Cutting Edge Scientific Researches With The Most Powerful Radio Telescopes—A survey

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Contents

This is a survey of current cutting edge scientific and engineering research projects which associated with the design, construction and utilization of the most powerful radio telescopes around the world, such as SKA/MWA, LOFAR, ALMA, FAST, VLA, VLBI, VLBA, etc.

1 Introduction

2 The Square Kilometre Array (SKA)[2]

SKA project is an international effort to build the world's largest radio telescope, with eventually over a square kilometre (one million square metres) of collecting area. The scale of the SKA represents a huge leap forward in both engineering and research & development towards building and delivering a unique instrument, with the detailed design and preparation now well under way. As one of the largest scientific endeavours in history, the SKA will bring together a wealth of the world's finest scientists, engineers and policy makers to bring the project to fruition.

2.1 The key science goals

The SKA will be able to conduct transformational science, breaking new ground in astronomical observations. SKA scientists have focussed on various key science goals for the telescope, each of which will re-define our understanding of space as we know it.

From challenging Einstein's seminal theory of relativity to the limits, looking at how the very first stars and galaxies formed just after the big bang, in a way never before observed in any detail, helping scientists understand the nature of a mysterious force known as dark energy, the discovery of which gained the Nobel Prize for physics, through to understanding the vast magnetic fields which permeate the cosmos, and, one of the greatest mysteries known to humankind ... are we alone in the Universe, the SKA will truly be at the forefront of scientific research.

Early science observations are expected to start in the mid-2020s with a partial array.

From [3]: The SKA aims to solve some of the biggest questions in the field of astronomy.

The unprecedented sensitivity of the thousands of individual radio receivers, combining to create the world's largest radio telescope will give astronomers insight into the formation and evolution of the first stars and galaxies after the Big Bang, the role of cosmic magnetism, the nature of gravity, and possibly even life beyond Earth.

If history is any guide, the SKA will make many more discoveries than we can imagine today.

The science key drivers for the SKA have been broken down in to key categories, each of which has its own working group to facilitate and manage the scientific goals.

Some Of The Main SKA Science Drivers Include:

- Galaxy evolution, cosmology and dark energy by mapping the cosmic distribution of hydrogen
- Strong-field tests of gravity using pulsars and black holes
- The origin and evolution of cosmic magnetism by high-sensitivity mapping of polarised synchrotron emission, combined with determinations of rotation measures (RM) for extended emission
- Probing the Cosmic Dawn by observing the redshifted 21cm line of neutral hydrogen which will provide detailed pictures of structure formation and reionisation
- The cradle of life by detecting extremely weak extraterrestrial radio signals, by imaging the thermal emission from dust in the habitable zone in unprecedented detail. In particular, the SKA will show where dust evolves from micron-sized interstellar particles to centimetre-sized and larger "pebbles", the first step in assembling Earth-like planets
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2.1.1 Galaxy evolution, cosmology and dark energy[8]

How do galaxies evolve? What is dark energy?
The acceleration in the expansion of the Universe has been attributed to a mysterious dark energy. The SKA will investigate this expansion after the Big Bang **by mapping the cosmic distribution of hydrogen**.

Our Universe is expanding, and we have recently discovered that this expansion is accelerating. Scientists are still trying to understand why this is happening, with theories such as a force known as "dark energy" being put forward. The detection of this acceleration won the Nobel Prize for physics in 2011.(for the discovery of the accelerating expansion of the Universe through observations of distant supernovae.)

This mysterious acceleration, however, is still one of the most fundamental mysteries of modern science and also one of the key questions the SKA will try to address.**One of the main science goals of the SKA is to investigate why this acceleration is taking place, by looking at the distribution of the most basic element, Hydrogen, throughout the cosmos. The SKA's unrivalled sensitivity will be able to track young, newly forming galaxies at the edge of the known Universe, and by mapping the distribution of**

Hydrogen, help us unravel this key mystery, and understand more how the earliest galaxies evolved.

Hydrogen is the most abundant element in the Universe and is the raw material from which stars form. Over 70% of our Sun is Hydrogen, and as a radio source, the Sun is one of the brightest objects not only in the visible sky but also in the radio.

Hydrogen atoms produce radio emission at a wavelength of 21cm or a frequency of 1420 MHz. This emission was first discovered from the hydrogen gas clouds within our Milky Way Galaxy in the 1930s by Karl Jansky, an engineer at Bell Laboratories.

Since then, hydrogen gas has been found in tens of thousands of galaxies, most of which are relatively near to the Milky Way. **Generally, astronomers find that spiral galaxies, like our Milky Way Galaxy, and irregular galaxies, like the Magellanic Clouds, often contain large amounts of hydrogen gas.** These galaxies also form stars and astronomers believe that hydrogen gas provides the raw fuel for star formation.

Aside from dark energy, this mysterious force thought to be causing the acceleration of the expansion in the Universe, there is also Dark Matter, which astronomers believe makes up a large fraction of all matter in the Universe. **The study of this came about after anomalies were found in the rotation rates and masses of galaxies, based on their visible characteristics and the values derived from observation.**

The SKA will revolutionise our study of how galaxies form and transform their gas into stars by detecting hydrogen gas in surveys which encompass as many as a billion galaxies, at distances much greater than is possible to detect today.

- What is dark energy?

  Cosmology is the study of the origin and fate of the Universe. Prior to the discovery that the expansion of the Universe is actually accelerating, astronomers had thought that the expansion should be slowing under the mutual gravitational attraction of galaxies. Instead, it seems that the Universe contains some additional component, which astronomers have termed "dark energy"

  This mysterious force appears to counteract and even surpass the mutual gravitational attraction causing acceleration in the expansion. It could however indicate that our understanding of gravity, as described by Einstein's General Theory of Relativity, is incomplete.

