COSMOLOGY, GALAXY FORMATION AND ASTROPARTICLE PHYSICS
ON THE PATHWAY TO THE SKA
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The Square Kilometre Array

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Abstract. The Square Kilometre Array (SKA) is a global project to design and build a new generation radio telescope at metre to centimetre wavelengths. It will have a collecting area of order one million square metres spread over at least 3000 km, a sensitivity 50 times higher than the EVLA, an instantaneous field of view (FOV) of several tens of square degrees and the possibility of more than one FOV allowing multiple simultaneous use. It will be an extremely powerful survey telescope with the capability to follow up individual objects with high angular and time resolution. The SKA science impact will be felt in astro-particle physics and cosmology, fundamental physics, galactic and extragalactic astronomy, and solar system science. Technological innovation, closely paralleling commercial IT developments, is the key to the design concepts under investigation and to the target cost of 1 billion Euros. Data transport rates are likely to be in the range of tera-bits/sec, with Pflops capacity required for the central processor. Much of the required technology is being developed in the course of the construction of several 1% SKA Pathfinder instruments. The final system design is planned from 2008 to 2010. Four possible locations for the telescope are under evaluation with a short-list of acceptable sites to be decided in August 2006 and a final choice expected late in this decade. Construction of the array will take most of the next decade.

1. Introduction

The Square Kilometre Array is under development by more than 50 institutes in 17 countries as the global radio telescope for the coming decades. It will operate at metre and centimetre wavelengths with enormous sensitivity and wide field of view, and will have unprecedented surveying power. The range of key science to be tackled by the SKA (Carilli and Rawlings 2004) covers the epoch of re-ionization, galaxy evolution, dark energy, cosmic magnetism, strong field tests of gravity, gravitational wave detection, transients, proto-planetary disks, and the search for extra-terrestrial life. The major increase in performance compared to existing telescopes and the flexibility inherent in the telescope design allows us to predict that unexpected discoveries will be made with the SKA. In this paper, I outline the telescope concept, the key science themes, the issues involved in a choice of location, the management of the project, and the timeline. Other contributions to these Proceedings will examine the science themes in much more detail.

2. The telescope concept

The SKA is to be a radio telescope with

- the sensitivity to detect and image hydrogen in the early universe through its enormous collecting area of about 1 million square metres. This will make it about 50 times more sensitive than the EVLA, and able to reach an rms noise level of 10 nano-Jy in an 8 hour integration for a continuum observation.
- 50% of the collecting area concentrated in the central 5 km diameter for optimal detection of hydrogen, pulsars, and magnetic fields.
- a fast surveying capability over the whole sky through its sensitivity and very large angle field of view of several tens of square degrees. The SKA will be 10000 times faster than the EVLA in surveying the sky.
- the capability for detailed imaging of compact objects like active galactic nuclei through its large physical extent of at least 3000 km.
- a frequency range from ≤ 100 MHz to 25 GHz.
- data transport to the central data processor via very wide-band (terabit/sec) fibre links.

This combination of an enormous increase in sensitivity across the frequency range, a wide field of view, and the capability to sample the spatial, frequency, and time domains with high resolution will revolutionize many fields of astronomy.

The Reference Design for the SKA is an interferometer array capable of imaging the radio sky at frequencies from $\leq$100 MHz to 25 GHz, and providing an all-sky monitoring capability at frequencies below 1 GHz. It covers the frequency band with three different kinds of receptors: 1) dipole arrays for $\leq$100-300 MHz to observe the Epoch of Re-ionization, 2) a small parabolic dish array, with phased focal plane arrays in the 300 MHz to 3 GHz range and broad-band single-pixel feeds above 3 GHz, and 3) aperture array tiles in the core of the array for all-sky monitoring in the frequency range 0.3-1 GHz and multiple independent field observations. In practice some overlap in frequency range may be expected at the low-, mid-, and high-band boundaries. These three receptor components all make use of the same data transport, processing, and software infrastructure. An artist's impression of the central core of the array is shown in Fig. 1.

