Using Magnetism to Reveal the Mysteries of the Universe

Melanie Johnston-Hollitt
Victoria University of Wellington

Federica Govoni, Ivan Agudo, Takuya Akahori, Rainer Beck, Annalisa Bonafede, Tobia Corrozzi, Sergio Colafrancesco, Luigina Feretti, Katia Ferriere, Bryan Gnesler, JinLin Han, Lisa Harvey-Smith, Marijke Haverkorn, George Heald, Mathieu Langer, Jean-Pierre Macquart, Ann Mao, Tim Robishaw, Larry Rudnick, Anna Scaife, Dominik Schleicher, Dominic Schnitzeler, Jeroen Stil, Keitaro Takahashi, Russ Taylor, Jimi Green, Tyler Bourke...
Magnetic Fields

- Magnetic fields are important in a number of astrophysics areas
- We’ve already heard the importance of magnetism for Pulsar science (Han, Karastergiou) for AGNs (Orienti) and for radio halos & mini halos (Cassano, Gitti)
- They also play an important role in the physics of jets, masers, radio relics etc
- Additionally understanding magnetic foregrounds is crucial for the EoR, inflation theory using B-mode polarisation of the CBM or to unveil the magnetic structure of the cosmic web.
Magnetic Field + X

Magnetic Field + Spiral Galaxy
Total 7464
Over 250 papers per year now

Magnetic Field + Galaxy Cluster
Total 9315
Over 500 papers per year now

Magnetic Field + AGN
Total 11,852
Over 800 papers per year now
Magnetic Field + X

I challenge you to try this for your own favourite type of source!

SKA is a unique tool to probe magnetic fields → big science impacts across all of astrophysics
SKA & Magnetism

• Historically it has been difficult to do detailed studies of the magnetic field of large numbers of objects due to limited sensitivity, resolution and polarisation calibration of the previous generation of radio telescopes.

• Additionally understanding the complex nature of polarised signals was difficult until the advent of techniques to allow us to probe the Faraday Spectra and to statistically disentangle effects of foregrounds along the line of sight.

• With the current generation of new or upgraded instruments along with better analysis techniques and computer modelling we are starting to see an increase in the science we can do with polarisation.

• In the age of the SKA this will only continue as we move to the Era of Precision Magnetism
Era of Precision Magnetism

- The SKA will give us
  - Higher sensitivity
  - Broader bandwidths
  - Widefields of view

- Each of which provides a unique capability for probing cosmic magnetism.
The Cosmic Magnetism WG is comprised of individuals with expertise spanning magnetism science.

Our role is to provide advice to the SKAO on issues relating to the design, construction and future operations of the SKA that pertain to the Observatory’s scientific capability, particularly for cosmic magnetism.

We will be moving to a 2 tier membership with ~15 ‘core’ members and an unlimited number of associate members.
Priorities of the WG

• The group present at the assessment WG in Jan reached consensus that our science priority is the ability to do polarisation surveys of different coverage and depth on SKA_SURVEY and SKA_MID. This will include an RM Grid/polarisation survey as the number 1 priority.

• Note the RM Grid experiment is not the only outcome from such surveys, it is a dataset which allows a range of science.

• Other science considered includes diffuse polarization at 600 MHz to detect filaments and support for higher/wider frequency follow up on individual source (AGN, galaxies, HTs etc).
Rotation Measure

- Rotation Measures are a frequency dependent rotation of the polarisation position angle due to the intervening magnetic field.

\[
RM = 812 \int_0^L n_e B_{\parallel} \, dl \quad \text{rad m}^{-2}
\]
Polarisation Survey

- **SKA_SURVEY**: Wide area survey with Band 2 (650 – 1760 MHz) down to 2 uJy

- **SKA_MID**: Deeper Survey on Band 2 over a limited area of sky down to 75 nJy. (10 sq. deg = 1 year)

- **SKA_MID**: Deeper Survey on Band 3 over a yet smaller area down to 75 nJy (3 sq. deg = 1 year)
Science Highlights of the Survey

- B-Field of the Milky Way
- B-Fields in nearby Galaxies
- B-Fields in Galaxy Clusters

(Taylor et al. 2009)

(Govoni et al. 2012)
Cluster Halo Simulation from realistic B-fields

(Chyzy et al. 2006)
Effelsberg 5 GHz
## RM Survey

<table>
<thead>
<tr>
<th>Decade Ago</th>
<th>Interpolated All-Sky RM (Johnston-Hollitt et al. 2004)</th>
<th>1,000 RM$s$ $\sim$ 0.02 sources/deg$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Now</td>
<td>NVSS + other surveys combined with statistical analysis (Oppermann et al. 2012, 2014 &amp; Vacca et al. 2014)</td>
<td>40,000 RM$s$ $\sim$ 1 source/deg$^2$</td>
</tr>
<tr>
<td>SKA</td>
<td>SKA1_SUR Band 2 with 2uJy sensitivity (Govoni et al. 2014)</td>
<td>12 – 40 million RM$s$ $\sim$ 300 -1000 sources/deg$^2$</td>
</tr>
</tbody>
</table>
Magnetic Field of the Milky Way

• RMIs obtained from extragalactic sources & pulsars combined with sophisticated statistical analysis will provide an unprecedented tomographic view of the magnetic field of our Galaxy.

