Magnetic Fields in Evolving Spiral Galaxies and their Observation with the SKA

Rainer Beck

MPIfR Bonn & SKA Science Working Group
Fundamental magnetic questions

- When and how were the first fields generated?
- Did significant fields exist before galaxies formed?
- How and how fast were fields amplified in galaxies and galaxy clusters?
- How did fields affect the evolution of galaxies and galaxy clusters?
- Is intergalactic space magnetic?
Observing Cosmic Magnetism with the SKA

(selected as a Key Science Project in 2003)
### SKA Magnetism Science Team

#### Members from German institutes:
- **Annalisa Bonafede, Univ. Hamburg**
- **Dominic Schnitzeler, MPIfR**
- **Rainer Beck, MPIfR**
- **Ann Mao, Madison/MPIfR**

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1. Magnetic fields in the Milky Way and nearby galaxies:
   • Role of gas flows, shocks turbulence, dynamo action for field amplification and ordering
   • Dynamical effects of magnetic fields in galaxy formation, disk stability, triggering of star formation, cosmic-ray acceleration and propagation, inflows / outflows
   • Magnetic fields in gas clouds (Zeeman splitting)

2. Magnetic fields in distant galaxies:
   • Amplification by starbursts and interactions
   • First appearance of ordered fields
3. Magnetic fields in galaxy clusters:

- Turbulent fields in cluster halos
- Field compression in cluster relics
- Field compression in interacting galaxies

4. Magnetic fields in intergalactic filaments:

- Tracing intergalactic shocks
- Role in structure formation

5. Magnetic fields in AGNs and jets
SKA Magnetism Science Team: Priorities for SKA1 (draft)

- All-sky survey of polarized sources and their Faraday rotation measures (RM)
  - SKA1-Survey
  - 650-1670 MHz (PAF Band 2)

- Deep survey of polarized sources and RMs in selected fields
  - SKA1-Mid
  - 950-1760 MHz (Band 2)

- Deep search for polarized emission of intergalactic filaments, galaxy groups and interacting galaxies
  - SKA-Mid
  - 350-1050 MHz (Band 2)

- High-resolution imaging of galaxies, galaxy clusters and AGNs
  - SKA-Mid
  - 4.6-13.8 GHz (Band 5)
Present-epoch galaxies: Strengths of total and ordered fields
(compilation by Fletcher 2010)

Magnetic fields in nearby galaxies are strong and dynamically important.

Average: \(16 \pm 15 \mu G\)
Excl. starburst: \(12 \pm 6 \mu G\)

Average: \(4 \pm 3 \mu G\)
Nearby galaxy NGC 6946: Total and polarized synchrotron emission (VLA+Effelsberg 5 GHz)

- The turbulent field is related to star formation
- The ordered field is related to spiral arms
Virgo polarization survey (VLA 5 GHz)

Field compression by interaction

Vollmer et al. 2007, 2013
Milky Way-type galaxy
NGC 891
(Effelsberg 8 GHz)

X-shaped magnetic field
in the halo:
Signature of outflows

Krause 2007
The Milky Way is similar to external galaxies – except for two field reversals.

**Figure 9.** Milky Way as seen (in polarization) by an extragalactic observer, face-on (above) and edge-on (below). Plotted “bars” (sometimes referred to as “vectors”) are the would-be-observed polarization angles, rotated 90° to line up with the magnetic field orientation. Lengths of bars are proportional to polarization intensity. Faraday depolarization and beam depolarization are neglected. The face-on plot is overlaid on the NE2001 thermal electron distribution.
Generation and amplification of cosmic magnetic fields

Stage 1: Field seeding

Stage 2: Field amplification

Stage 3: Field ordering
Primordial seed fields in the Epoch of Reionization

Brightness temperature

Strong impact on predicted HI spectra

Schleicher et al. 2009

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<th>Model</th>
<th>$B_0$ [nG]</th>
<th>$f_*$</th>
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<tr>
<td>1</td>
<td>0</td>
<td>0.1%</td>
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<tr>
<td>2</td>
<td>0.02</td>
<td>0.1%</td>
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<tr>
<td>3</td>
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<td>4</td>
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<tr>
<td>5</td>
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</tr>
<tr>
<td>6</td>
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<tr>
<td>7</td>
<td>0.8</td>
<td>1%</td>
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Evolution of magnetic fields (1)

**Phase 1** ($z \approx 40-20$): Formation of halos

- Generation of seed magnetic fields by the Biermann battery or the Weibel instability or plasma fluctuations
- Amplitude: $\approx 10^{-18} \text{ G} - 10^{-6} \text{ G}$ (locally)

Medvedev et al. 2004
Phase 2 (z ≈ 20-10): Merging of halos and virialization:

- Amplification of seed fields by turbulent gas flows (small-scale dynamo)
- Turbulence is driven by accretion shocks and SN explosions
- Timescale of amplification: ≈ 3 \(10^8\) Gyr
- Amplitude: ≈ 10\(^{-5}\) G
Simulation of a small-scale dynamo in young galaxies

Equipartition with turbulent energy is reached within $\approx 10^8$ yr, almost independent of the seed field.
Evolution of magnetic fields (3)