Following a decade of feasibility studies and prototyping, the major elements of the Reference Design are now under

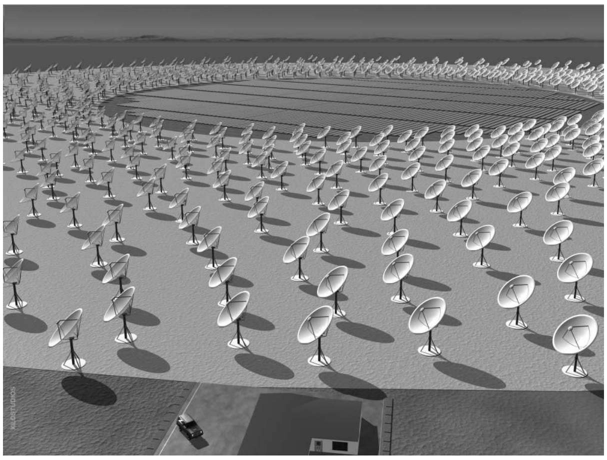

Fig. 1. Artist's impression of the SKA central core.

development around the world as part of a coordinated effort involving design studies and the construction of science-capable 1% SKA Pathfinder telescopes. In Europe, a Design Study (SKADS) is underway, funded in part by the European Commission. The Low Frequency Array (LOFAR) is under construction in the Netherlands and Germany. The extended New Technology Demonstrator (xNTD) and the Mileura Wide-field Array-Low Frequency Demonstrator (MWA-LFD), are under construction in Western Australia, as is the Karoo Array Telescope (KAT) in South Africa, and the Allen Telescope Array (ATA) in the USA.

New concepts for cheap, mass production parabolic dishes are being investigated in the context of the ATA, KAT, and MIRA, as well as via separate projects in Canada, the USA and India. These involve hydro-formed (Fig. 2), metal panel, and composite technologies. Phased arrays in the low-band are being pursued in the context of LOFAR, LFD-MWA and the Long Wavelength Array in the USA, and in the mid-band as dense aperture arrays in SKADS (Fig. 3) and as focal plane arrays in small dishes in Australia, the Netherlands, and Canada, as well as in SKADS. The requirements for long distance data transport over fibre links for the SKA are being investigated in the context of fibre-linking the European VLBI Network. And finally, high speed data processing techniques and associated software for operations, calibration and imaging are being developed in each of the SKA Pathfinder projects. An exposition of many of the engineering issues involved in the design of the SKA can be found in *The SKA – an engineering perspective* (Ed. P. J. Hall).

During the course of 2007, the design and implementation experience around the world will be drawn together as the Initial Design Concept. This will be reviewed by an external panel in early 2008 prior to commencing the overall system design leading to construction (see Sect. 6).

3. Key Science for the SKA

Highlights of the key science areas are summarized in the following sections. The full science case for the SKA can be found in *Science with the SKA* 2004 (Eds. C. Carilli and S. Rawlings). Documents outlining the discovery potential of the SKA, and the unique and complementary aspects of the science case can be found Cordes et al. (2006) and Gaensler & Lazio (2006).

Fig. 2. Detail of the ATA parabolic dish.

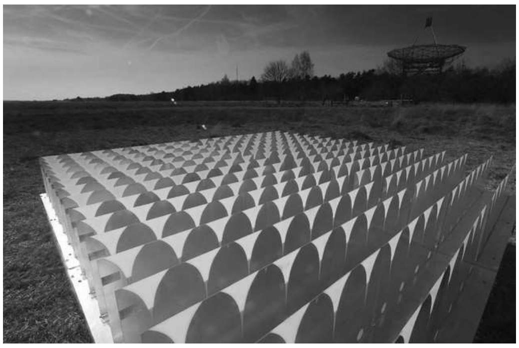

Fig. 3. SKADS aperture array concept.

3.1. Probing the Dark Ages after Recombination

One of the major themes of current cosmology is the exploration of the Epoch of Re-ionization in the early universe, its timing, its triggers, and the early evolution of the objects responsible for the re-ionization. This is being tackled across the electromagnetic spectrum in various ways, but most progress can be expected at infra-red and radio wavelengths. In the infra-red, the focus is on detecting the first stars and galaxies to form from the neutral hydrogen which filled the early universe after recombination. In the radio, emission from the HI 21 cm line and molecular lines like CO provide the best observational window through which to observe directly the era when gas was

