Cosmic Magnetism

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on behalf of the SKA Cosmic Magnetism SWG

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Outline of the Talk

• Cosmic magnetism science drivers in the SKA1 era

• Observational techniques

• Key SKA1 observations for cosmic magnetism
  (Milky Way, external galaxies, cluster of galaxies, cosmic web)

• Scientific improvements with SKA1

• Inputs to the baseline design
Magnetic fields play an important role in the formation and evolution of many astrophysical objects. Despite their importance, the evolution, structure, and origin of magnetic fields are still open questions. **SKA1** will open a new era in the observation of astrophysical magnetic fields.
Cosmic Magnetism Science Drivers

1) The Galactic magnetic field

2) Magnetism and galaxy evolution

3) Magnetic fields in galaxy clusters

4) Detection and characterization of magnetic fields in the cosmic web

Fletcher et al. (2011)

Vacca et al. (2010)

Oppermann et al. (2012)

Akahori & Ryu (2010)
Cosmic Magnetism Science Drivers

Magnetic field studies to address important questions:

- What is the relation between super-massive black holes and their environment?
  Broadband depolarization $\rightarrow$ thermal environment of radio galaxies and AGN.
  
  e.g. O'Sullivan et al. (2013)

- How do galaxies and structures evolve over cosmic time?
  Broadband polarization $\rightarrow$ overall evolution of magnetic fields with redshift

  e.g. Hammond et al. (2012)

- What are the physical properties of absorbing systems?
  Broadband Faraday Rotation $\rightarrow$ covering fraction and turbulence

  e.g. Bernet et al. (2012)
Observational Techniques

Much of what we know about cosmic magnetism comes from sensitive total intensity (Stokes I) and polarization (Stokes Q and U) radio observations.

- Presence of field
- Orientation of field
- Strength of field
- Spatial scales of field

Synchrotron Radiation

Fletcher et al. (2011)
The polarized angle of the radio signal is subject to the FARADAY ROTATION as it traverses a magnetized plasma.

\[ \phi \left[ \text{rad/m}^2 \right] = 812 \int_0^L n_e \left[ \text{cm}^{-3} \right] B_{\parallel} \left[ \mu \text{G} \right] \, \text{d}l \]

Radio emission in the background of an external Faraday screen:
Faraday depth = Rotation Measure (RM)

\[ \Psi_{\text{obs}} = \Psi_{\text{int}} + \text{RM} \lambda^2 \]

Govoni et al. (2006)
Magnetized plasma

To avoid significant internal depolarization the polarized emission is better studied at high frequencies (~1GHz or higher).

A high Faraday resolution can be achieved much more easily at low frequencies.

Therefore we need both, high and low frequencies.

Faraday Rotation

Radio emission emitted by a magnetized plasma: Faraday Rotation effect leads to a frequency-dependent depolarization of the signal.

FARADAY DEPTH:

\[ \phi_{[\text{rad/m}^2]} = 812 \int_0^L n_e[\text{cm}^{-3}] B_{||[\mu_\text{G}]} \, dl \]

Observational Techniques

Faraday Rotation

Rotation Measure Synthesis to recover the polarized signal

Burn (1966), Brentjens & de Bruyn (2005), Heald (2009), Pizzo et al. (2011)
Broadband Polarimetry: a unique physical probe

A broadband frequency coverage is necessary to properly interpret the data

Polarimetry of PKS B1610-771

O'Sullivan et al. (2012)
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O'Sullivan et al. (2012)
Key SKA1 Observations for Cosmic Magnetism

To pave the way for broadband spectropolarimetric surveys to be performed with SKA1 and SKA2, there are several polarization surveys under way or planned e.g.

LOFAR: Heald et al. (2012), Beck et al. (2013)

POSSUM with ASKAP: Gaensler et al. (2010)

GMIMS with single-dish telescopes: Wolleben et al. (2009)

GALFACTS with Arecibo: Taylor & Salter (2010)
Key SKA1 Observations for Cosmic Magnetism

GALFACTS: Arecibo Sky Polarization Survey

Taylor & Salter (2010)
Key SKA1 Observations for Cosmic Magnetism

Wide-band spectropolarimetric surveys at \(~1\) GHz will be crucial to build the foundation for SKA2 experiments and will guide initial studies of magnetic fields in the Milky Way, in many external galaxies and clusters, and in the overall magnetized intergalactic medium.

Possible SKA1 surveys suitable for cosmic magnetism studies

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Frequency</th>
<th>Field of View</th>
<th>Resolution</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>SKA1-mid</td>
<td>~1 GHz</td>
<td>30 deg$^2$</td>
<td>1''</td>
<td>0.01(\mu)Jy/beam</td>
</tr>
<tr>
<td>SKA1-survey</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SKA1-mid</td>
<td>~1 GHz</td>
<td>30.000 deg$^2$</td>
<td>2''</td>
<td>1(\mu)Jy/beam</td>
</tr>
<tr>
<td>SKA1-survey</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1) Dense spaced RM grid of background sources
2) Faraday Rotation synthesis approach

An all-sky grid of Faraday rotation measures \(~300-1000\)x denser than the most accurate all-sky map actually available (Taylor et al 2009)
NRAO VLA Sky Survey Rotation Measures

≈ 40000 sources (≈ 1 source per deg2)

(Taylor et al 2009)
The Galactic Magnetic Field

Magnetic fields play a crucial role in our Galaxy:

1) Govern the structure and the dynamics of the interstellar medium

2) Regulate the process of star formation

3) Accelerate cosmic rays

Being able to model the Galactic magnetic field is very important for accurate foreground subtraction to address magnetic fields in the Cosmic web, CMB polarization, Epoch of Reionization and propagation of Ultra-High Energy Cosmic Rays.
Reconstruction of the Galactic Faraday depth, mostly based on the Taylor et al. (2009) data.
Magnetism and Galaxy Evolution

SKA1 will permit detailed investigation of the structure of the magnetic fields in the interstellar medium of galaxies and in galaxy halos, and to measure the magnetic field power spectrum.

