+(8/3)a^2+(8/9)a^4) \]

(B) Constant density of cosmic-ray electrons (CREs):

\[ I_{\text{syn}} \sim \langle B_\perp^2 \rangle \sim \langle B_\perp \rangle^2 (1+a^2) \]

Fluctuations in \( B_\perp \):

\[ a = \frac{\langle \delta B_\perp^2 \rangle^{0.5}}{B_\perp} \]

We need to map the fluctuating field!
Origin:

Seeding – Amplifying - Ordering
Seeding

$z \approx 40-20$: Formation of protogalactic halos

- Generation of seed magnetic fields by:
  - Biermann battery
  - Weibel instability (Medvedev et al. 2004)
  - Plasma fluctuations (Schlickeiser 2012)

- Amplitude: $\approx 10^{-18} \text{ G} ... 10^{-6} \text{ G}$ (locally)

- Primordial fields useful, but not needed
Amplifying

\[ z \approx 20-10: \text{ Merging of protogalactic halos and virialization} \]

- Amplification of seed fields by turbulent gas flows, driven by accretion shocks and SN explosions (small-scale dynamo)
- Timescale of amplification: \( \approx 3 \times 10^8 \) Gyr
- Amplitude: \( \approx 10^{-5} \) G (equipartition with kinetic energy)
$z \approx 10^{-2}$: Formation of galactic disks

- No further amplification needed
- Field ordering (anisotropic fields) by shear or MHD waves
- Field ordering (regular fields) by the mean-field (large-scale) dynamo, interacting with MHD waves
- Timescale of ordering: several rotation periods ($\approx 10^9$ Gyr)
Large-scale dynamo in the disk + turbulent dynamo in the spiral arms

- Large-scale regular field with reversals (like in the Milky Way)
- Increase of turbulent fields in spiral arms

Moss et al. 2013
Power spectrum of dynamo-generated magnetic fields

- Power law at small scales
- Peaks in the spectrum due to large-scale fields

R. Stepanov, priv. comm. (model from Moss et al. 2013)
Small-scale dynamo action

- Small-scale dynamo action can supply turbulent seed fields (e.g. in protogalaxies)

- However: There is no conclusive evidence for turbulent field amplification on the solar surface (Stenflo 2012)

- Small-scale solar fields are probably generated from large-scale fields by tangling

- There are two types of small-scale fields: turbulent and tangled
How to distinguish the two types of small-scale fields by observations?

Turbulent fields:
- Power-law turbulence spectrum (Kolmogorov)
- Related to star-forming activity
- Low volume filling factor
- Large fluctuations in synchrotron emission

Tangled fields:
- Power spectrum not known
- Related to regular fields
- High volume filling factor
- Moderate fluctuations in synchrotron emission
Proposed SKA1 project

High spatial resolution with high S/N:
- Restrict to a sample of ≈30 nearby galaxies
- Resolve ≈1 pc in the LMC/SMC, ≈20 pc in M33 and ≈100 pc in M83 and NGC253
- Detect field strengths of ≥10-15 μG
  \( \rightarrow \text{Angular resolution of } \approx 5'' \text{ (} \approx 1'' \text{ for SKA2)} \)

Measure intrinsic structure and angles of strong ISM magnetic fields with high precision:
- Small Faraday rotation
- Small Faraday depolarization
  \( \rightarrow \text{Frequency } > 3 \text{ GHz} \)
Proposed SKA1 project

SKA-MID Band 4 (2.8–5.18 GHz):

- $|\text{RM}| = 50–200 \text{ rad/m}^2$: <60° at 4 GHz
- Intrinsic $|\text{RM}| \leq 500 \text{ rad/m}^2$ can be measured
- Faraday resolution $\approx 430 \text{ rad/m}^2$ (sufficient to detect field reversals)

Synergy with SKA-MID Band 2 (0.95–1.76 GHz):

- Measure RMs with higher precision
- Measure Faraday spectra (RM Synthesis)
- Kinematic data from HI