Proceedings of *Magnetic Fields in the Universe:*
From Laboratory and Stars to Primordial Structures
Aug. 21st – 27th 2011, Zakopane, Poland
Eds. M. Soida, K. Otmianowska-Mazur, E.M. de Gouveia Dal Pino & A. Lazarian

Future Observations of Cosmic Magnetic Fields with the SKA and its Precursors

Rainer Beck

Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany

Abstract

The origin of magnetic fields in the Universe is an open problem in astrophysics and fundamental physics. Polarization observations with the forthcoming large radio telescopes, especially the Square Kilometre Array (SKA), will open a new era in the observation of magnetic fields and should help to understand their origin. Low-frequency radio synchrotron emission, to be observed with LOFAR, MWA and the SKA, traces low-energy cosmic ray electrons and allows us to map the structure of weak magnetic fields in the outer regions and halos of galaxies, in halos and relics of galaxy clusters and in the Milky Way. Polarization at higher frequencies (1–10 GHz), to be observed with the SKA and its precursors ASKAP and MeerKAT, will trace magnetic fields in the disks and central regions of galaxies and in cluster relics in unprecedented detail. All-sky surveys of Faraday rotation measures towards a dense grid of polarized background sources with ASKAP (project POSSUM) and the SKA are dedicated to measure magnetic fields in intervening galaxies, clusters and intergalactic filaments, and will be used to model the overall structure and strength of magnetic fields in the Milky Way. "Cosmic Magnetism" is key science for LOFAR, ASKAP and the SKA.

1 Introduction

The Square Kilometre Array (SKA) is the most ambitious radio telescope ever planned. With a collecting area of about one square kilometer, the SKA will be about ten times more sensitive than the largest single dish telescope (305 m diameter) at Arecibo (Puerto Rico), and fifty times more sensitive than the currently most powerful interferometer, the Expanded Very Large Array (EVLA, at Socorro/USA). The SKA will continuously cover most of the frequency range accessible from ground, from 70 MHz to 10 GHz in the first and second phases, later to be extended to at least 25 GHz. The third major improvement is the enormously wide field of view, ranging from 200 square degrees at 70 MHz to at least 1 square degree at 1.4 GHz. The speed to survey a large part of the sky, particularly at the lower frequencies, will hence be ten thousand to a million times faster than what is possible today. The SKA is dedicated to constrain fundamental physics on the dark energy, gravitation and magnetism.

2 Technical design of the SKA

The SKA will be a radio interferometer and consist of many antennas which are spread over a large area to obtain high the resolving power. The three separate SLA core regions of 5 km diameter each will contain about 50% of the total collecting area and comprise dish antennas and the two types of aperture arrays (Fig. 4). The mid-region out to about 180 km

Figure 1: SKA sparse aperture array station of dipole elements for about 70–450 MHz. Graphics: Swinburne Astronomy Productions and SKA Project Office (SPO).

Figure 2: SKA parabolic dishes for about 450 MHz–3 GHz. Graphics: Swinburne Astronomy Productions and SPO.

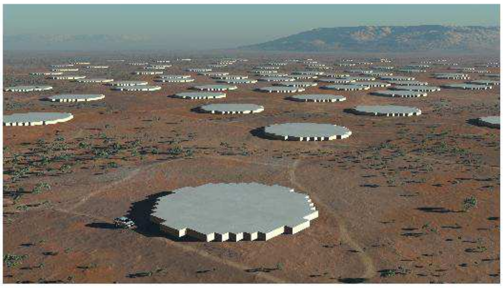

Figure 3: SKA dense aperture array station made up of 3 m x 3 m "tiles" for about 500 MHz–1 GHz. Graphics: Swinburne Astronomy Productions and SPO.

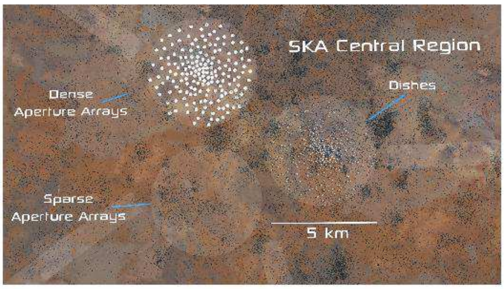

Figure 4: SKA core stations for the mid-frequency aperture array and for the dish array (to be built in South Africa) and the low-frequency array (to be built in Australia). Graphics: Swinburne Astronomy Productions and SPO.

radius from the core comprises dishes (Fig. 2) and sparse aperture array antennas (Fig. 1) aggregated into stations distributed on a spiral arm pattern. Remote stations with about 20 dish antennas each will spread out to distances of at least 3000 km from the core and located on continuations of the spiral arm pattern. The overall extent of the array determines the angular resolution, which will be about $0.1''$ at 100 MHz and $0.001''$ at 10 GHz.