  There are two broad approaches that the SKA will pursue in studying cosmology:

  - The first approach involves a large survey of galaxies, searching for their (redshifted) 21 cm hydrogen emission. An extremely large survey of galaxies is required in order to sample a large enough of volume in the Universe that one can detect relatively subtle effects.
  - Another approach by which the SKA can study cosmology and dark energy is to observe the gravitational effects of galaxies and clusters of galaxies on the path of radio waves through the Universe.

Einstein's Theory of Relativity relates mass to energy and shows that both mass and energy contribute to gravitation. Concentrations of mass have the effect of disturbing the path that radio waves take in their path to the Earth. In effect, concentrations of mass, such as galaxies and clusters of galaxies, can act as giant lenses in space.

Thus, if there is a galaxy behind another galaxy, or behind a cluster of galaxies, the shape of the background galaxy will appear distorted because the path(s) that the radio waves have taken has been distorted by the foreground galaxy or cluster.

By measuring the amount of distortion of background galaxies, astronomers can infer how much mass (both regular matter and dark matter) is between the background galaxies and us and a measure of how this mass is distributed. In turn, how the mass is distributed can be affected by the properties of dark energy, and aspects of cosmology. **Thus, measurements of the shapes of large numbers of galaxies can be used to constrain models of the cosmology of the Universe.**

- How do galaxy evolve?
  Radio telescopes have played a pivotal role in the understanding of galactic evolution. Their ability to "see" regions beyond the optical view of a galaxy have brought significant insights into how galaxies form and develop. However, despite this progress, it is still a mystery as to how the early galaxies, in the millions of years following the Big Bang, began to evolve: where did they get their material? What drives their rotation? What has shaped them? The SKA's unrivalled sensitivity and resolution will be able to track young, newly forming galaxies at cosmological distances, and, through mapping the distribution of Hydrogen, help us unravel these key mysteries.

- Rotation & dark matter
  Hydrogen gas moving at different velocities within a galaxy will be detected at slightly different frequencies because of the Doppler effect. Astronomers can infer how quickly a galaxy is rotating by measuring the range of frequencies over which a galaxy's 21cm radiation occurs. From these measurements, it is possible to deduce the total mass of the galaxy, as it must have enough mass to ensure that it remains whole (and essentially does not fly apart!). This amount of mass can be compared with that estimated from

the stars and gas that we can visibly observe in the galaxies.

Often the hydrogen gas is rotating faster, sometimes much faster, than the amount of mass contributed by the stars and gas would suggest, implying there has to be some other kind of matter within galaxies – so-called dark matter – that produces no light, but produces gravitational attraction such that the galaxy does not fly apart.

Redshift explained:
Astronomers typically measure distances to very distant galaxies using the redshift effect. Consider observing the hydrogen gas in a distant galaxy. To an astronomer in that galaxy, the hydrogen gas emits radio emission at its characteristic 21cm wavelength.

However, because the galaxy is distant, it takes some time for the radio emission to travel to astronomers here on Earth. During that time, the Universe expands, which has the effect of increasing the wavelength at which we detect the radio emission from the hydrogen gas. The difference between the observed wavelength and expected wavelength is then a measure of how distant the galaxy is as well as being a measure of how much time has elapsed since the light was emitted.

For instance, with a large sample of galaxies, one can track how galaxies form into clusters. How quickly the clusters form is partly a balancing act between gravity, which causes galaxies to fall together into a cluster, and dark energy, which acts to separate the galaxies. How big, and how rapidly, clusters form is a measure of the strength of dark energy, which can help astronomers understand better what it is.

- Origin of gas & satellite galaxies
  Observations of the hydrogen gas in spiral galaxies, like our Milky Way Galaxy, **are revealing small clouds of hydrogen at large distances from the galaxy, but how did that gas get there?** There are at least three possibilities:
  1. The gas has been blown out of the galaxy by powerful winds from hot, young stars, and once sufficiently far away from the influence of the stars, has started to fall back onto the galaxy.
  2. The gas represents 'pristine' or 'primordial' material from the very early Universe. It is possible that not all of the hydrogen in the Universe was captured within galaxies. Some of it is likely to still be in the space between the galaxies. Over time, that gas may slowly fall into galaxies, probably in the form of small clouds.
  3. The gas represents starless satellite galaxies. **Numerical simulations of how galaxies form suggest that a major galaxy like the Milky Way should be surrounded by many smaller galaxies. However, various attempts to find such a quantity of smaller satellite galaxies have been unsuccessful. It is possible that some of these satellite galaxies have not yet formed stars, but consist only of gas(那就是数值模拟设置的演化时间太长了?把它设短**

一些能符合现在的观测(small clouds of hydrogen)吗?) (or the numerical simulations are not fully describing all of the physics!).

- Ongoing Observations
  Observations of many more galaxies are required to distinguish between the possibilities, and the SKA will conduct surveys for clouds of gas and search for undiscovered star-less satellite galaxies lurking around major galaxies.

  Both the star light and the hydrogen gas in galaxies in the relatively local Universe have been mapped in exquisite detail over the last few years by projects which are providing key scientific input into the SKA such as the HI Parkes All Sky Survey (HIPASS), Arecibo Legacy Fast ALFA (ALFALFA) survey, the 2dF Galaxy Redshift Survey and the Sloan Digital Sky Survey (SDSS).

