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Memo 88

Science with the Square Kilometre Array: Uniqueness and Complementarity

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EXECUTIVE SUMMARY

Many exciting new astronomical facilities either are being planned or are under construction for operation in the period 2010–2030. Fundamental questions relating to the origin of life, the formation of galaxies, and the structure and evolution of the Universe recur across the science cases of many of these facilities. In this document, we consider the areas in which the Square Kilometre Array (SKA) will be uniquely positioned to address fundamental science. A summary of our findings is as follows:

Galaxy Evolution Neutral hydrogen is the basic material from which stars form. The SKA will revolutionize the study of hydrogen in external galaxies, because of its unique ability to map this gas in a wide variety of environments, over a huge range of redshifts, and free from obscuration. Furthermore, in contrast to telescopes at other wavelengths, the huge field of view of the SKA will allow effective surveying and identification of galaxies over a significant cosmic volume.

Epoch of Reionization The SKA will have the powerful and exclusive capability to directly image the high-redshift intergalactic medium as it is progressively ionized by the first stars and galaxies. In addition, the SKA will detect low-excitation lines from high-redshift CO, thereby providing the most direct measures of galaxy masses and dynamics at the end of the Dark Ages.

Black Hole Spin Through measurements of black hole spin, the SKA will be the key instrument for testing descriptions of gravitation such as the Cosmic Censorship Conjecture and the “No Hair” Theorem. The binary black hole / pulsar systems to be observed by the SKA have the advantage of being relatively simple compared to the objects that LIGA or LISA will study, and can be subjected to measurements of extraordinary precision through pulsar timing.

Cosmic Magnetic Fields The SKA will have the unquestionably unique ability to reveal the role played by magnetic fields in the evolving Universe, through all-sky observations of radio polarization and Faraday rotation. Important support will be provided by Planck, Auger and LSST, which will provide a Faraday-free template of the Milky Way, measure the magnetic field strength in the local Universe, and determine the redshifts of sources in the SKA’s “rotation measure grid”, respectively.

Search for Extraterrestrial Intelligence The SKA will be without peer for SETI experiments, because it is the only current or planned instrument that will have sensitivity to unintended emissions from other civilizations, as might result from equivalents of airport radar or broadcast television.

Theories of Gravity High precision measurements are required to conduct stringent tests of gravity. In the strong-field limit, the SKA will be the prime candidate for discovering any deviations from General Relativity, while Gaia will be a sensitive probe of weak-field behavior. The SKA, LIGO, and LISA will beautifully complement each other in the search for and study of gravitational radiation, since each facility will be sensitive to gravitational waves over a distinct range of frequencies.

Protoplanetary Disks There are many synergies between ALMA, JWST, extremely large ground-based telescopes, and the SKA in the study of protoplanets. The key advantages of the SKA will be its low operating frequency and very high angular resolution. Together, these capabilities will allow the SKA to observe disks in which planetary formation is *on-going*. This puts SKA studies in a completely different physical regime than for the wavelengths covered by other telescopes.

Prebiotic Molecules Both the SKA and ALMA will be powerful probes of prebiotic molecules: ALMA will be sensitive to molecules in compact hot cores, while the SKA will study these species in diffuse, cold clouds. Because of its relatively low observing frequencies, the SKA is also likely to be sensitive to more complex molecules with larger numbers of atoms.

Dark Energy The SKA will measure how the mysterious influence of dark energy has slowly evolved over cosmic time, using neutral hydrogen observations to determine the three-dimensional positions of a vast sample of galaxies. However, no single technique amongst future dark energy experiments is likely to yield a definitive answer on its own. The main advantages of the SKA will be the reduced systematic uncertainties and inherent redshift information that will accompany its HI data, while significant caveats are uncertainty over the number density of HI-emitting galaxies as a function of redshift, and the technological challenges associated with conducting the large survey proposed.

First Supermassive Black Holes A multi-wavelength approach is required to find and study the first black holes. The SKA and Constellation-X are best suited to carry out the deep surveys needed to find distant black hole candidates, but optical and infrared spectra will be needed to determine the redshifts of these sources.

1 INTRODUCTION

The Square Kilometre Array (SKA)¹ will be one of a suite of new, large astrophysics facilities for the 21st century, probing fundamental physics, the origin and evolution of the Universe, the structure of the Milky Way Galaxy, and the formation and distribution of planets. The SKA will be at least 50 times more sensitive and have a vastly larger field of view than any other centimeter- to meter-wavelength telescope ever built. In addition to answering fundamental scientific questions, the vast increase in sensitivity provided by the SKA will also almost certainly lead to the discovery of new and totally unexpected celestial phenomena.