To meet the ambitious specifications and keep the cost to a level the international community can support, planning and construction of the SKA requires many technological innovations such as light and low-cost antennas, detector arrays with a wide field of view, low-noise amplifiers, high-capacity data transfer, high-speed parallel-processing computers and high-capacity data storage units. The enormous data rates of the SKA will demand online image production with automatic software pipelines.

The frequency range spanning more than two decades cannot be realized with one single antenna design, so this will be achieved with a combination of different types of antennas. Under investigation are the following designs for the low and mid-frequency ranges:

1. An aperture array of simple dipole antennas with wide spacings (a "sparse aperture array") for the low-frequency range (about 70–450 MHz) (Fig. 1). This is a software telescope with no moving parts, steered solely by electronic phase delays. It has a large field of view and can observe towards several directions simultaneously.
2. An array of several thousand parabolic dishes of about 15 meters diameter each for the medium-frequency range (about 450 MHz–3 GHz), each equipped with a wide-bandwidth single-pixel "feed" (Fig. 2). The surface accuracy of these dishes will allow a later receiver upgrade to higher frequencies.

As an "Advanced Instrumentation Programme" for the full SKA, two additional technologies for substantially enhancing the field of view in the 500–1000 MHz range are under development: aperture arrays with dense spacings, forming an almost circular station 60 m across (Fig. 3) and phased-array feeds for the parabolic dishes (see below).

3 Technical developments

Technical developments around the world are being coordinated by the SKA Science and Engineering Committee and its executive arm, the SKA Project Office. The technical work itself is funded from national and regional sources, and is being carried out via a series of verification programs. The global coordination is supported by funds from the European Commission under a program called PrepSKA, the Preparatory Phase for SKA, whose primary goals are to provide a costed system design and an implementation plan for the telescope by 2012.

A number of telescopes provide examples of low frequency arrays, such as the European LOFAR (Low Frequency Array) telescope, with its core in the Netherlands, the MWA (Murchison Widefield Array) in Australia, PAPER (Precision Array to Probe the Epoch of Reionization), also in Australia, and the LWA (Long Wavelength Array) in the USA. All these long wavelength telescopes are software telescopes steered by electronic phase delays (phased aperture array). Examples of dishes with a single-pixel feed are under development in South Africa (MeerKAT, Karoo Array Telescope).

Dense aperture arrays comprise up to millions of receiving elements in planar arrays on the ground (Fig. 3) which can be phased together to point in any direction on the sky. Due to the large reception pattern of the basic elements, the field of view can be up to 250 square degrees. This technology can also be adapted to the focal plane of parabolic dishes. Prototypes of such wide-field cameras are under construction in Australia (ASKAP, Australian SKA Pathfinder), the Netherlands (APERTIF) and in Canada (PHAD).

The data from all stations have to be transmitted to a central computer and processed online. Compared to LOFAR with a data rate of about 150 Gigabits per second and a central processing power of 27 Tflops, the SKA will produce much more data and need much more processing power - by a factor of at least one hundred. Following "Moores law" of increasing computing power, a processor with sufficient power should be available by the next decade. The energy consumption for the computers and cooling will be tens of MegaWatts.

4 SKA timeline

The detailed design for low and mid frequencies will be ready until 2013. The development of technologies for the high-frequency band will start in 2013. Construction of the SKA is planned to start in 2016. In the first phase (until about 2020) about 10% of the SKA will be erected (SKA_1) (Garrett et al. 2010), with completion of construction at the low and mid frequency bands (SKA_2) by about 2024, followed by construction at the high band.

The members of the SKA Organisation agreed on a dual site solution for the SKA with two candidate sites fulfilling the scientific and logistical requirements: Southern Africa, extending from South Africa, with a core in the Karoo desert, eastward to Madagascar and Mauritius and northward into the continent, and Australia, with the core in Western Australia. The dishes of SKA_1 will be built in South Africa, combined with the MeerKAT telescope, and further dishes will be added to the ASKAP array in Australia. All the dishes and the mid-frequency dense aperture array for SKA_2 will be built in Southern Africa. The low-frequency sparse aperture array of dipole antennas for SKA_1 and SKA_2 will be built in Australia.

