Recommendations on Key Science Projects

Report of the International Science Advisory Committee to the International Square Kilometre Array Steering Committee

INTRODUCTION

Defining Key Science Projects

A crucial part of defining the Square Kilometre Array (SKA) project, both within the SKA community and to a wider audience, is to develop a small set of key science projects in which the SKA can make a fundamental contribution. The key science projects will be used to attract funding and publicity, will be the focus of efforts to ensure that SKA capabilities will be complementary to those of other future telescopes, and will be those projects which will primarily constrain the choice of design and site for the SKA.

To identify key science projects, the International Science Advisory Committee (ISAC) formed a Key Science Projects Subcommittee, who throughout 2003 have formulated and then coordinated the process through which the ISAC has converged on key science projects. To summarize, the criteria adopted in Geraldton for key science projects were:

1. Can address important but currently unanswered questions in fundamental physics or astrophysics.
2. Is science which is either unique to the radio band and to the SKA, or is something which is complementary to other data-sets but in which the SKA plays a key role.
3. Excites the broader community, and is of relevance and interest to funding agencies.

Call For Proposals

A "call for proposals" for key science projects was issued to the community in Aug 2003. In response to this call, 21 one-page proposals for key science projects were received. These were reviewed by the Key Science Projects Subcommittee, who provided feedback and allowed proposers a brief chance to revise and merge proposals. A total of 17 final proposals were accepted.

Ranking by ISAC

The 17 final proposals were distributed to the ISAC in Nov 2003. ISAC members were asked to vote on each proposal, providing a rating from 1 (no compliance) to 5 (complete compliance) for each of the above three criteria. The results of this voting process were presented and discussed at the SKA Science Retreat in Leiden in Nov 2003.

RECOMMENDATIONS OF THE ISAC

Key Science Projects

The list of ranked proposals shows a clear gap between the top eight proposals and the bottom nine. The ISAC consequently decided to exclude the bottom nine proposals from further consideration.

The eight remaining proposals are all closely spaced in rankings. The ISAC consequently did not feel it a productive exercise to revote on or cull this list of eight proposals further. Fortunately, these eight proposals group themselves naturally into five coherent projects, which we consequently present to the ISSC (in no particular order) as the ISAC's recommendation on key science projects for the SKA:

- **Strong Field Tests of Gravity Using Pulsars and Black Holes:** Pulsar surveys with the SKA can discover tens of thousands of pulsars, amongst which we expect to find a pulsar in orbit around a stellar-mass black hole, thousands of millisecond pulsars which can form an immense pulsar timing array, and pulsars in close orbit around the supermassive black hole at the Galactic Center. 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.

- **Probing the Dark Ages:** The epoch at which the first luminous objects in the Universe formed, and then reionized the neutral IGM, can only be studied at near-IR through radio wavelengths. In the redshifted H I line the SKA can map out the complicated processes occurring during the Epoch of Reionization; through redshifted CO, the SKA can detect star-forming galaxies at these redshifts; with deep continuum observations, the SKA can detect the first AGNs. The ensemble of these data can provide unique information on how the first galaxies and black holes assembled themselves, and how they influenced their environment. *[This topic is a combination of the "origins" aspects of proposals on the EoR, on Galaxy Evolution, and on Supermassive Black Holes.]*

- **The Origin and Evolution of Cosmic Magnetism:** Radio astronomy is uniquely placed in its capability to study magnetic fields at large distances, through studies of Faraday rotation, polarized synchrotron emission and the Zeeman effect. Through an all-sky continuum survey, the SKA could measure rotation measures for $\sim 10^8$ polarized extragalactic sources, with an average spacing between sightlines of $\sim 60''$. The sheer weight of statistics in these data, combined with deep polarimetric observations of nearby galaxies and clusters, would allow us to completely characterize the evolution of magnetic fields in galaxies and clusters from redshifts $z > 3$ to the present, to measure the strength and structure of the magnetic field in the IGM, 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.