  Our challenge now with the SKA is to provide equally good measurements in the distant Universe. Such measurements will enable astronomers to track how galaxies acquired the hydrogen gas, from which stars could form, as well as track the various processes by which galaxies might gain or even lose gas.

- How does the increased sensitivity and resolution of the SKA play a role in this work?
  Sensitivity is a measure of the minimum signal that a telescope can distinguish above the random background noise. The more sensitive a telescope, the more light it can gather from faint and distant objects.

  The SKA's sensitivity stems from the huge number of radio receivers at low, mid and high frequencies, which will combine in each frequency range from the locations in Africa and Australia to form a collecting area equivalent to a single radio telescope 1km wide.

  Resolution is a measure of the minimum size that a telescope can distinguish, effectively going from a blurry image to discerning the detail. The large distances between receivers of the SKA will provide the ability to distinguish the details. The combined factors of sensitivity and resolution will dwarf all existing telescopes currently in operation, and give the SKA an unparalleled view of the early formation of our Universe.

  Radio wavebands are particularly advantageous for this experiment because the point-spread function is well determined and stable (being simply the interferometer baseline distribution), solving the principle systematic difficulty inherent in the method.

  In addition to detecting hydrogen emission in galaxies, the SKA will also **perform the**

deepest ever radio continuum survey, probing the star-formation history of the Universe as a function of redshift in a manner independent of the dust extinction (dust hiding objects behind it, which affects optical telescopes).

With radio surveys, the dust which blocks a large proportion of the visible light is penetrated, revealing the complex structures and individual stars which lie within.

It will be of great interest to scientists who will be able to link the star formation properties of galaxies to their hydrogen contents, as a function of redshift and environment. Furthermore, a high resolution radio continuum survey over wide areas allows a precise measurement of the coherent shape distortions of distant galaxies imparted by the foreground cosmic web, distortions similar to that created by a lens being placed in front of an object being seen in visible light, but using the force of gravity instead of a lens.

This weak gravitational lensing encodes a vast body of cosmological information, and its exploitation will become one of our key cosmological probes within the next decade.

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nteresting facts
A small portion of the hiss you get when you detune an old style analogue TV was due to radio waves from the Big Bang itself, that is the birth of the Universe.
Data from space telescopes looking at the Cosmic Microwave Background sky has shown the Universe is approximately 13.8 billion years old.
The SKA will enable scientists to study this galactic formation at distances much greater than is possible to detect today.

2.1.2 Strong-field tests of gravity using pulsars and black holes

Was Einstein right about gravity? The SKA will investigate the nature of gravity and challenge the theory of general relativity.

2.1.3 The origin and evolution of cosmic magnetism[6]

What generates giant magnetic fields in space?
The SKA will create three-dimensional maps of cosmic magnets to understand how they stabilise galaxies, influence the formation of stars and planets, and regulate solar and stellar activity.

Magnetism has been fundamental for travelling and exploring our planet, with the Earth's magnetic field guiding birds, bees and compass needles.
Furthermore, the effect of the Earth's magnetic field on charged particles from the Sun has both shielded us from their harmful effects and entranced us with the beautiful aurorae light-

ing up the northern and southern polar skies.
Through decades of astrophysical research, we have established that magnetism is ubiquitous in our Universe, with interstellar gas, planets, stars and galaxies all showing the presence of magnetic fields. Generating magnetic fields on such large physical scales cannot be achieved through permanent magnets like those found in school science kits, but instead requires huge densities, volumes or motions of electrically charged material, such as the gas that pervades the Milky Way or the outflows of material from the energetic centres of galaxies

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Cosmic magnetism spans an enormous range in its strength, varying by a factor of a hundred billion billion between the weak magnetic fields in interstellar space and the extreme magnetism found on the surface of collapsed stars. Because these cosmic magnetic fields are all-pervasive, they play a vital role in controlling how celestial sources form, age and evolve.

- The challenge and opportunities with magnetism
  The challenge in studying cosmic magnetism is that, while stars and galaxies can be seen directly by the light they emit, magnetic fields are invisible even to the largest optical telescopes instead requiring the detection of polarised radiation, radiation which exhibits the effects of magnetic fields.

  One such example is synchrotron emission, produced when fast-moving (close to the speed of light) electrons, are trapped in magnetic fields, in a similar manner to the way planets are caught by the Sun's gravity. If we see a heavenly body emitting synchrotron emission, we know that this object must be magnetic, and we can use its properties to determine how strong its magnetic field is and what direction a compass might point if it were near it.

  Not all objects, however, are energetic enough to produce synchrotron emission and in these cases other mechanisms are utilised. **The spectrally narrow emission from atoms and molecules can be split by the effects of magnetic fields, into two or more emission 'lines'. This effect, known as "Zeeman Splitting" after the Dutch Physicist Pieter Zeeman, provides a direct measure of the magnetic environment of the atoms and molecules.**

  Another remarkable mechanism is when the polarised radiation from a distant object passes though the magnetic field of an intervening object and is altered. This effect, known as "Faraday rotation" after the British Scientist Michael Faraday, provides a measure of the magnetic environment of the intervening object (specifically the plane of polarisation is rotated by an angle proportional to the strength of the magnetic field and the density of the medium).

  The difficultly with both these techniques is to truly understand the magnetic fields we are seeing we require many hundreds or even thousands of measurements, in the case of Faraday rotation, many distant galaxies or pulsars, lying directly behind the magnetised gas we want to study – like trying to make an environmental study of a large lake, dipping one's finger in the water at one location is not enough!