5 Key science projects

Apart from the expected technological spin-offs, five main science questions (Key Science Projects) drive the SKA (Carilli & Rawlings 2004).

- Probing the dark ages

  The SKA will use the emission of neutral hydrogen to observe the most distant objects in the Universe. The energy output from the first energetic stars and the jets launched near young black holes (quasars) started to heat the neutral gas, forming bubbles of ionized gas as structure emerged. This is called the Epoch or Reionization. The signatures from this exciting transition phase should still be observable with help of the HI radio line, redshifted by a factor of about 10. The lowest SKA frequency will allow us to detect hydrogen at redshifts of up to 20, to search for the transition from a neutral to an ionized Universe, and hence provide a critical test of our present-day cosmological model.

- Galaxy evolution, cosmology, and dark energy

  The expansion of the Universe is currently accelerating, a not understood phenomenon, named “dark energy”. One important method of distinguishing between the various explanations is to compare the distribution of galaxies at different epochs in the evolution of the Universe to the distribution of matter at the time when the Cosmic Microwave Background (CMB) was formed. Small distortions in the distribution of matter, called baryon acoustic oscillations, should persist from the era of CMB formation until today. Tracking if and how these ripples change in size and spacing over cosmic time can then tell us if one of the existing models for dark energy is correct or if a new idea is needed. A deep all-sky SKA survey will detect hydrogen emission from Milky Way-like galaxies out to redshifts of about 1. The galaxy observations will be “sliced” in different redshift (time) intervals and hence reveal a comprehensive picture of the Universe’s history.

  The same data set will give us unique information about the evolution of galaxies, how the hydrogen gas was concentrated to form galaxies, how fast it was transformed into stars, and how much gas did galaxies acquire during their lifetime from intergalactic space. The HI survey will simultaneously give us the synchrotron radiation intensity of the galaxies which is a measure of their star-formation rate and magnetic field strength.

- Tests of General Relativity and detection of gravitational waves

  Pulsars are ideal probes for experiments in the strong gravitational field around black holes have yet been made. We expect that almost all pulsars in the Milky Way will be detected with the SKA (Fig. 5) plus several 100 bright pulsars in nearby galaxies. The SKA will search for a radio pulsar orbiting around a black hole, measure time delays in extremely curved space with much higher precision than with laboratory experiments and hence probe the limits of General Relativity.

Regular high-precision observations with the SKA of a network of pulsars with periods of milliseconds opens the way to detect gravitational waves with wavelengths of many parsecs, as expected for example from two massive black holes orbiting each other with a period of a few years resulting from galaxy mergers in the early Universe. When such a gravitational wave passes by the Earth, the nearby space-time changes slightly at a frequency of a few nHz (about 1 oscillation per 30 years). The wave can be detected as apparent systematic delays and advances of the pulsar clocks in particular directions relative to the wave propagation on the sky.

- The cradle of life

  The SKA will be able to detect the thermal radio emission from centimeter-sized "pebbles" in protoplanetary systems which are thought to be the first step in assembling Earth-like planets. Biomolecules are observable in the radio range. Prebiotic chemistry - the formation of the molecular building blocks necessary for the creation of life - occurs in interstellar clouds long before that cloud collapses to form a new solar system. Finally, the SETI (Search for Extra Terrestrial Intelligence) project will use the SKA to find hints of technological activities. Ionospheric radar experiments similar to those on Earth will be detectable out to several kpc, and Arecibo-type radar beams, like those that we use to map our neighbor planets in the solar system, out to as far as a few 10 kpc.

- Origin and evolution of cosmic magnetism

  Synchrotron radiation and Faraday rotation revealed magnetic fields in our Milky Way, nearby spiral galaxies, and in galaxy clusters, but little is known about magnetic fields in the intergalactic medium. Furthermore, the origin and evolution of magnetic fields is still unknown. The SKA will measure the Faraday rotation towards several tens of million polarized background sources (mostly quasars), allowing us to derive the magnetic field structures and strengths of the intervening objects, such as, the Milky Way, distant spiral galaxies, clusters of galaxies, and in intergalactic space – see below.