Five science topics have been identified by the international community as being key science projects (KSPs) for the SKA (Carilli & Rawlings 2004). These are:

- Probing the Dark Ages (Carilli et al. 2004)
- Galaxy Evolution, Cosmology and Dark Energy (Rawlings et al. 2004); and
- The Origin and Evolution of Cosmic Magnetism (Gaensler, Beck & Feretti 2004);
- Strong Field Tests of Gravity Using Pulsars and Black Holes (Kramer et al. 2004);
- The Cradle of Life (Lazio, Tarter & Wilner 2004);

These KSPs all represent unanswered questions in fundamental physics and astrophysics. Furthermore, each of these projects has been selected using the criterion that it represents science which is either unique to the SKA, or is a topic which is complementary to other data sets, but in which the SKA plays a key role (Gaensler 2004).

In addition to the SKA, there are a variety of other facilities either under construction or planned for the first decades of the 21st century. These include the Atacama Large Millimeter Array (ALMA); the space-based, infrared (IR) optimized James Webb Space Telescope (JWST); large-area optical telescopes that can repeatedly image the entire sky such as the Large Synoptic Survey Telescope (LSST); one or more large, ground-based optical/IR telescopes with an aperture between 25 and 50 meters (extremely large telescopes, or ELTs); a next-generation gamma-ray facility, the Gamma Ray Large Area Space Telescope (GLAST); new X-ray satellites with huge increases in collecting area, such as Constellation-X and XEUS; a space-based, gravitational-wave facility, the Laser Interferometer Space Antenna (LISA); and international efforts to establish an on-line Virtual Observatory.

In this document we expand on the KSP criterion of complementarity, by explaining in detail the context of SKA capabilities with regard to other major observatories currently in the planning and development stages.

2 PROBING THE DARK AGES

The focus of this KSP is the formation of the first structures, as the Universe made the transition from largely neutral to its largely ionized state today. As in the study of cosmology and large-scale structure discussed in §3, probing the baryonic pre-galactic medium (PGM) will require a panchromatic approach. The PGM evolves in three distinct phases. At high redshifts ($z > 1100$) the PGM is hot, fully ionized, and optically thick to Thomson scattering, and hence coupled to the photon field. As the Universe expands, the PGM cools and eventually recombines, leaving a surface of last scattering (the CMB), plus a neutral PGM. This neutral phase lasts from $z = 1100$ to $z \sim 14$. At some point between $z \sim 14$ and 6, hydrogen in the PGM is “reionized,” due to ultraviolet radiation from the first luminous objects, leaving the fully reionized IGM seen during the “realm of the galaxies” ($6 > z \geq 0$). The ionized, dense PGM at very high redshift has been well studied through extensive observations of the CMB. Likewise, the reionized, rarefied IGM at low redshift has been well characterized through quasar absorption line studies. The middle phase — the existence of a neutral IGM during the so-called “dark ages,” and the process of reionization of this medium — is the last directly observable phase of cosmic evolution that remains to be verified and explored. The epoch of reionization (EoR) is crucial in cosmic structure formation

¹See <http://www.skatelescope.org>.