- **The Cradle of Life:** There is increasing interest in the community in astrobiology and in the search for Earth-like planets. The SKA has the unique potential for finding evidence of extra-solar terrestrial planets and of other life like us. At 20 GHz, the SKA will provide thermal imaging at 0.15-AU resolution out to a distance of 150 pc, encompassing many of the best studied Galactic star forming regions. Such observations will allow us to study the process of *terrestrial* planet formation; such systems will evolve on timescales of months. 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. Finally, the SKA will have the resolution and sensitivity to study the $J = 1 - 0$ transitions of amino acids and other complex carbon biomolecules, and to follow their progress from molecular clouds to protoplanets. *[This topic is a combination of the proposals on SETI/Astrobiology and on Terrestrial Planet Formation.]*

- **The Evolution of Galaxies and Large Scale Structure:** The original motivation for building the SKA was to detect H I in normal galaxies at high redshift. Such an experiment promises a particularly exciting result, in that the vast volume of space probed by an SKA H I galaxy survey will provide an exquisite matter power spectrum, with which we can compute the Universe's Equation of State, and map out the strength of Dark Energy as a function of cosmic epoch. At the same time, the SKA's unique capability to observe the neutral atomic component of gas in galaxies will allow us to chart the kinematics, merger history and environment of ordinary galaxies as they evolve from redshifts $z \approx 5$ to the present. *[This topic is a combination of the proposal on Dark Energy, and the evolutionary aspect of the proposal on Galaxy Evolution.]*

Why a Square Kilometre?

A key part of the case for an SKA has always been the need for a full square kilometre of collecting area. This was originally motivated by the need to detect normal galaxies in H I at high redshift.

However, most of the key science projects recommended above will involve large surveys rather than single pointings, and thus survey speed or sky coverage are potentially more useful requirements than raw collecting area. The ISAC thus raised the the issue in their discussions as to whether one should abandon the basic requirement of one square kilometre of collecting area. Ultimately there was strong opposition to this proposal, most participants feeling that the concept of 1 km^2 was a simple and powerful idea.

The ISAC thus recommends that the need for a square kilometre of collecting area be retained as the underlying specification for this telescope. Within the key science projects recommended above, this specification is still motivated by the need to detect H I in galaxies at high redshifts, although other science goals (e.g., thermal imaging of protoplanetary disks at sub-AU resolution) also drive one to comparable requirements. In any case, the ISAC strongly recommends that the entire SKA community adopt a unified response as to why a square kilometre is required, and that this response be directly based on the requirements for key science projects (as listed in Table 1 below).

Exploration of the Unknown

At a wider level, the ISAC wishes to emphasize the incredible contributions made by radio astronomers over the last 70 years, more often than not simply by designing instruments with new and innovative capabilities. In the 21st century, the SKA offers an unparalleled opportunity to add to the many discoveries of unexpected phenomena made by radio astronomers in the 20th century. Thus, while there was general consensus that topics like "The Exploration of Phase Space" or the "Transient Radio Sky" do not easily fit the criteria for key science projects, the ISAC recommends that a guiding principle of the design process should be that, whenever cost and engineering constraints allow, the SKA be maximally flexible.

Synergy with National and Institutional Roadmaps

The ISAC have reviewed the science cases of various other organizations and projects (e.g., NASA, ESA, NSF). Most major astronomical initiatives for the 21st century seem to be grouped into three main thrusts: "The Origin of Galaxies", "The Origin of Life", and "Tests of Fundamental Physics". We have expressly avoided adopting these broad themes to be key science projects in themselves, but have ensured that all five recommended topics do fit within one of these themes. In this way, we feel that our five proposed projects will be of interest to the wider community and to funding agencies, but retain the requirement that they represent unique SKA science.

Risk vs Reward

In adopting any key science project, there is always a trade-off between higher risk science with huge potential rewards, and projects which will have guaranteed results but which come with a less exciting pay-off. The ISAC feels that each of the recommended key science projects contains aspects which include both high-risk and guaranteed projects, so that each topic contains a solid promise of fundamental new advances in our understanding, without raising excessive concerns that the project might not be realistic or feasible.