From the five Key Science Projects two major science goals have been identified that drive the technical specifications for the first phase (SKA_1):

- Origins: Understanding the history and role of neutral hydrogen in the Universe from the dark ages to the present-day.
- Fundamental Physics: Detecting and timing binary pulsars and spin-stable millisecond pulsars in order to test theories of gravity.

6 Future magnetic field observations

Next-generation radio telescopes will widen the range of observable magnetic phenomena. At low frequencies, synchrotron emission will be observed from aging electrons far away from their places of origin. Low frequencies are also ideal to search for small Faraday rotation

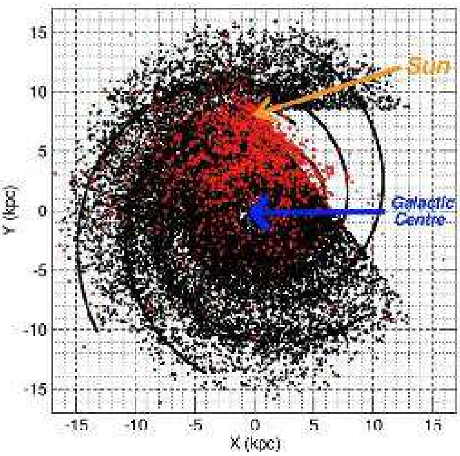

Figure 5: Known pulsars in the Milky Way (red) and pulsars expected with the SKA (black). Simulation: Michael Kramer, MPIfR Bonn.

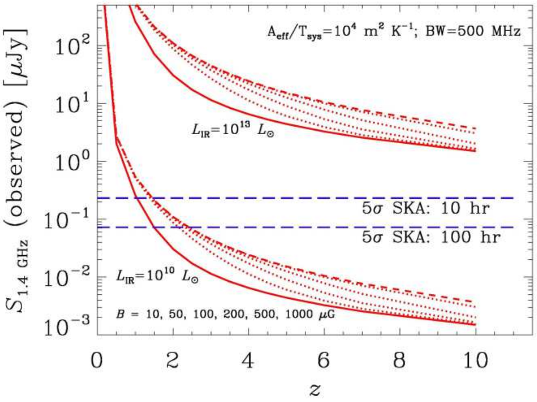

Figure 6: Total synchrotron emission of galaxies at 1.4 GHz as a function of redshift z and magnetic field strength B, and the 5σ detection limits for 10 h and 100 h integration time with the SKA (Murphy 2009).

measures from weak interstellar and intergalactic fields (Arshakian & Beck 2011) and in steep-spectrum cluster relics (Brunetti et al. 2008). The recently completed LOFAR (operating at 10–240 MHz), followed by the MWA and the LWA (both under construction), are suitable instruments to search for weak magnetic fields in outer galaxy disks, galaxy halos and cluster halos. First LOFAR results have been presented at this conference (Anderson et al., Mulcahy et al., this volume).

LOFAR will detect all pulsars within 2 kpc of the Sun and discover about 1000 new nearby pulsars, especially at high latitudes (van Leeuwen & Stappers 2010). Most of these are expected to emit strong, linearly polarized signals at low frequencies. This will allows us to measure their RMs and to derive the magnetic field structure near to the Sun.

Deep high-resolution observations at high frequencies, where Faraday effects are small, require a major increase in sensitivity of continuum observations, to be achieved by the EVLA and the SKA. The detailed structure of the magnetic fields in the ISM of galaxies, in galaxy halos, cluster halos and cluster relics will be observed. The magnetic power spectra can be measured (Vogt & Enßlin 2005). Direct insight into the interaction between gas and magnetic fields in these objects will become possible. The SKA will also allow to measure the Zeeman effect of weak magnetic fields in the Milky Way and in nearby galaxies.

Detection of polarized emission from distant, unresolved galaxies will reveal large-scale ordered fields (Stil et al. 2009), to be compared with the predictions of dynamo theory (Arshakian et al. 2009). The SKA will detect Milky-Way type galaxies at $z \leq 1.5$ (Murphy 2009) and their polarized emission at $z \leq 0.5$ (assuming 10% polarization). Cluster "relics" are highly polarized (van Weeren et al. 2010) and will also be detectable at large redshifts.