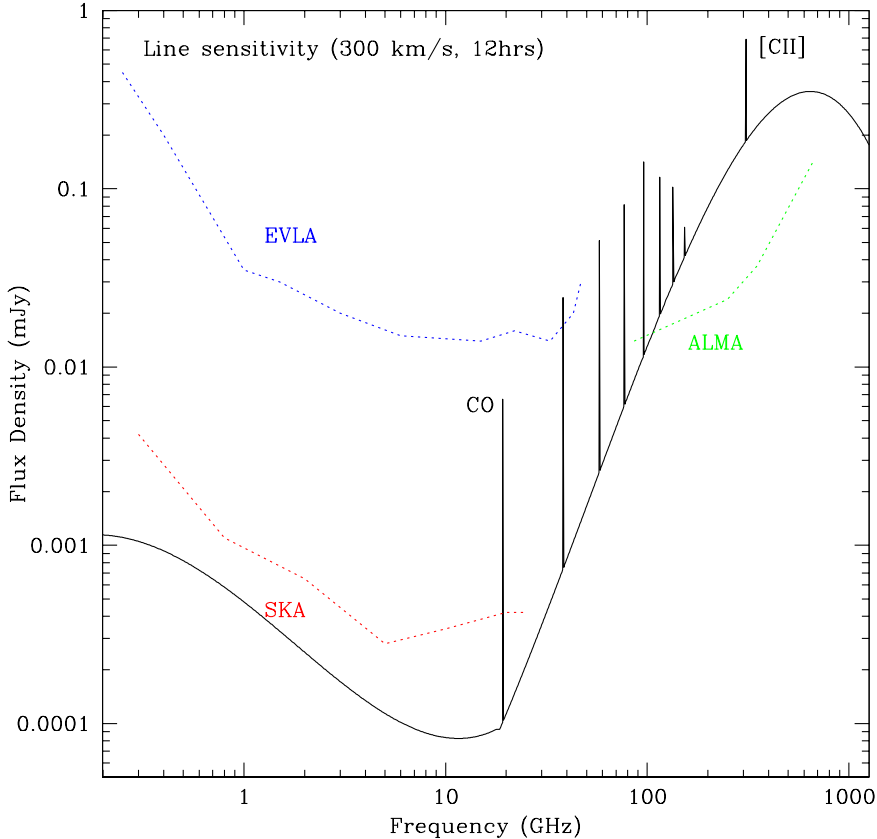


Figure 1. The dotted curves show the (1σ) sensitivity to spectral line emission for the EVLA, SKA, and ALMA in 12 hours. The solid curve is the emission spectrum, including continuum CO, and [C II] lines, for a source at $z = 5$ with 10% the luminosity of Arp 220 (i.e., a source with far-infrared luminosity $\sim 10^{11} L_{\odot}$).

studies, since it sets a fundamental benchmark indicating the formation of the first luminous objects, either star forming galaxies or active galactic nuclei (AGN).

The study of the first stars, galaxies, and AGN, which act to reionize the Universe at $z \geq 6$, is one of the main science drivers for virtually all future large telescopes, from the radio, through the optical, infrared, and X-ray (Figures 1 and 2). The SKA provides the key ability to see through the dust and to study the radio continuum emission associated with star formation and accreting massive black holes in these first galaxies, as well as to detect the corresponding lower order molecular line transitions (Carilli et al. 2004). In comparison, at (sub-)mm wavelengths, ALMA will reveal the dust and higher order molecular line emission from the first galaxies, as well as fine structure line emission from ionized gas. Further into the mid- to near-infrared, JWST will image the first stars and ionized gas in the most distant galaxies. Complementing all these efforts will be gamma-ray and optical/near-IR observations of gamma-ray bursts and their afterglows. The end of the lives of the first, most massive stars may be detectable as gamma-ray bursts, although these are necessarily limited-duration observations.

2.1 The Neutral Medium

Recent observations have set the first constraints on the EoR, corresponding to the formation epoch of the first luminous objects (Fan, Carilli & Keating 2006). Studies of Gunn-Peterson (GP) absorption, and related phenomena, suggest a qualitative change in the state of the intergalactic medium (IGM) at $z \sim 6$, indicating a rapid

0.1 × Arp220 -- 12hr Continuum

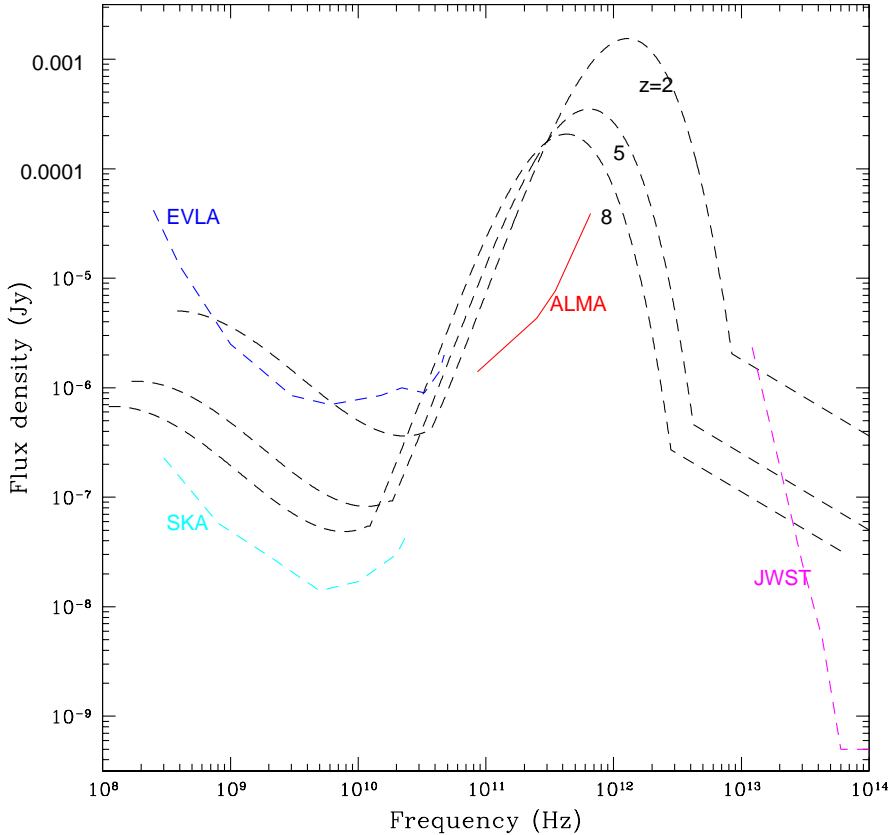


Figure 2. The solid curves show the (1σ) sensitivity to continuum emission for the EVLA, SKA, ALMA, and JWST, in 12 hours. The dashed curves are the continuum emission spectrum for a source at $z = 2, 5,$ and $8,$ with 10% the luminosity of Arp 220 (i.e., a source with far-infrared luminosity $\sim 10^{11} L_{\odot}$).

