SKA and the Magnetic Universe

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SKA Key Science

- Testing Theories of Gravitation with pulsars

- The Dark Ages:
  Epoch of re-ionisation, first black holes

- The Cradle of Life:
  Protoplanets, biomolecules, SETI

- Evolution & Large-scale Structure:
  Galaxies, Hubble Flow & Dark Energy

- Cosmic Magnetism
Cosmic Magnetism

Magnetism is crucial in:
- cloud collapse / star formation
- stellar activity / stellar outflows
- ISM turbulence / gas motions
- supernova remnants
- stability of galactic disks
- acceleration / propagation / confinement of cosmic rays
- heating in galaxy clusters
- AGNs / Jets

Magnetism is one of the fundamental forces in Nature, but its role and origin is largely unknown!
Fundamental Questions

- **STRUCTURE**
  - What are the **strength and structure** of the magnetic field in the interstellar, intracluster and intergalactic medium?
  - What is the **interplay** between the magnetic fields and the gas?

- **EVOLUTION**
  - How were the present-day magnetic fields **amplified** and maintained?
  - How did magnetic fields **evolve** as galaxies evolve?

- **ORIGIN**
  - Were the **seed fields** in galaxies and clusters **primordial**, or were they ejected by stars, supernova remnants, or AGNs?
  - Is there a connection between field formation and **structure formation** in the Early Universe?
  - *When and how were the first magnetic fields generated?*
Magnetism and Radio Astronomy

Most of what we know about cosmic magnetism is from radio waves!

- Total & polarized synchrotron emission
  - strength & orientation of $\langle B \perp \rangle$ & $B \perp$
- Faraday rotation
  - strength & sign of $\langle B \parallel \rangle$
- Zeeman splitting
  - strength & sign of $B \parallel$

M51 (Fletcher & Beck 2004)

PSR B1154-62 (Gaensler et al 1998)

HVC 132+23-212 (Kazès 1991)
Synchrotron Emission from the Milky Way (Perseus - Auriga)

Polarization opens a new domain to study magnetic fields!

Effelsberg 21cm (Reich et al 2003)
M51
VLA + Effelsberg
(Fletcher & Beck 2004)
COMA Cluster

Center

500 kpc

RADIO: WMAP, 90 cm (Feretti et al. 1992)
RMs of Background Sources

- Useful probe of \( B \) in the Milky Way, clusters, Ly-\( \alpha \) absorbers, ...
- Now: RMs of \(~1200\) polarized extragalactic sources + \(~300\) pulsars
- But: Sparse sampling at high \(|b|\) : \(~0.03\) source / deg\(^2\)
- Galactic plane surveys with ATCA, DRAO: \(~2\) src / deg\(^2\)
- New Effelsberg survey (\( \delta > -20^\circ \)) : \(~1500\) new RMs, \(~0.5\) src / deg\(^2\)

Spiral Arms in the Milky Way

- Pulsar RMs + field model (Han et al. 2002)
- Pulsar RMs + wavelet model (Stepanov et al. 2002)
- Pulsar + extragalactic RMs (Brown & Gaensler 2004)
- Pulsars to be detected with the SKA (Cordes 2001)
RMs Through Galaxies & Clusters

RMs of 21 polarized sources shining through M31 (Han et al 1998)

5 RMs through Abell 514 (Govoni et al 2001)

RM through Abell 514 (Govoni et al 2001)

RMs through 30 clusters (Johnston-Hollitt 2003)
Field Direction in Spiral Galaxies

Preferably *inwards*? 