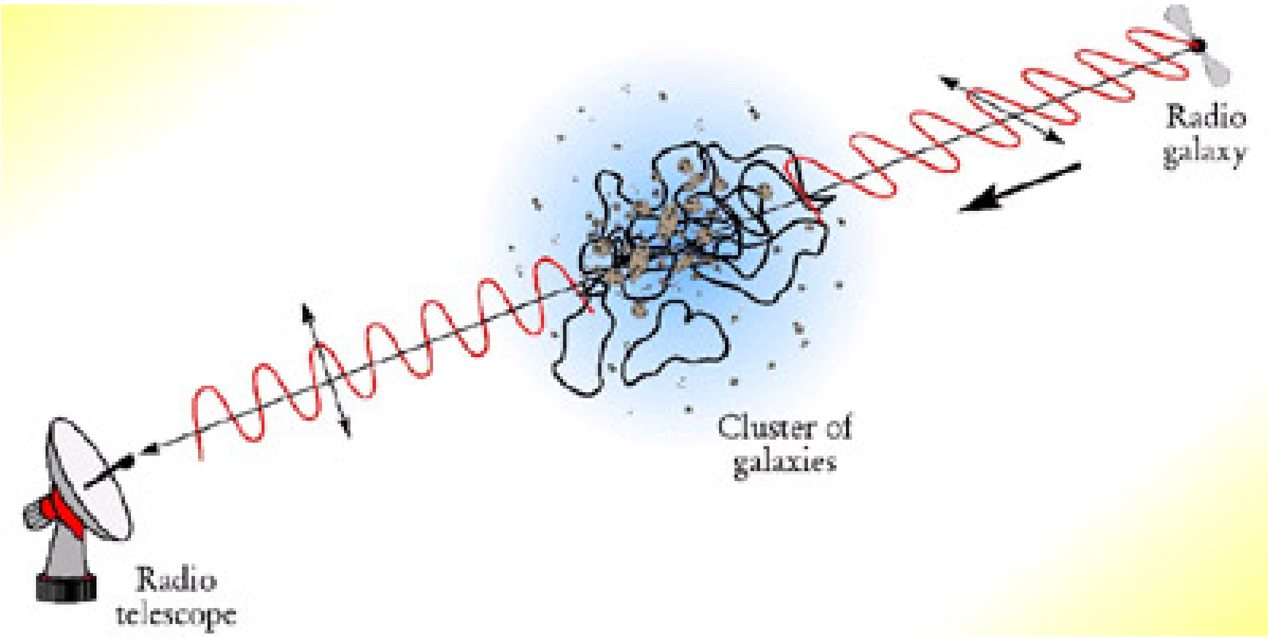

Figure 1: When the polarised radio emission from a background galaxy passes through a foreground cloud of magnetic gas, the emission undergoes Faraday Rotation. This effect can be detected with a radio telescope, and used to measure the strength of cosmic magnetic fields. Reprinted with permission from "Intergalactic Magnetic Fields" by Philipp P. Kronberg, Physics Today, December 2002, p. 40. Copyright 2002, American Institute of Physics.[6]

Since the Square Kilometre Array (SKA) will be so much more sensitive than current telescopes, we can use it to revolutionise the study of magnetic fields in space. If we point the SKA at any part of the sky, we will detect the radio emission from thousands of distant faint galaxies, spread like grains of sand all over the sky. These galaxies will be so closely spaced that we can use the Faraday rotation of their polarised radio emission to make detailed studies of the magnetism of all sorts of foreground objects.
Even if we want to study a relatively small cloud of gas, there will be hundreds of background galaxies whose light shines through it, allowing us to build up a detailed picture of the cloud's magnetism.

Through the mechanisms of Faraday rotation, Zeeman splitting and measuring the direct affects of magnetic fields on the polarised properties of radiation, we will be able to address many important unanswered questions:

What is the shape and strength of the magnetic field in our Milky Way, and how does this compare to the magnetism in other galaxies? Is the Universe itself magnetic, and what role has this had on the formation of individual stars and galaxies? Where and how do the magnetic fields originate?
These are all questions for which the unique and fascinating capabilities of the SKA will provide incredible insight. We know that magnetism surrounds us, but with the SKA, we will transform our understanding of what these magnets look like, where they came from, and what role they have played in the evolving Universe.

The main platform on which the SKA's studies of cosmic magnetism will be based will be an All-Sky SKA Rotation Measure Survey, in which a year of observing time will yield Faraday rotation measures (RMs) for compact polarized extragalactic sources, an increase by five orders of magnitude over current data sets, and by three orders of magnitude over what could be accomplished with the Extended Very Large Array (EVLA). This data-set will provide an all-sky grid of RMs at a spacing of just 20–30 arcsec between sources; many these sources will have redshifts from the Sloan Digital Sky Survey (SDSS) and its successors. This RM grid will be a powerful probe for studying foreground magnetic fields at all redshifts.

- Understanding cosmic magnetism
  Understanding the Universe is impossible without understanding magnetic fields. **They fill interstellar space, affect the evolution of galaxies and galaxy clusters, contribute significantly to the total pressure of interstellar gas, are essential for the onset of star formation, and control the density and distribution of cosmic rays in the interstellar medium (ISM).**
  In spite of their importance, the origin of magnetic fields is still an open problem in fundamental physics and astrophysics. Did significant primordial fields exist before the first stars and galaxies? If not, when and how were magnetic fields subsequently generated? What maintains the present-day magnetic fields of galaxies, stars and planets?
  The most powerful probes of astrophysical magnetic fields are radio waves.
  Synchrotron emission measures the field strength, while its polarisation yields the field's orientation in the sky plane and also gives the field's degree of ordering. Faraday rotation yields a full three-dimensional view by providing information on the field component along the line of sight, while the Zeeman effect provides an independent measure of field strength in cold gas clouds.
  However, measuring cosmic magnetic fields is a difficult topic still in its infancy, restricted to nearby or bright objects.