increase in the neutral fraction of the IGM, from $x_{\text{HI}} < 10^{-4}$ at $z \leq 5.5,$ to $x_{\text{HI}} > 10^{-3},$ perhaps up to 0.1, at $z \geq 6.$ Conversely, transmission spikes in the GP trough, and the evolution of the Ly- α galaxy luminosity function, indicate $x_{\text{HI}} < 0.5$ at $z \sim 6.5,$ while the large scale polarization of the CMB implies a significant ionization fraction extending to higher redshifts, $z \sim 11 \pm 3.$ The results suggest that reionization is less an event than a process, with the process beginning as early as $z \sim 14,$ and with the “percolation” or “overlap” phase ending at $z \sim 6.$ The implication is that the formation of the first luminous objects (stars and AGN) occurs in a “twilight zone,” heavily obscured at (observed) optical wavelengths by a partially neutral IGM, and observable only at near-infrared through radio wavelengths, and in the hard X-ray band.

The SKA is being designed to study both the process of reionization and the first luminous objects. Observations at frequencies below 200 MHz provide the SKA with the unique and powerful capability to carry out direct “tomographic imaging” of the neutral IGM, during the transition phase from a fully neutral IGM during the dark ages, and then through the percolation phase (Furlanetto & Briggs 2004).

2.2 The First Metals

Operating at shorter wavelengths, the SKA will provide key complementary information on the physical processes involved in the formation of the very first galaxies. At wavelengths as short as 12 mm (25 GHz), the SKA opens a unique and powerful new window into the study of the first galaxies, through observations of the lower order molecular emission lines from common species such as CO, HCN and HCO $^{+}.$ The lower order CO

transitions provide the cleanest measure of the total molecular gas mass (the fuel for galaxy formation) and the best method for determining galaxy dynamics, and hence total (gravitating) mass (Walter et al. 2003; Solomon & Vanden Bout 2005). As demonstrated in Figure 1, ALMA cannot see the lowest three CO transitions for $z \geq 5$ and the lowest six transitions for $z \geq 10$; in contrast, the SKA easily covers the lowest-order CO transitions at these high redshifts.

The high dipole moment molecules observable by the SKA, such as HCN, are critical tracers of the dense molecular clouds directly involved in active star formation (Carilli et al. 2005). The SKA will also have the sensitivity to image the star formation activity within the first galaxies, unhindered by dust obscuration, and will be able to reveal the potentially obscured first generation of accreting massive black holes.

2.3 The First Supermassive Black Holes

The first supermassive black holes formed rapidly, as evidenced by the quasars observed at redshifts $z \approx 6$. Understanding how quickly supermassive black holes can form — particularly given the apparently close link between black hole and bulge mass for galaxies at the current epoch — is a common theme for next generation instruments. Currently, optical surveys are revealing the most distant quasars, and even deeper surveys with an ELT may reveal even more distant objects. Optical/infrared surveys will be complemented by surveys at radio (SKA) and X-ray (Constellation-X, XEUS) wavelengths, since both of these are less affected by any potential obscuration. Conversely, deep radio continuum surveys with the SKA are likely to reveal numerous distant supermassive black hole candidates, but a radio continuum survey can give only a qualitative estimate of the redshift of an object. Thus, spectra obtained with an ELT will be essential to determining the redshift of quasar candidates resulting from an SKA survey.

3 GALAXY EVOLUTION, COSMOLOGY, AND DARK ENERGY

The focus of this KSP is to probe the structure of the Universe and its fundamental constituent, galaxies, by carrying out all-sky surveys of continuum emission, and of H I to a redshift $z \approx 2$. These surveys can simultaneously probe cosmology (including dark energy) and the properties of galaxy assembly and evolution (Rawlings et al. 2004).

We emphasize that one of the main lessons we have learnt in the study of star formation in our own Galaxy (and of galaxy formation to the highest redshifts) is that a full understanding of the physics of galaxy formation requires a panchromatic approach. Information across the electromagnetic spectrum is essential for disentangling the rich physics involved in this complex and beautiful process. Nevertheless, the H I line, only detectable at radio wavelengths, acts as a singular probe of these phenomena.