• While the large-scale field is less likely to improve, the details of the turbulent component of the Galactic field will be much more constrained.

• Additionally the magnetic fields of Galactic objects on scales less than 100 pc will be probed in detail.
Johnston-Hollitt et al. (2004) 
~1000 extra-galactic RMs

Oppermann et al. (2012) 
~40,000 extra-galactic RMs

SKA 1 SURVEY 
~12 – 40 million extra-galactic RMs

See talks by Sui Ann Mao and Valentina Vacca
Magnetic Field of the Milky Way

- Complementary information will be provided by pulsars, masers & Zeeman splitting (see talk by Tim Robishaw).
- 2300 pulsars currently known, SKA1 to increase that 10 fold. Pulsar timing gives accurate distances for many of these -> 3D tomography (cf talk by JinLin Han).
Magnetic Fields of other galaxies

- A polarisation survey will allow not only direct imaging of the magnetic field of other galaxies (see talks by Rainer Beck & George Heald), but also statistical RM to be examined over the disk of these galaxies.
- With at least 10 RMs per galaxy it's possible to determine the overall field type, with 1000 RMs can do 3D tomography.
Cluster Magnetic Fields

• We know there are magnetic fields in galaxy clusters. We don’t know their extent, filling factors, or relationship to or influence on the dynamical state of the cluster.

• Statistical studies of RMss through clusters have been undertaken since the late 80s (Hennesey et al. 1989, Kim et al. 1999, Clarke et al. 2001, Johnston-Hollitt et al 2004, ... Bonafede et al. 2013)

• Results have been hampered by:
  – Contributions from foregrounds (intrinsic and extrinsic)
  – Poor sampling (low no. of sources across a cluster)
  – Poor polarisation data (nπ-ambiguity, bad fits)

• A decade ago it was proposed that the SKA would address many of these issues (Feretti & Johnston-Hollitt 2004)
Cluster Magnetic Fields

- Previously cluster B-fields detected statistically with 1-2 RMss per cluster
- Now can do 10s of RMss through a cluster eg Bonafede et al. 2013 obs of Coma on JVLA
  
  With SKA will to thousands of RMss per cluster eg A3667 3 RMss in 3 years a decade ago vs 1000 – 3000 with SKA Survey in 4 hours.

See talk by Annalişa Bonafede
Cluster Magnetic Fields

• Increase in cluster RMs gives possibilities such as probing the magnetic field through cluster relics and using extended sources in the cluster as RM screens to probe the internal structure of the magnetic field.
Cluster Magnetic Fields

- Looking to SKA2 the increase in sensitivity will be coupled with an increase in resolution which provides interesting possibilities to probe the small scale turbulent field in cluster by use of ‘corkscrew’ radio galaxies.

See talk by Annalisa Bonafede
Cluster Magnetic Fields

- Path length through the cluster is the same for the red and yellow patches. Therefore can look for statistical differences which will probe the B-field on very small scales.
- For sources with long tails, transverse to the cluster we can measure a change as a function of radius.
- SKA2 should find 5000 – 20,000 of these sources.

See talk by Annalisa Bonafede
Not just about number of RMs

- Previously RMs were done on linear fits to only a few data points.
- This leads to poor results in complex cases and doesn’t account for screens along the line of sight.
- Broadbands on modern telescopes have revolutionized RMs allowing for complex Faraday spectra to be recovered.
- This allows the possibility to not only use the polarised light from background galaxies to understand large-scale foregrounds, but to study the intrinsic properties of the sources themselves. See talk by Bryan Gaensler

SKA 1

• Ultimately SKA1 surveys will give us the ability to:
  – Obtain an unprecedented view of the magnetic field of the Milky Way which combined with Pulsars will allow a 3D model accurate to scales of hundreds of pcs to be constructed
  – Probe the magnetic field of galaxy clusters not just statistically but individually allowing understanding of the extent of the fields & constraints on the filling factors and turbulence scales
  – Examine in detail the magnetic field of nearby galaxies both directly and through RMs projected through such sources.
  – Provide fundamentally better understanding of complex Faraday spectra leading to new astrophysics.

• What will a de-scoped SKA1 do?
  – Depends on what is lost. Probably the lest problematic reduction would be a loss of sensitivity as this would allow much of the science from polarisation surveys to still be achievable albeit it at a much reduced level
Summary

- The SKA is a unique instrument for probing magnetic fields across cosmic time.
- It will provide “transformational” science in the field of magnetism.
- This science will have broadly applicable across much of astrophysics.

Answer: Well, from the SKA we know...