- The SKA's role
  Through the unique sensitivity and resolution of the Square Kilometre Array (SKA), the

window to The Magnetic Universe can finally be fully opened. Apart from the questions we can pose today, it is important to bear in mind that the SKA will certainly discover new magnetic phenomena beyond what we can currently predict or even imagine.
For the Milky Way and for nearby galaxies and clusters, high-sensitivity mapping with the SKA of polarised synchrotron emission, combined with determinations of rotation measures (RM) for extended emission, for pulsars and for the background RM grid mentioned above will allow us to derive detailed three-dimensional maps of the strength, structure and turbulent properties of the magnetic field in these sources, which can be compared carefully with the predictions of various models for magnetic field generation.

At intermediate redshifts, polarised emission from galaxies will often be too faint to detect directly, but the magnetic fields of these sources can be traced by the RMs they produce in the polarised background grid. This will allow detailed studies of the magnetic field configuration of individual objects at earlier epochs; comparison with studies of local galaxies will allow us to understand how magnetised structures evolve and amplify as galaxies mature.

Furthermore, from a statistical standpoint, the large number of RMs obtained from intervening galaxies and Ly-alpha absorbers will allow us to distinguish between competing models for galaxy and magnetic field evolution as a function of redshift.

At yet higher redshifts, we will take advantage of the sensitivity of the deepest SKA fields, in which we expect to detect the synchrotron emission from the youngest galaxies and proto-galaxies. RMs of the most distant polarised objects (e.g., gamma-ray bursts and quasars beyond the epoch of re-ionisation) can constrain magnetic field strengths at the earliest epoch of galaxy formation, and help distinguish between primordial and seed origins for present-day magnetic fields.

Using the unique sensitivity of the SKA, it may even be feasible to measure Faraday rotation against the Cosmic Microwave Background produced by primordial magnetic fields.

Fundamental to all these issues is the search for magnetic fields in the intergalactic medium (IGM). All empty space may be magnetised, either by outflows from galaxies, by relic lobes of radio galaxies, or as part of the cosmic web structure. Such a field has not yet been detected, but its role as the likely seed field for galaxies and clusters, plus the prospect that the IGM field might trace and regulate structure formation in the early Universe, places considerable importance on its discovery.

This all-pervading cosmic magnetic field can finally be identified through the all-sky RM survey proposed above. Just as the correlation function of galaxies yields the power spectrum of matter, the analogous correlation function of this RM distribution can then provide the magnetic power spectrum of the intergalactic medium (IGM) as a function of cosmic epoch and over a wide range of spatial scales. Such measurements will allow us to develop a detailed model of the magnetic field geometry of the IGM and of the overall Universe.

In summary, the sheer weight of RM statistics from the SKA, combined with deep polarimetric observations of individual sources, will allow us to characterize the geometry and evolution of magnetic fields in galaxies, clusters and the IGM from high redshifts through to the present, to determine whether there is a connection between the formation of magnetic fields and the formation of structure in the early Universe, and to provide solid constraints on when and how the first magnetic fields in the Universe were generated.

Find out more: The origin and evolution of cosmic magnetism – B. M. Gaensler(Harvard-Smithonian Center for Astrophysics), R. Beck(Max-Planck-Institut für Radioastronomie), L. Feretti(Istituto di Radioastronomia CNR/INAF) – in Science with the Square Kilometre Array, 2004

Abstract:
Magnetism is one of the four fundamental forces. However, the origin of magnetic fields in stars, galaxies and clusters is an open problem in astrophysics and fundamental physics. When and how were the first fields generated? Are present-day magnetic fields a result of dynamo action, or do they represent persistent primordial magnetism? What role do magnetic fields play in turbulence, cosmic ray acceleration and galaxy formation? Here we demonstrate how the Square Kilometer Array (SKA) can deliver new data which will directly address these currently unanswered issues. Much of what we present is based on an all-sky survey of rotation measures, in which Faraday rotation towards $> 10^7$ background sources will provide a dense grid for probing magnetism in the Milky Way, in nearby galaxies, and in distant galaxies, clusters and protogalaxies. Using these data, we can map out the evolution of magnetised structures from redshifts $z > 3$ to the present, can distinguish between different origins for seed magnetic fields in galaxies, and can develop a detailed model of the magnetic field geometry of the intergalactic medium and of the overall Universe. With the unprecedented capabilities of the SKA, the window to the Magnetic Universe can finally be opened.

We thank JinLin Han, [also], ..., for useful comments.[1]

Interesting fact
On Earth our magnetic field helps to channel the stream of particles from the Sun, known as the solar wind to the poles, forming the aurora seen in high northern and southern latitudes. These aurorae have also been observed on the outer gas giant planets as far out as Neptune, showing just how much of an influence the Solar wind has.

2.1.4 Probing the Cosmic Dawn[9]

How were the first black holes and stars formed?
The SKA will look back to the Dark Ages, a time before the Universe lit up, to discover how the earliest black holes and stars were formed.

- The first black holes and stars
  Our understanding of cosmology has expanded greatly in recent years. On the one hand, detailed observations of the cosmic microwave background (CMB) have shown us a 'baby picture' of the universe as it was only 300,000 years after the Big Bang. During the next roughly half billion years, structures on all scales began to collapse under gravity and the first galaxies formed.