3.1 Dark Energy

Future studies of dark energy have been extensively considered by the Dark Energy Task Force in the USA (Albrecht et al. 2006) and by the Science Committee of the Particle Physics and Astronomy Research Council in the UK (Trotta & Bower 2006).

The study of dark energy has attracted a large number of proposals suggesting a variety of methods and implementations. In general the methods probe dark energy by measuring some combination of the cosmic distance-redshift relations, the expansion history of the Universe, or the growth rate of cosmic structure. Four techniques are generally considered to hold the most promise for future dark energy experiments: (1) baryon acoustic oscillations, (2) galaxy cluster surveys, (3) supernovae surveys, and (4) weak lensing. The SKA will conduct surveys relevant to acoustic oscillations and weak lensing. In comparison, an X-ray Joint Dark Energy Mission (JDEM) satellite would study dark energy using galaxy clusters, while the LSST or an optical/near-IR JDEM satellite could use any of the above approaches. A combination of methods is likely to be important to address the potential presence of systematic uncertainties in any one technique, and to distinguish the kinematic effects of dark energy from deviations in the laws of gravity on large scales.

A general conclusion of the various reviews is that the overall dark energy performances of the SKA, LSST, and JDEM space mission will be roughly equivalent. The most notable point in favor of the SKA is that it is the only planned ground-based facility capable of performing an all-sky spectroscopic redshift survey to high redshift; consequently, the SKA will provide a substantially higher baryon oscillation accuracy than the LSST. Unlike the LSST or JDEM, the SKA does not utilize supernovae as a dark energy technique, but this is more than compensated for by the use of baryon oscillations to measure cosmic distances and expansion history.

The main advantages of the SKA for probing dark energy are that baryon oscillations are thought to be the technique least affected by systematic uncertainties, and that data on weak lensing (potentially the most powerful probe of dark energy) need all-sky coverage, very high source density and source redshift information, as only the SKA can provide. The potential caveats for SKA dark energy experiments are that there is considerable uncertainty in extrapolations of the number density of H I-emitting galaxies as a function of redshift,² that it is yet to be demonstrated that a very wide field-of-view is affordable, and that radio frequency interference will be an issue for deep surveys.

As mentioned above, the current expectation is that no single technique is likely to yield a definitive answer. High precision demands careful attention to systematic effects, both instrumental and astrophysical. The different techniques, particularly if carried out at different wavelengths, will have different systematic effects. Combining these results will allow higher precision constraints to be placed on the properties of dark energy. Moreover, in many cases, the various techniques yield dark-energy or cosmological constraints that are in some sense “orthogonal” to each other. For these reasons, recent reviews have consistently recommended a multi-technique, multi-wavelength approach to the dark energy problem.

3.2 Galaxy Evolution

Galaxy assembly is now understood to proceed predominantly hierarchically, with smaller systems merging to form steadily larger systems. In contrast, star formation in the Universe reached a peak around a redshift $z \approx 2$ and has been declining ever since. A broad theme for many next-generation telescopes is to understand the interrelation between these processes of star formation and galaxy assembly, and to investigate possible environmental dependences.

It is essential to have a complete inventory of neutral hydrogen (H I), the basic ingredient for star formation and galaxy assembly — only the SKA can provide this. In addition to the full H I picture, the SKA will provide an unbiased view of the star formation rate in galaxies; radio wavelengths penetrate even the most dusty galaxies, which are highly obscured at optical wavelengths. The SKA will uniquely image the distribution of neutral hydrogen out to high redshift and in a wide range of environments (e.g., van der Hulst et al. 2004). H I spectra also provide a kinematic probe of the depth of each galaxy’s potential well, allowing direct tests of galaxy evolution models which deal with mass as well as light. ALMA will measure the mass of molecular gas in galaxies, i.e., the regions of highest gas density where gas is transformed from an atomic to a molecular phase as galaxies collapse and the main phase of star formation begins, over a very wide range of redshifts. While ALMA will begin observations before the SKA, the tiny field of view for ALMA in comparison with that planned for the SKA means that the SKA will be much more effective in surveying and identifying obscured star-forming galaxies over a large cosmic volume. Moreover, molecular gas, only traces the densest regions of the ISM, whereas the H I is also present abundantly in intergalactic space where the densities are too low to form molecular hydrogen efficiently.

More broadly, multi-wavelength observations will probe the entire process by which galaxies are transformed from their initial gaseous phase to largely stellar dominated objects over a large fraction of cosmic time. The SKA will map the distribution of neutral hydrogen out to a redshift of at least $z \sim 1$ and potentially as high as $z \sim 3$; ALMA will show how this neutral gas transforms into the molecular mass from which stars form; an ELT will show the stars themselves, and will measure the star formation rate to high redshift using supernova statistics; JWST will track the build-up of the Hubble sequence to $z \sim 3$; and next-generation X-ray missions (Constellation-X or XEUS) will probe the assembly of galaxy clusters. In the ultraviolet, we note that aside

²This uncertainty can only be resolved with actual high-redshift measurements from SKA prototypes.

from the Cosmic Origins Spectrograph instrument that may be eventually installed on HST, there is no current planning for future ultraviolet missions that can probe intergalactic hydrogen at any interesting redshifts.