Bright starburst galaxies are not expected to host ordered fields. Unpolarized synchrotron emission from starburst galaxies, signature of turbulent magnetic fields, will be detected with the SKA out to large redshifts, depending on luminosity and magnetic field strength (Fig. 6), and from cluster halos. However, for fields weaker than $3.25\,\mu$G $(1+z)^2$, energy loss of cosmic-ray electrons is dominated by the inverse Compton effect with CMB photons, so that the energy appears mostly in X-rays, not in the radio range. On the other hand, for strong fields the energy range of the electrons emitting at a 1.4 GHz drops to low energies, where ionization and bremsstrahlung losses become dominant (Murphy 2009). In summary, the mere detection of synchrotron emission of galaxies at high redshifts will constrain the range of allowed magnetic field strengths.

If polarized emission from galaxies, cluster halos or cluster relics is too weak to be detected, the method of *RM grids* towards background QSOs can still be applied and allows us to determine the field strength and pattern in an intervening galaxy. This method can be applied to distances of young QSOs ($z \simeq 5$). Regular fields of several μG strength were already detected in distant galaxies (Bernet et al. 2008, Kronberg et al. 2008). Mean-field dynamo theory predicts RMs from evolving regular fields with increasing coherence scale at $z \leq 3$ (Arshakian et al. 2009). (Note that the observed RM values are reduced by the redshift dilution factor of $(1+z)^{-2}$.) A reliable model for the field structure of nearby galaxies, cluster halos and cluster relics needs RM values from a large number of polarized background sources, hence large sensitivity and high survey speed (Krause et al. 2009).

The *POSSUM* all-sky survey at 1.1–1.4 GHz with the ASKAP telescope (under construction) with about $30\,\mathrm{deg}^2$ field of view will measure about 100 RMs of extragalactic sources per square degree within 10 h integration time.

The *SKA Magnetism Key Science Project* plans to observe a wide-field survey (at least $10^4\,\mathrm{deg}^2$) around 1 GHz with 1 h integration per field which will detect sources of 0.5–1 μJy flux density and measure at least $1500\,\mathrm{RMs}\,\mathrm{deg}^{-2}$. This will contain at least $1.5\,10^7$ RMs from compact polarized extragalactic sources at a mean spacing of $\simeq 90''$ (Gaensler et al. 2004). This survey will be used to model the structure and strength of the magnetic fields in the Milky Way, in intervening galaxies and clusters and in the intergalactic medium (Beck & Gaensler 2004). The SKA pulsar survey will find about 20,000 new pulsars which will mostly be polarized and reveal RMs (Fig. 5), suited to map the Milky Way's magnetic field with high precision. More than 10,000 RM values are expected in the area of the galaxy M 31 and will allow the detailed reconstruction of the 3-D field structure. Simple patterns of regular fields can be recognized out to distances of about 100 Mpc (Stepanov et al. 2008) where the polarized emission is far too low to be mapped. The evolution of field strength in cluster halos can be measured by the RM grid method to redshifts of about 1 (Krause et al. 2009).

If the filaments of the local Cosmic Web outside clusters contain a magnetic field (Ryu et al. 2008), possibly enhanced by IGM shocks, we hope to detect this field by direct observation of its total synchrotron emission (Keshet et al. 2004) and possibly its polarization, or by Faraday rotation towards background sources. For fields of $\approx 10^{-8} - 10^{-7}\,$G with 1 Mpc coherence length and $n_e \approx 10^{-5}\,\mathrm{cm}^{-3}$ electron density, Faraday rotation measures between 0.1 and $1\,\mathrm{rad\,m}^{-2}$ are expected which will be challenging to detect even with LOFAR. More promising is a statistical analysis like the measurement of the power spectrum of the magnetic field of the Cosmic Web (Kolatt 1998) or the cross-correlation with other large-scale structure indicators like the galaxy density field (Stasyszyn et al. 2010).

If an overall IGM field with a coherence length of a few Mpc existed in the early Universe and its strength varied proportional to $(1+z)^2$, its signature may become evident at redshifts of $z > 3$. Averaging over a large number of RMs is required to unravel the IGM signal. The goal is to detect an IGM magnetic field of 0.1 nG, which needs an RM density of ≈ 1000 sources deg^{-2} (Kolatt 1998), achievable with the SKA. Detection of a general IGM field, or placing stringent upper limits on it, will provide powerful observational constraints on the origin of cosmic magnetism.

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