Krause & Beck (1998)
Galaxies at $z = 0.1 \rightarrow \sim 3$

Radio emission and B vectors of the QSO PKS 1229-021 at $z = 1.0$ (Kronberg et al 1992)

Residual RMs of QSOs embedded in intervening clouds (Welter et al 1984)

Field model of the foreground spiral galaxy at $z = 0.395$ with $B \sim 1–4 \, \mu$G (Kronberg et al 1992)

Poor data!
SKA All-Sky RM Survey

- Image the sky to $S \approx 0.1 \mu$Jy at 1.4 GHz ("SKA FIRST")
- FOV $\approx 1 \text{ deg}^2$, 1h / pointing ($\sim$1 year total), $\langle p \rangle \approx 5\%$

→ RMs for $\sim (1–5) \times 10^8$ polarized extragalactic sources, spaced by only $\sim 30''–50''$ on the sky!

plus:

RMspolarized extragalactic sources, spaced by only $\sim 30''–50''$ on the sky!

plus:

RM of several 1000 Galactic pulsars and several 100 pulsars in nearby galaxies

Radio sources (total emission) in the ATCA Phoenix Deep Field (Hopkins et al. 2003)
When and how were the first magnetic fields generated?
Seed Fields from Young Galaxies?

1. Biermann battery in Pop III stars
   ▼
2. Stellar dynamos
   ▼
3. Supernova ejecta or stellar winds
   ▼
4. ~ 10^6 remnants incorporated in galactic disc
   ▼
5. ≥ 10^{-9} G seed field

Battery + dynamo in first AGNs (z = 5?)
▼
Jets
▼
Extended radio lobes
▼
Formation of disc from infalling matter contaminated by radio lobe
▼
Rees (2004)
Magnetic Fields in Protogalaxies

“SKA Deep Field”:

- thousands of “normal” spiral galaxies at $z \sim 3$ detectable with the SKA (1.4 GHz: size = 1 - 3”, flux $\geq 0.2 \, \mu$Jy)
- their radio flux strongly depends on field strength and on star formation rate (and may be polarized)

HDF galaxies with $z > 4$ (Driver et al 1998)
Dynamical Importance of Primordial Intergalactic Fields

Rees (2000)
Early primordial fields could have been generated by battery effects, during inflation or phase transitions.

A primordial intergalactic (IGM) field may have regulated structure formation in the early Universe.

Present-day fields of $B \geq 1 \, \mu G$ could have evolved from $B_0 \sim 10^{-9} - 10^{-10} \, G$ primordial seed fields at $z > 5$ by compression and dynamo action.

Upper limits of intergalactic fields from existing studies: $B_{\text{IGM}} < 10^{-8...9} \, G$ (model dependent).
Search for Primordial Fields

- The SKA All-sky Survey will provide a large sample of RMs
- Expected RMs from a homogeneous IGM field:
  \[ \lambda \propto (1+z)^{-2}; \quad n_e \propto (1+z)^3; \quad B \propto (1+z)^2 \rightarrow \text{RM}_{\text{IGM}} \propto (1+z)^3 \]
- But: IGM fields are probably tangled
- Note: The Galactic foreground has to be subtracted properly

Mean and median RM vs z for
- B = 6 nG (Blasi et al 1999)
- B = 1 nG (Kolatt 1998)
Search for Primordial Fields

- RM of GRB afterglows, high-z AGNs, high-z (radio) galaxies, and of the CMB:
- A CMB field of $B_0 \sim 10^{-9}$ G may be detectable as $R_{\text{CMB}}$ (Kosowky & Loeb 1996)

GRB 000131 at $z = 4.5$ (Bloom et al 2001)

Radio galaxy at $z = 5.2$ (van Breugel et al 1999)

BICEP CMB Polarization
SKA Specifications for Polarimetry

- Frequency: at least 1–10 GHz, 0.3–20 GHz ideal
- Large field of view: >1 deg² at a resolution of <1"
- High sensitivity: < 0.1 μJy, confusion limited
- Large bandwidth: > 400 x 1 MHz at 1.4 GHz
- Significant concentration (> 50%) of antennae in central core (~ 5 km)
- High polarization purity (−40 dB at field center, −30 dB at field edges)
Conclusions

SKA’s Magnetic Universe …

- can address *unanswered questions* in fundamental physics & astrophysics
- is science which is *unique to the radio band and to the SKA*
- will almost certainly yield *new and unanticipated results*!