3.3 The Local Cosmic Web

On the largest scales, a filamentary “cosmic web” of galaxies, clusters, and superclusters is being revealed through a combination of theoretical and observational analyses. The strands of this web mark the pathways by which large-scale structure assembles. X-ray observations of high ionization species may already be revealing local strands of this cosmic web, and future X-ray missions will undoubtedly give a more complete picture. However, these observations are limited to elements with low fractional abundances, and the metallicity of the gas is uncertain. By contrast, the SKA will be able to probe intergalactic hydrogen (potentially both the ionized and neutral components), offering a direct probe of the baryonic component of the local cosmic web.

4 THE ORIGIN AND EVOLUTION OF COSMIC MAGNETISM

Magnetic fields are an essential part of many astrophysical phenomena, but fundamental questions remain about their evolution, structure, and origin. The focus of this KSP is tracing magnetic field evolution and structure across cosmic time. The foundation for these experiments will be an all-sky SKA survey of Faraday rotation measures (RMs), in which the Faraday rotation toward $> 10^7$ background sources will provide a dense “RM grid” for probing magnetism in the Milky Way, nearby galaxies, and in distant galaxies, clusters and protogalaxies (Beck & Gaensler 2004; Gaensler et al. 2005).³ Using these data, we can map out the evolution of magnetized structures from redshifts $z > 5$ to the present, and can thus reveal what cosmic magnets look like, how they formed, and what role they have played in the evolving Universe (Gaensler, Beck & Feretti 2004).

Radio astronomy has a colossal advantage over other wavebands when it comes to studying astrophysical magnetism. At large distances, extinction, spatial resolution and sensitivity all severely limit measurements of magnetism in other wavebands. However, in the radio band, not only is the Universe transparent, but an object does not even have to emit to be detected in Faraday rotation — all that is needed is a sufficiently bright background source.

Thus for the SKA KSP on cosmic magnetism, *the science envisioned is unquestionably unique to the SKA*. Nevertheless, there are a number of aspects to the magnetism KSP for which other facilities will certainly play an important supporting role. Some of the expected synergies are as follows.

4.1 The Magnetic Field Of The Milky Way

The next generation of cosmic microwave background (CMB) experiments aim to make high-sensitivity, full Stokes, images of the entire sky in the millimeter band. Most notable amongst these experiments will be Planck, an ESA mission scheduled for launch in early 2008, which will provide high-sensitivity images of the entire sky in nine frequency bands between 30 and 860 GHz, at angular resolutions of 30 arcmin or better. Five of these bands, between 30 and 350 GHz, will have the capability to image linear polarization. Other future CMB polarization experiments include EBEX, Spider, BRAIN, Clover and CMBpol.

In order to study cosmological polarization signals, foreground emission from the Milky Way must be accurately accounted for. Any successful polarized CMB experiment will thus deliver a map of Galactic polarization over the entire sky, and its decomposition into contributions from dust emission and from synchrotron emission (Page et al. 2006). These Galactic foregrounds will be line-of-sight integrals and cannot be inverted directly to give the full three-dimensional structure of the magnetic field. However, models of the three-dimensional Galactic magnetic field can be forward propagated and then compared to these observations (Enßlin et al. 2006). CMB polarization measurements are at high enough frequencies that they are largely free from the effects of Faraday rotation. Thus, they will be highly complementary to SKA measurements in that, combined with ground-based

³In addition, Faraday rotation will be detected toward all of the pulsars detected in the census conducted as part of the “Strong Field Tests of Gravity” KSP, discussed in §5.

absolute calibration measurements, they will provide a relatively low angular resolution (i.e., as compared to the approximate $1'$ RM grid), all-sky template of the magnetic field. This can be combined with the RM grid to develop a full three-dimensional picture of Galactic magnetism.

4.2 Magnetic Fields in Supernova Remnants and Galaxy Clusters

Radio synchrotron emission is a critical probe of magnetic fields in supernova remnants (SNRs) and clusters of galaxies. A typical assumption in the derivation of cluster magnetic fields from radio observations is that there is equipartition between the energy in particles and fields (Pacholczyk 1970; Beck & Krause 2005). In order to make more accurate measurements, additional information is needed. An independent estimate of the magnetic field strength can be obtained from detection of hard X-ray inverse Compton emission due to the scattering between the radio-emitting electron populations and the CMB photons. When combined with synchrotron data, these X-ray observations can be used to derive the spatial distribution of the source magnetic field strength. To make these measurements, high angular resolution imaging in hard X-rays (10–50 keV) is required, observations which will become possible with future missions such as NeXT, HEXIT-SAT and SIMBOL-X.