IMPLICATIONS FOR SKA SPECIFICATIONS

Table 1 shows a flow-down from key science projects to SKA design specifications. All these parameters are representative, and are subject to further discussion, simulation and costing.

High sensitivity (i.e., an "SKA") is clearly an "enabling" aspect of the SKA for all programs, although the requirement that $A_{\rm eff}/T = 20\,000$ m^2 K^{-1} can be relaxed at the lowest (due to increase in $T_{\rm sys}$) and highest (due to decreased efficiency) frequencies without precluding the key science projects.

The low frequency limit is set by observations of the neutral IGM during the EoR. The nominal value is of ~ 0.1 GHz, based on recent Gunn-Peterson and WMAP results. The LOFAR telescope will act as a path-finder in this area, and will help to refine this specification. The high frequency limit (~ 20 GHz) is driven by observations of terrestrial planet formation and molecular line emission from objects within the EoR, although both pulsars and cosmic magnetism have an important high frequency component. Increase to 35 GHz is desirable, but not fundamental to achieving the key science goals.

Baselines out to a few thousand kilometres are required for imaging the sub-AU scales associated with terrestrial planet formation, for pulsar astrometric programs, and for imaging the synchrotron emission from the first supermassive black holes. A significant concentration of collecting area, at least 20% within a diameter of 1 km, and 50% within 5 km, is essential for untargeted pulsar and SETI searches, for studying redshifted H I emission from the EoR, and for imaging of diffuse polarized emission in magnetic field studies.

Most of the programs have a survey component, and hence could benefit from a field of view larger than the nominal specification of 1 deg^2 at 1.4 GHz, but in most cases the goal can be met within this specification. The one exception is constraining the equation of state of Dark Energy through the study of very large scale structure. This program is fundamentally enabled through a large increase in the FOV, since the "cosmic mapping speed" becomes dramatically faster than planned optical surveys. Several programs (e.g. continuum imaging in the Dark Ages proposal, RM mapping in the Magnetism proposal) require imaging of the full field of view at a spatial resolution (at 1.4 GHz) of $0\farcs1$ or better.

Multifielding is highly desirable for the H I galaxy survey needed to probe large scale structure, and may also be needed for pulsar timing. For the former, a dedicated wide-field beam is needed if this survey is to be completed in a timeframe which makes such efforts competitive with work being carried out at optical wavelengths. For the latter, on-going simulation work is being carried out to determine the minimum number of independent beams required to maintain a pulsar timing array.

Table 1. SKA specifications implied by Key Science Project goals.

Topic	$A_{\rm eff}/T$ (m^2 K^{-1})	Frequencies (GHz)	Max Baseline (km)	Special
Gravity	20 000 at 1.4 GHz timing array	0.5–15 Galactic Center	3000 astrometry	multifielding desirable? (TBD); significant central core
Dark Ages	10 000 at 0.1 MHz & 20 GHz CO emission at $z > 6$ (M 82) H I structure at $6 < z < 13$	0.1–20	3000 H I absorption SMBH studies	35 GHz for CO studies; central core for H I; full FOV imaging at 1.4 GHz
Magnetism	20 000 at 1.4 GHz RM grid	0.3–10 large RMs	300 confusion-limited imaging at 1.4 GHz	–40 dB pol'n purity; central core; full FOV imaging at 1.4 GHz
Cradle of Life	10 000 at 20 GHz 10 K rms at 1 mas in 100 hrs	≥ 20 terrestrial planet formation	3000 0.15 AU at 150 pc at 20 GHz	100 pencil beams within FOV for targeted searches; central core
Evolution & LSS	20 000 at 1.4 GHz M_* galaxy at $z = 2$	0.3–1.4 galaxies to $z = 4$	300	dedicated beam with FOV of 200 deg^2 at 0.7 GHz is highly desirable to increase survey speed

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