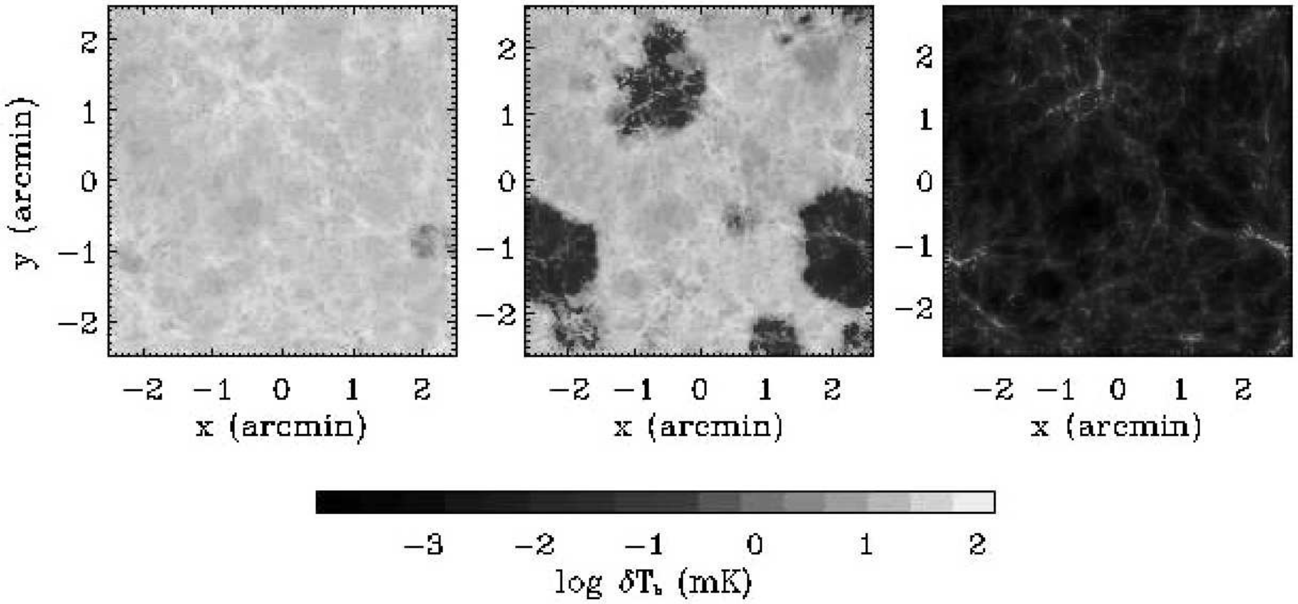

Fig. 4. Simulations of 21 cm hyperfine radiation at high redshifts, showing temperature fluctuations and the growth of structures (Furlanetto & Briggs 2004).

first turned into gas and stars. LOFAR (Low Frequency Array) and MWA (Mileura Wide-field Array) are under construction in the Netherlands and Australia respectively with the aim of detecting the statistical signature of the re-ionization in the redshifted neutral hydrogen. With its massive increase in sensitivity, the SKA will make the first direct detections of structure in the HI at these redshifts and provide images as a function of redshift of the re-ionizing regions in the neutral gas (Fig. 4), thus giving us detailed information on the re-ionization process and the first objects to form.

3.2. Galaxy Evolution and Dark Energy

A major theme of current physics as a whole is the nature of the forces that are apparently driving the universe apart at an ever accelerating rate. Is the so-called Dark Energy related to Einstein's vacuum energy or the manifestation of some new physics? The SKA will be one of three next generation facilities using different approaches to tackle the question in the next decade; the others are the Large Synoptic Telescope and the Joint Dark Energy Mission. The sensitivity of the SKA to neutral hydrogen emission in the redshift range out to 1.5 and its astounding survey capability will allow the telescope to do a hemisphere survey to locate and measure the spatial distribution of 10^9 galaxies via their hydrogen emission and spectroscopic redshifts. Baryonic oscillations established at time of recombination provide characteristic length scales (*cosmic ruler*) in the distribution of galaxies on the sky. The measured distribution of baryonic matter made by the SKA can be compared with that of the microwave background radiation emitted at a redshift of about 1100 to examine the effects of Dark Energy on the geometry of the universe.