In the case of RM data, the information about the magnetic field strength can only be derived if the density of the ionized medium along the line is known or assumed. Future X-ray satellites which will map the X-ray sky at low energies (XEUS and Constellation-X) will provide a precise knowledge of the X-ray surface brightness of clusters, i.e., of their thermal gas density, allowing the accurate and correct interpretation of the sensitive RM measurements.

Another limitation to understanding the role of magnetic fields in both galaxy clusters and SNRs is a lack of information about the dynamics of the hot, X-ray emitting gas, whose turbulent motions both generate and are constrained by the corresponding magnetic fields (Inogamov & Sunyaev 2003; Subramanian, Shukurov & Haugen 2006). XEUS and Constellation-X will provide the high-resolution X-ray spectroscopy needed to make these measurements.

4.3 Intergalactic Magnetic Fields

One of the main applications planned for the SKA's RM grid is to localize the RM measurements of distant galaxies in three dimensions, by also determining the redshift for each source. This distribution can be used to chart the topology and strength of large scale intergalactic magnetic fields and their relation to the cosmic web (Kolatt 1998; Blasi, Burles & Olinto 1999). While the RMs will come from the SKA, optical surveys will be needed to provide the corresponding redshifts. For deep RM surveys covering a few hundred degrees of sky, WFMOS will be able to provide the needed redshifts through spectroscopy. For a shallower RM survey over the entire sky, redshifts will be obtained photometrically, for which the wide-field imaging capabilities of the LSST and SkyMapper will be crucial.

Cosmic rays at the very highest energies, $\gtrsim 10^{20}$ eV, are unaffected by Lorentz forces in the magnetized intergalactic medium (IGM), and thus should exhibit trajectories which point back toward their origin. However, at progressively lower energies, cosmic rays are increasingly deflected by magnetic fields along the line of sight (Dolag et al. 2004). The multi-pole moments, auto-correlation functions, and other clustering properties of these particles provide a stochastic measure of the IGM magnetic field strength as a function of scale (Sigl, Miniati & Enßlin 2004). Air-shower experiments such as HiRes and Auger will soon accumulate a statistically interesting sample of ultra-high-energy cosmic rays through which these deflections can be detected and studied. Future space-based missions such as EUSO may further extend the sensitivity of these measurements. These data will be a useful complement to the RM grid (the latter of which will probe the direction and strength of the IGM magnetic field along many specific lines of sight; e.g., Xu et al. 2006).

4.4 Magnetic Fields Over Cosmological Epochs

ALMA will have the capability of observing continuum polarization in at least some of its frequency bands. As pointed out by Wielebinski (2006), some starburst galaxies will be bright enough at these frequencies to be

detected in linearly polarized synchrotron radiation to large distances. Such measurements may be useful for probing magnetism in star formation regions as a function of cosmic epoch. The ability of ALMA and JWST to find star-forming galaxies at $z > 5$ will also be important for identifying targets that can then be subjected to very deep continuum observations with the SKA. The total intensity and polarization information from these observations can then be used to characterize the growth and organization of magnetic fields in galaxies at high redshifts.

Magnetic fields at the epoch of recombination, if they exist, would serve as primordial seed fields for future structure formation. This weak initial field could potentially be detected either through its imprint on CMB power spectra or through Faraday rotation induced against the CMB itself (Kosowsky & Loeb 1996; Giovannini 2006). While either measurement will be extremely challenging, Planck may have the capability to see the former, while SKA, at its highest operating frequencies, may detect the latter.

5 STRONG FIELD TESTS OF GRAVITY USING PULSARS AND BLACK HOLES

The goal of this KSP is to identify a set of pulsars on which to conduct high precision timing measurements from which gravitational physics can be extracted (Kramer et al. 2004). The nature of the gravitational force is intimately related to the nature of space and time itself. Today, these pulsar timing observations provide the most stringent tests of strong-field gravity, but the effects of gravity manifest themselves in a much wider variety of phenomena, requiring a broad array of experiments to provide rigorous tests. In this section, we discuss various observational aspects of gravitational physics that will be probed by both the SKA and other gravitational observatories. Figure 3 illustrates some of the limits and capabilities discussed below.

In addition to the experiments described below, probing dark energy has a clear relevance to understanding gravity. The SKA's contribution to dark energy measurements is discussed in §3.