- How will the SKA peer in to this largely unknown era?
  Space and ground-based telescopes have given us unprecedented views of distant Universe. Optical and infrared telescopes have imaged galaxies at distances over 13 billion light years from Earth, at a time when the Universe was less than a billion years old. The promise of large infrared telescopes in space and giant optical telescopes on the ground should reveal even more distant and sensitive views of early galaxies.
  Space telescopes like Planck that observe the CMB radiation have mapped the light from the very early Universe, just after the moment of the Big Bang.
  One of the last frontiers in cosmology is to explore this cosmological dawn when the first galaxies formed, and the SKA is the most sensitive radio telescope that will conduct such studies. This period in the early Universe that will be studied started around 380,000 years after the Big Bang, when the Universe was mostly dark until the first galaxies began to shine.
  It is an age in which these proto-galaxies and quasars formed and has been one of the most difficult epoch's of the Universe to explore, as these objects are exceptionally faint and much of their light is absorbed by intervening matter as it travels toward us.
  The sensitive optical and infrared sky surveys have shown that these young galaxies are unlike anything we observe in the local Universe, with stars that could be orders of magnitude larger than our own Sun, and with much shorter lifetimes.
  The SKA, through imaging of the atomic Hydrogen gas, will provide pictures of the period during and after the formation of the earliest sources of light in our Universe, providing the first detailed measurements ever of the conditions under which they formed occurring in this mysterious time.

- What is the epoch of reionisation?
  Prior to the first structures such as galaxies and stars forming in the Universe most of the gas, which was predominantly Hydrogen in the early universe, was fairly evenly distributed and electrically neutral. This is known as the Dark Ages.
  A special property of neutral hydrogen is that it produces weak radiation at a wavelength of 21cm, which in theory can be used to study this period, but in practice, its signal is very faint, and difficult to detect through the Earth's ionosphere.
  However, once the first celestial objects, proto-galaxies and stars, started to form through

gravitational instabilities, their light ionised pockets of the gas around them, switching off the 21cm emission from these regions. Astronomers have labelled this important event as "reionisation".

This era in the formation of the Universe has proven difficult to study. Not only are proto-galaxies extremely distant and faint, the key problem is that much of their light in optical and even out to the infra-red is absorbed as it travels toward us.

Tantalising clues from the Wilkinson Microwave Anisotropy Probe (WMAP) and the Sloan Digital Sky Survey (SDSS) telescopes have scientists excited, as these objects display characteristics which are unlike anything they have seen before.

For example, the first proto-galaxies may form through different mechanisms than our own Milky Way, and the stars inside these objects may be hundreds of times more massive than our own sun.

- Quasars

  The quest to observe the first luminous objects in the universe has long been an important driver of astronomy in general and cosmology in particular.

  Interest in these objects has only grown recently with new observations by the WMAP and high-redshift quasars selected from the SDSS.

  A "quasar" or quasi-stellar radio source is a very energetic and distant active galactic nucleus. They are exceptionally bright, and very far away.

  First identified as being high redshift (z) objects, they emit strongly in the radio end of the spectrum.

  While the nature of these objects was controversial until as recently as the early 1980s, there is now a consensus in the science community that they are compact regions nearby black holes in the central areas of massive galaxies.

  As they occur at such vast distances, they are part of the jigsaw aiming to piece together the formation of the early Universe from its Hydrogen rich beginnings, through to the time period when then first stars and galaxies started to form.

  The fraction of ionised hydrogen left over from the Big Bang provides evidence for the time of formation of the first stars and quasar black holes in the early Universe. Think of the neutral fraction as the percentage of neutral Hydrogen present when things star to form in the early universe.

  The emission from a patch of the IGM depends on its density, temperature, and neutral fraction.

  When the first sources of light turn on, the IGM will be visible first in absorption and then in emission as these sources heat their surroundings.

  Fluctuations across the sky will show us how structure grows (through density variations) and how the heating occurs (whether through shocks or radiation from the first objects).

  The protogalaxies will also ionise surrounding pockets of gas, shutting off 21cm emission around bright objects. The pattern of ionised and neutral gas, and its evolution with time, will teach us about the sources responsible for reionisation.

The SKA will provide detailed pictures of structure formation and reionisation through observations of the redshifted 21cm line of neutral hydrogen. Unlike constraints from the CMB, line radiation allows us to separate the contributions from different redshifts. Through multifrequency observations, we can therefore construct fully three-dimensional maps of neutral gas in the universe. Such maps are crucial for studying the time dependence of reionisation.

Observations from the Sloan Sky Survey have shown evidence for a sharp rise in the neutral fraction of the intergalactic medium (IGM) at z 6, implying that epoch of reionization ends at this time.

On the other hand, WMAP has found a surprisingly large electron scattering optical depth to the cosmic microwave background (CMB) radiation, implying that reionization began at z 20.

Reconciling these observations requires reionisation to be a complex process, with the ionising sources having qualitatively different (and time-dependent) characteristics from all galaxies that we can currently observe and with feedback from protogalaxies playing a crucial role in regulating the formation of subsequent generations of objects.

- So what will the SKA provide?
  The Square Kilometre Array will study the detailed properties of the first luminous objects in the universe, and be able to take snapshots of the 21cm emission at many different epochs, before, during and after reionisation, yielding detailed information about the formation of the first structures in the universe. It will provide the best measurements available of the characteristics of the first light sources in the universe.
  Moreover, the SKA will have the sensitivity to make high-resolution spectra of high-redshift radio sources. These spectra will yield detailed information about the early evolution of the cosmic web, the growth of ionised regions around protogalaxies, and even provide the only known direct way to observe minihalos, small clumps of dark matter and gas in the IGM that are predicted by many structure formation theories.