- Global galaxy energetics?
- How cosmic magnetism in galaxies evolve with time?
- Interaction with intergalactic environment?

Polarimetry of galaxies at high redshift

- **Integrated polarimetry to quantify measure disk fields to high redshift.** [Stil et al. (2009), Arshakian et al. (2009)]

- **RM Synthesis of emission from background QSOs may reveal the field structure in the disk or halo of intervening galaxies.** [Beck et al. (2012), Bernet et al. (2013)]
Magnetism and Galaxy Evolution

Effelsberg imaging of integrated polarization reveals presence of global fields in disk galaxies.

SKA1 Deep fields will detect thousands of galaxies in polarization out to redshifts beyond 4.

Stil et al. (2009)

POSSUM
\[ \sigma = 10 \ \mu Jy \]

Local galaxies only

SKA1
\[ \sigma = 0.1 \ \mu Jy \]

p > 1 uJy
1180 per square degree

p > 100 uJy
0.105 per square degree
SKA1 will have the potential of measuring the RM toward a large number of sources by deriving a detailed description of the strength, structure, and radial decrease of cluster magnetic fields.

The sensitivity of current radio facilities limit the RM studies to a few radio galaxies per cluster.
Magnetic Fields in Galaxy Clusters

SKA1 will permit to investigate the polarized emission from radio halos and relics. Relics are bright and highly polarized and hence are observable until high redshifts, even if not resolved.

- Constrain the cluster magnetic field power spectrum. (Murgia et al. 2004)

- Detect merger shocks in the intracluster medium not visible in X-ray images. (Brown & Rudnick 2011)
Magnetic fields in the Cosmic Web

- Can it be detected?
- How did it arise?
- What are its properties and relation to large scale structure of matter?

Akahori & Ryu (2010, 2011)
Cosmic magnetism needs a frequency range as large as possible. It is important not to have gaps in frequency range between the instruments, already in the initial phases of the project.

For SKA1-survey, if PAF Band1 will not be initially available, going to slightly lower frequencies would be better for RM synthesis. In this case, starting from 500 MHz would be better than starting from 650 MHz.
High angular resolution is necessary to:
- Obtain detailed RM images (external Faraday screen)
- Avoid Beam depolarization

SKA1-low may not provide a sufficient resolution to overcome the beam depolarization.

We support the possibility to have SKA1-low with longer baselines to reduce the beam depolarization.
Detection of Large Scale Structure with SKA1

Field of View $\sim \lambda/D$
Large Angular Scale $\sim \lambda/B_{\text{min}}$

Detection of Large Scale Structures with SKA1

**SKA1-mid (580 – 1015 MHZ)****
**SKA1-mid (950 – 1670 MHZ)****

**SKA1-low (50 – 350 MHZ)**
Increasing the size of stations of SKA1-low will reduce the FoV and increase the minimum baseline. The latter effect may limit the possibility to detect large angular scale structures even with mosaicking observations.

The minimum baseline of SKA1-mid, SKA1-survey, and SKA1-low should be clearly discussed in the Baseline Design. We recommend reducing the minimum baseline as much as possible. We also recommend considering SKA1-low stations not larger than 35 m.
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Polarization Purity of SKA1

A high polarization purity is fundamental to detect polarized signal from astrophysical sources seen down to sub-mJy levels.

Tab. 5 Baseline Design

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SKA1-survey</th>
<th>SKA1-mid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Far-out sidelobe level</td>
<td>&lt;50 dB</td>
<td>&lt;30 dB</td>
</tr>
<tr>
<td>Polarization purity</td>
<td>-30 dB</td>
<td>-30 dB</td>
</tr>
<tr>
<td>Receiver</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Pointing repeatability</td>
<td>10, 17, 180 arcsec</td>
<td>P, S, D respectively arcsec, rms</td>
</tr>
<tr>
<td>Receiver noise temperature &amp; Feed Losses</td>
<td>&lt;15 K</td>
<td>Assumed for performance estimates</td>
</tr>
</tbody>
</table>

Note that we intend post-calibration polarization purity!!

Information on polarization performances of SKA1-low is missing in the Baseline Design.
Proper specification on polarization are required for SKA1-mid and SKA1-survey.
Given the apparent similarity in capabilities, we suggest optimizing some aspect of one of the two instruments for deep cm observations and some aspect of the other instrument for wide-field cm observations.

An even higher survey speed is recommended for the instrument dedicated to wide field observations.
Conclusions

SKA1 will open a new era in the observation of astrophysical magnetic fields.
Conclusions

Inputs to the SKA1 System Baseline Design (Dewdney et al. 2013) in order to maximize scientific return in the context of Cosmic Magnetism.

1) Frequency

Cosmic magnetism needs a frequency range as large as possible. It is important not to have gaps in frequency range between the instruments, already in the initial phases of the project. For SKA1-survey, if PAF Band1 will not be initially available, going to slightly lower frequencies would be better for RM synthesis.

2) Angular Resolution

High angular resolution reduce beam depolarization.
(SKAlow: longer baselines)

3) Largest Angular Scale

Minimum baseline to be reduced as much as possible.
(SKAlow stations not larger than 35 m).

4) Polarization Purity

Proper information on polarization performances are missed in the Baseline Design.

5) Survey Speed

Apparent similarity in capabilities between SKA1-mid and SKA1-survey. An even higher survey speed is recommended for the instrument dedicated to wide field observations.