3.3. The Origin and Evolution of Cosmic Magnetism

Magnetic fields can be found almost everywhere in the universe with field strengths ranging by a factor of 10^{20} from interstellar and intergalactic space to the extreme fields found on the surfaces of neutron stars. Our knowledge of how magnetic fields are formed and how they evolve across cosmic time is rather rudimentary, and many fundamental questions remain. The radio band is very well suited to answer these questions since it is much less limited by extinction, angular resolution, and sensitivity compared to other wavebands. The SKA will carry out an all-sky survey of Faraday rotation measures toward of order 10^7 sources at cosmological distances that will allow us to probe magnetism in our Galaxy, nearby galaxies and in distant galaxies, clusters and protogalaxies.

3.4. Strong Field Tests of Gravity using Pulsars and Black Holes

Pulsars are the most accurate clocks known in the universe, a property that can be used to exquisite effect in mapping space-time around other neutron stars and black

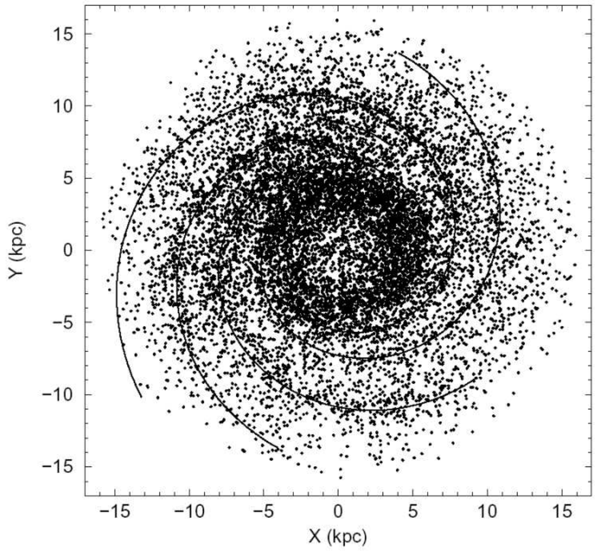

Fig. 5. Simulated Galactic pulsar population discovered in a SKA survey of the entire sky (Cordes et al. 2004).

holes, and in serving as test masses able to respond to long wavelength gravitational waves. Their pulsed radiation can also be used as probes of the gas and magnetic fields through which it passes. Pulsar surveys with the SKA are expected to discover of order 20000 pulsars (Fig. 5), amongst which one expects to find a pulsar in orbit around a stellar-mass black hole, of order one thousand millisecond pulsars which can form an immense pulsar timing array for detecting 5-100 nHz gravitational waves from binary super-massive black holes in the cores of galaxies, and pulsars in close orbit around the super-massive black hole at the Galactic Centre. These data can be used to provide fundamental and detailed tests of our understanding of gravity, in regimes that cannot be probed by any other experiment.

3.5. The Cradle of Life

The formation of planets and their evolution including the possible development of life forms is a subject of great fascination to professional and layman alike. At wavelengths of about 1 cm (20 GHz), the SKA will provide thermal imaging at 0.15-AU resolution of proto-planetary disks out to a distance of 150 pc, encompassing many of the best-studied Galactic star-forming regions. At these wavelengths, the SKA will be sensitive to thermal emission from dust pebbles of order 1 cm in the disks. Such observations will allow us to study the process of terrestrial planet formation, and in particular how pebble sized particles accrete to form larger objects, one of the major uncertainties in the hierarchical process of planet formation. In addition, for the first time with the SKA, we will have the capability of detecting leakage radiation from ETI transmitters out to a few hundred parsecs, involving of order a million solar type stars.

4. Site Selection

Selection of the site for the SKA is one of the major decisions to be made in the life of the project, and will involve evaluation of scientific, technical, infrastructure and other issues for the candidate sites. The physical characteristics required for the SKA site are:

- a very quiet radio frequency environment, particularly for the core region
- a large physical extent (>3000 km)
- land availability and characteristics that allow an optimum distribution of antennas in the core region and beyond
- low ionospheric turbulence for high quality observations at frequencies below 1 GHz, and
- low troposphere turbulence for high quality observations at frequencies above 15 GHz

The International SKA Steering Committee initiated the search for the SKA site in 2001 with a request for Expressions of Interest from countries around the world. This was followed by a Request for Proposals in September 2004 which resulted in four submissions by the December 2005 deadline. Measurements of radio frequency interference (RFI) at each of the core sites were carried out for one month per site by a team from the ASTRON institute in the Netherlands under contract to the International SKA Project Office. In addition the sites carried out their own RFI measurements for a year.