**Phase 3** \((z \approx 10^{-2})\): Formation of disks

- Turbulence is driven by SN explosions and MRI in the disk
- Field ordering (stretching) by **shear**
- Field ordering (regular fields) by the **mean-field (large-scale) dynamo**
- No further amplification needed
- Timescale of ordering: \(\approx 1-2 \times 10^9\) Gyr
MHD-MRI model of spiral galaxies (without large-scale dynamo action)

The magnetic field affects the galaxy evolution:

- Spiral arms are more patchy
- Star-formation rate is lower
- Vertical outflows occur

Pakmor & Springel 2013
Global cosmic-ray driven large-scale dynamo model

Hanasz et al. 2009
Predictions of the dynamo model

- Strong turbulent magnetic fields at $z < 10$
  → **Total synchrotron emission** from young galaxies can be observed at $z < 10$

- Strong but "spotty" regular fields at $z < 3$
  → **Polarized radio emission** and some Faraday rotation can be observed at $z < 3$

- Large-scale coherent regular magnetic fields in dwarf or Milky Way-type galaxies at $z < 0.5$
  → **Large-scale patterns of Faraday rotation** can be observed at $z < 0.5$

- Large galaxies ($>15$ kpc) may not yet have generated fully coherent fields

- **Major mergers** may disrupt regular fields, but increase the turbulent field strength (Moss et al., submitted)
The radio-FIR correlation: Magnetic fields in distant galaxies

- Total radio synchrotron emission should break down at some redshift $z$ due to Inverse Compton loss with the CMB background.

- FIR/radio ratio should increase with $z$.

- This is **not** observed: Magnetic fields must still be strong in distant galaxies:
  \[ B > B_{CMB} = 3.25 \, \mu G \, (1+z)^2 \]

- Synchrotron emission seems to even increase relative to FIR.

- **But this cannot hold at very high redshifts**

$q$: ratio of FIR/radio luminosities

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Murphy 2009
The radio-FIR correlation: Magnetic fields in distant starburst galaxies

The critical redshift of the breakdown of the radio-FIR correlation Will give us information on the evolution of magnetic fields in young galaxies

(Schleicher & Beck 2013 – see Dominik’s talk)
Detecting total emission from distant galaxies with SKA2

$A_{\text{eff}}/T_{\text{sys}} = 10^4 \text{ m}^2 \text{ K}^{-1}$; $\text{BW} = 500 \text{ MHz}$

$S_{1.4 \text{ GHz}} (\text{observed}) [\mu\text{Jy}]$

$L_{\text{IR}} = 10^{13} L_\odot$

$B = 10, 50, 100, 200, 500, 1000 \mu\text{G}$

$S_{1.4 \text{ GHz}} (\text{predicted}) [\mu\text{Jy}]$

$A_{\text{eff}}/T_{\text{sys}} = 10^4 \text{ m}^2 \text{ K}^{-1}$; $\text{BW} = 500 \text{ MHz}$

$S_{1.4 \text{ GHz}} (\text{observed}) [\mu\text{Jy}]$

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$A_{\text{eff}}/T_{\text{sys}} = 10^4 \text{ m}^2 \text{ K}^{-1}$; $\text{BW} = 500 \text{ MHz}$

$S_{1.4 \text{ GHz}} (\text{predicted}) [\mu\text{Jy}]$

$B = 10, 50, 100, 200, 500, 1000 \mu\text{G}$

$5\sigma \text{ SKA: 10 hr}$

$5\sigma \text{ SKA: 100 hr}$

Murphy 2009
Detecting polarized emission from distant galaxies with SKA1

SKA1

\[ p > 1 \, \text{uJy} \]

1180 per square degree

POSSUM

\[ p > 100 \, \text{uJy} \]

0.105 per square degree

Stil & Taylor, unpubl.
Population of intervening galaxies towards polarized quasars: Faraday rotation at high frequencies ($\approx$5-10 GHz) is stronger for more distant quasars ($z>1$) → kpc-scale, $\mu$G-strong regular fields exist in distant galaxies

Kronberg et al. 2008, Bernet et al. 2008
Magnetic fields in distant intervening galaxies

Magnetized outflows of galaxies are huge:

- Intervenors may be very frequent
- Dispersion of transient signals may be strong

Bernet et al. 2013
Observation of magnetic fields in distant galaxies with SKA1 deep fields

- Total synchrotron emission ($z < 3-4$)
- Polarized synchrotron emission ($z < 2-3$)
- Faraday rotation in intervening galaxies against background sources ($z < 5$)

*The evolution of galactic magnetic fields can be traced for the first time*
Summary: Observing cosmic magnetism with SKA1

Diffuse polarization:

- Polarization survey of distant galaxies and cluster relics:
  SKA1-MID (deep)
- Detailed magnetic field structure in nearby galaxies:
  SKA1-MID high band (deep)
- Weak magnetic fields in cluster halos and intergalactic filaments:
  SKA1-MID low band or SKA1-LOW high end (deep)

RM of polarized background sources:

- Field pattern of the Milky Way:
  SKA1-SUR (survey)
- 3-D structure of the Milky Way’s magnetic field (pulsar RMs):
  SKA1-MID (survey)
- Evolution of galactic magnetic fields:
  SKA1-MID (deep)
- Evolution of galactic and intergalactic magnetic fields (intervenors):
  SKA1-SUR (survey)