Interesting facts

In the early part of the 20th century, Slipher, Hubble and others made the first measurements of the redshifts and blueshifts of galaxies beyond our own Galaxy.

The largest observed redshift, corresponding to the greatest distance and furthest back in time, is that of the cosmic microwave background. The numerical value of its redshift is about $z = 1089$ ($z = 0$ corresponds to present time), and it shows the state of the Universe about 13.8 billion years ago, about 379,000 years after the Big Bang.

2.1.5 The cradle of life[7]

Are we alone?

The SKA will be able to detect very weak extraterrestrial signals and will search for complex molecules, the building blocks of life, in space.

Searching for life and planets

Are we alone in the Universe? Whether there is life on other worlds is a fundamental issue in astronomy and biology, and an important question for humankind.

When you mention extra-terrestrial life, most people think of little green men and alien invasions, but the science of looking for life on other worlds is gathering real momentum, such as through discoveries of complex organic molecules in comets, nebula and interstellar space, which form some of the building blocks for life as we know it.

The range of complexity in these organic molecules is vast, and it's leading scientists to speculate more and more that life could be common in planets within the habitable zones around stars.

The SKA will be able to detect extremely weak extraterrestrial radio signals if they were to exist, greatly expanding on the capabilities of projects like SETI.

Astrobiologists will use the SKA to search for amino acids, the building blocks of life, by identifying their spectral signatures at specific frequencies.

Recent discoveries have shown that gas giant planets (similar to Jupiter) are common around other stars like the Sun. Though there is no conclusive evidence yet for potentially habitable, small, rocky planets like Earth, careful observations with more sensitive telescopes have detected a number of candidate terrestrial-like planets, larger than Earth. Many scientists believe these habitable worlds, in the so-called "Goldilocks zone" where conditions are just right for life, must exist, and it's only a matter of time before they are detected, either by inferred observations or potentially directly.

Remote sensing of young stars shows they are surrounded by dusty discs which contain the materials needed to form Earth-like planets. By observing the process of planet building, the SKA will tell us how Earth-like planets are formed.

Although planets forming in the habitable zone of Sun-like protostars are currently far too small to be detected directly, the dust from which they form has a lot of surface area that intercepts starlight and converts the energy into heat which can be detected at short radio wavelengths.

The SKA will image the thermal emission from dust in the habitable zone in unprecedented detail. In particular, the SKA will show where dust evolves from micron-sized interstellar particles to centimetre-sized and larger "pebbles", the first step in assembling Earth-like planets.

Observations show that gas giant planets are surprisingly common in the habitable zone around other stars, unlike in our Solar System. This surprising discovery raises many questions:

- What accounts for the diversity in planetary systems?
- Are terrestrial planets common in the habitable zone?
- Do gas giant planets form in the inner disk or do they migrate there?
- What are the implications for Earth-like planets?

The SKA will image features in discs related to planet formation. The presence of giant protoplanets can open up nearly empty gaps in the disc material, revealing their presence, and they may also drive large-scale spiral waves through the disc.
Because orbital times in the inner disc are short, just a few years, observations made over time can track the evolution of these features. Giant planets may form by the slow growth of dust grains into large rocks that capture gas, or by rapid gravitational instabilities that disrupt the surrounding disc. The SKA will discern which mechanisms are active, and where in the disc they occur, which will reveal the impact of newborn giant planets on their Earth-like counterparts. When viewed from afar, the signatures of forming planets imprinted on circumstellar dust may be the most conspicuous evidence of their presence.
The gaps in the dust clouds are much easier to detect than the planets themselves because of their much larger surface area. It's akin to seeing the wake of a boat from an airplane when the boat itself is too small to be visible. The SKA may be the only instrument capable of imaging the inner regions of discs where Earth-like planets form.
What about signals from a technologically advanced extraterrestrial civilisation? The SKA will be so sensitive that it will be able to detect signals comparable in strength to television transmitters operating on planets around the closest stars to the Sun out to dozens of light years. The SKA will be able to search for these "leakage" signals from other civilisations for the first time.
The SKA's sensitivity will allow it to expand the volume of the Galaxy that can be searched for intentional beacons by a factor of 1000, using a wider range of frequencies than attempted before. The detection of such extraterrestrial signals would forever change the perception of humanity in the Universe.
The search is on, and the SKA will be at the forefront of one of human kinds greatest quests.

2.1.6 Flexible design to enable exploration of the unknown

While this is truly exciting and transformational science, history has shown that many of the greatest discoveries have happened unexpectedly. The unique sensitivity and versatility of the SKA will make it a discovery machine.
We should be prepared for the possibilities.

2.1.7 SKA Science and Engineering Books

For the full SKA science case in detail see the SKA Science book:

- **135 Chapters, 1200 Contributors, 2000 Pages Of SKA Science**
  Advancing Astrophysics with the Square Kilometre Array - 2015
  The last SKA science book, *Science with the Square Kilometre Array*, was published in 2004
  Individual chapters are available for download on the Proceedings of Science website.