The four candidate sites are:

- Argentina: the core site proposed is in western Argentina in a mountain valley at an elevation of 2600 m. Remote stations would be located in southern Argentina and south-east Brazil.
- Australia: The proposed core site is on a flat desert plain in Western Australia at an elevation of 460 m. Remote stations would be located across Australia and potentially in New Zealand as well.
- China: The proposed core site is located in Guizhou province in south western China in the Karst depression region at an elevation of 800 m. Remote stations would be located mostly to the north.
- Southern Africa: The proposed core site is in a desert valley in the Karoo region of the Northwest Cape Province at an elevation of 1100 m. Remote stations would be located in Botswana, Namibia, Mozambique, Madagasgar, Mauritius, Kenya, and Ghana.

The proposals and the RFI monitoring results are currently under evaluation by a number of expert committees prior to examination first by an external advisory committee and finally by the International SKA Steering Committee. A decision on a short-list of acceptable sites

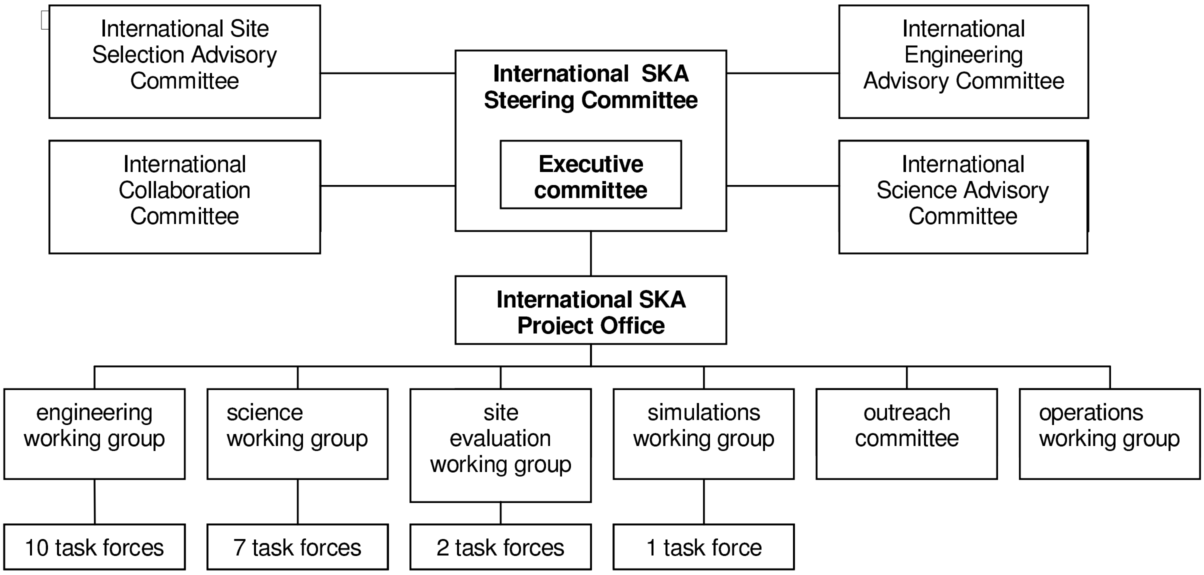

Fig. 6. SKA management structure.

for the SKA will be made by the Steering Committee in August 2006. The final decision on the location of the telescope will be made towards the end of the decade by the government departments and funding agencies involved in the SKA project.

5. Management Structure

The current international management structure of the SKA project centres on the International Steering Committee (ISSC) appointed by the parties involved and governed by a Memorandum of Agreement (MoA), and the International SKA Project Office (ISPO) collectively funded by the parties to the MoA.

The ISSC has 7 representatives from each of Europe, USA, and the Rest of the World plus one at-large member. The ISSC concerns itself with coordinating all aspects of the global project and setting the overall goals and timeline. The ISPO reports to the ISSC and coordinates international activity in developing the science case, system design and related pivotal technology issues, site proposal process and assessment, telescope performance simulation, operations and outreach. The structure is shown in Figure 6.

6. Timeline

The major milestones foreseen in the project are the following:

2006	short-list of acceptable sites
2008	external review of concept design
2009-2010	costed system design completed, final site selection, agreement on funding
2011	start construction of the SKA
2014	science with 10% SKA
2020	construction completed, full science operations

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