- **Science And Engineering Books**
  1. ***Advancing Astrophysics with the Square Kilometre Array*, editor: SKA Organisation, 2015**
     Download links:
     Volume 1
     Volume 2
     Individual chapters
  2. ***Science with the Square Kilometer Array: Motivation, Key Science Projects, Standards and Assumptions 2004*, eds: C. Carilli, S. Rawlings.**
     link, also
  3. ***The SKA: an engineering perspective*, P.Hall, Springer, 2005 – reprinted from Experimental astronomy, Vol 17, Nos 1-3, 2004**
     link

2.2 SKA Science Working Groups & Focus Groups[4]

The science working groups (SWGs) and Focus Groups (FGs) have developed and evolved to provide a conduit for interaction with the astronomical community. They are now intended to cover all science areas that will be addressed with the SKA. Inevitably there is some level of overlap between the groups, and their titles are unable to capture all the science areas that the groups cover, please see individual pages for full details of what science is covered by each group.

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2.2.1 Cosmology

Cosmology
Cosmology Working Group Documentation
The presentations from the Science Assessment Workshop can be found here.
The Cosmology presentations from the 2014 SKA Science Meeting can be found here.
The Cosmology Banner is here
SKA Documents

Related 2004 "Science with the Square Kilometre Array" Chapters:
"Galaxy evolution, cosmology and dark energy with the Square Kilometre Array" Rawlings et al.
"21cm tomography of the high-redshift univers with the Square Kilometre Array" Furlanetto

& Briggs
"Cosmology with the SKA" Blake et al.
"Extragalactic water masers, geometric estimation of H0 and characterization of dark energy" Greenhill
"Strong gravitational lensing with SKA" Koopmans et al.
"Measuring changes in the fundamental constants with redshifted radio absorption lines" Curran et al.
"Sunyaev-Zeldovich effects, free-free emission, and imprints on the cosmic microwave background" Burigana et al.
"Searching for intergalacic shocks with the Square Kilometre Array" Keshet et al.

2.2.2 Gravitational Waves

2.2.3 Cradle of Life

2.2.4 Epoch of Reionization

2.2.5 Extragalactic Continuum (galaxies/AGN, galaxy clusters)

2.2.6 Extragalactic Spectral Line

2.2.7 HI galaxy science

2.2.8 Magnetism

2.2.9 Our Galaxy

2.2.10 Pulsars

2.2.11 Solar, Heliospheric & Ionospheric Physics

2.2.12 Transients

2.2.13 High Energy Cosmic Particles (Focus Group)

2.2.14 VLBI

2.3 SKA Technology[5]

2.4 Unprecedented Scale

The SKA will eventually use thousands of dishes and up to a million low-frequency antennas that will enable astronomers to monitor the sky in unprecedented detail and survey the entire sky much faster than any system currently in existence.

Its unique configuration will give the SKA unrivalled scope in observations, largely exceeding the image resolution quality of the Hubble Space Telescope.

It will also have the ability to image huge areas of sky in parallel a feat which no survey telescope has ever achieved on this scale with this level of sensitivity. With a range of other large telescopes in the optical and infra-red being built and launched into space over the coming decades, the SKA will perfectly augment, complement and lead the way in scientific discovery.

2.5 Co-hosting

Both South Africa's Karoo region and Western Australia's Murchison Shire were chosen as co-hosting locations for many scientific and technical reasons, from the atmospherics above the sites, through to the radio quietness, which comes from being some of the most remote locations on Earth.

South Africa's Karoo will host the core of the high and mid frequency dishes, ultimately extending over the African continent. Australia's Murchison Shire will host the low-frequency antennas.

2.6 A global effort

World leading scientists and engineers designing and developing a system which will require supercomputers faster than any in existence in 2015, and network technology that will generate more data traffic than the entire Internet.

2.7 Phased development

In Australia, the SKA low-frequency telescope will comprise 512 stations in a large core and three spiral arms creating a maximum baseline of 65km. Each of the stations will contain around 250 individual antennas, meaning almost 130,000 will be installed on site in total.

Initially, 476 of these stations will be constructed with a maximum baseline of 40km. The further away antennas are from the core of the telescope, the more expensive they become, so slightly reducing the number in the early stages of construction will allow the SKA to stay within the budget available at the time construction begins. The remainder will be added when funding allows.

2.8 Precursors and pathfinders

Even before the SKA comes online, a series of demonstrator telescopes and systems known as pathfinders and precursors, are already operational or under development across the world, paving the way for the kinds of technology which the SKA will need to pioneer to make the huge data available to scientists.

13 June 2014, SKA Science Conference, Giardini Naxos, Italy , game-changing-science-with-the-ska-discussed-in-sicily
The talks given throughout the week highlighted the integral role pathfinder telescopes have played in the process (such as the JVLA in the US, LOFAR in the Netherlands, etc.). A

number of these pathfinder telescopes were deployed from the beginning with the goal in mind to enable engineers to test technologies and allow astronomers to conduct early research and refine the key science fields leading up to the SKA. As such, they are a great success in themselves.

Precursor telescopes – pathfinder telescopes located on the SKA core sites in Western Australia and South Africa – have also seen great progress. The Murchison Widefield Array (MWA) in Western Australia which is conducting research in the low frequencies has been routinely operating since July 2013, the Australian SKA Pathfinder (ASKAP) also in WA is currently being commissioned with 6 of its 36 antennas already conducting science-grade observations, and MeerKAT, the South African precursor telescope under construction, with its first antenna recently inaugurated.

"We've had an intense week of first class science presentations from the community that truly show just how much the SKA will add to our understanding of the Universe." concluded Prof Robert Braun, Director of Science at the SKA Organisation. "Not only has the science case for the SKA grown even stronger, but we're also more excited than ever about the "unknown unknowns", the other discoveries we cannot even predict but are sure the SKA will bring".

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