5.1 Direct Detection of Gravitational Waves

While timing measurements of double-neutron-star binary systems have provided the strongest evidence for the existence of gravitational waves, these observations are necessarily indirect. Great efforts are going into the development of systems which can make a direct detection of gravitational waves by measuring their effects on the local space-time metric. These systems fall into three main classes: ground-based laser interferometer systems such as the Laser Interferometer Gravitational-Wave Observatory (LIGO), space-based laser interferometer systems such as LISA, and pulsar timing arrays. As illustrated in Figure 3, these three classes of systems are highly complementary, in that they are sensitive to different frequency ranges: 10–1000 Hz for LIGO, 0.1–100 mHz for LISA, and 5–100 nHz for pulsar timing arrays. In addition, the Gaia astrometric mission may also be able to detect the presence of gravitational waves by searching for minute fluctuations in star positions which would be correlated in widely separated regions on the sky.

The prime targets for ground-based laser interferometer systems are coalescing double-neutron star systems. These events may be detected at rates of a few per year with Advanced LIGO, due for completion around 2013. Gravitational waves from rapidly spinning aspherical neutron stars (with a frequency of twice the neutron-star spin frequency) and gravitational-wave bursts from supernovae may also be detectable.

LISA is most sensitive to coalescing supermassive black holes binary systems in the cores of galaxies but the rate of these is quite uncertain. Another likely class of source are “extreme-mass-ratio inspiral” (EMRI) events where a star spirals into a massive black hole, generating gravitational waves as it goes. These events last several years and hundreds may be detectable at any given time. LISA is also sensitive to gravitational waves from close stellar binary systems in our Galaxy. In fact there are so many of these that they will form a “noise” background for the other sources. (In discussing prospective LISA science, we note that NASA funding for LISA is currently on indefinite hold, so the future for this experiment is uncertain; it currently seems unlikely that this project can be completed before 2015.)

Pulsar timing arrays can detect low-frequency gravitational waves passing over the Earth by comparing timing residuals from a large number of pulsars widely distributed across the celestial sphere. Only millisecond pulsars

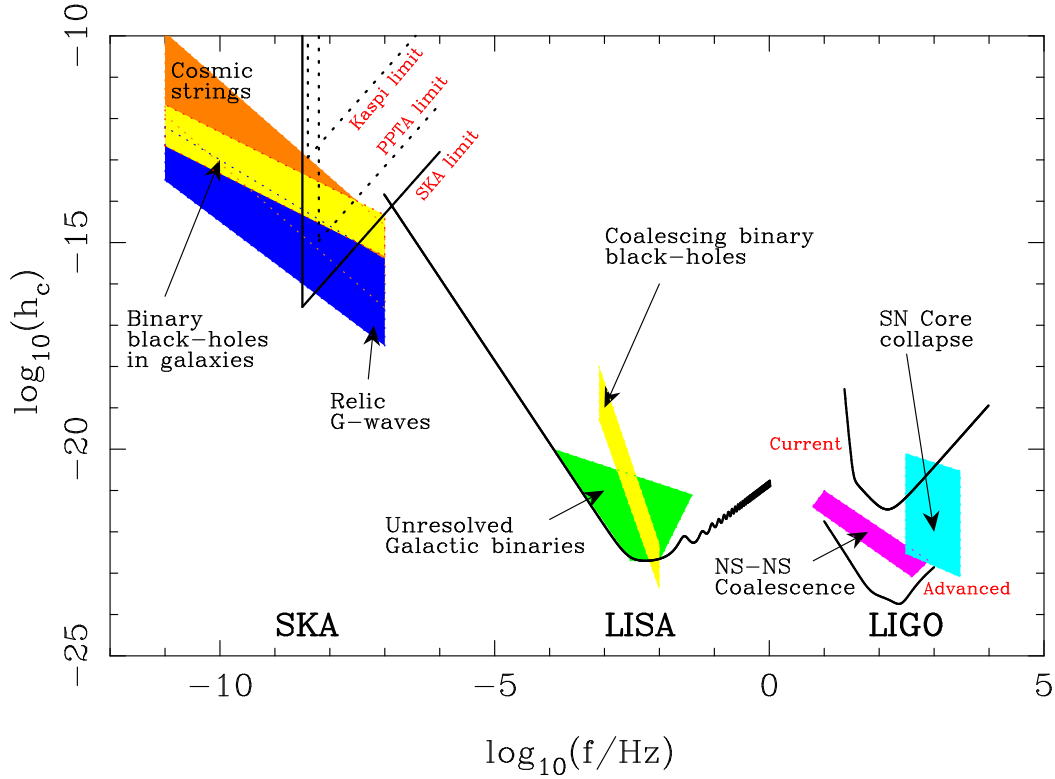


Figure 3. The characteristic strain, h_c , produced by a gravitational wave as a function of frequency, f . The colored regions indicate the expected strains from various sources. The expected sensitivities for LIGO (both Current and Advanced), LISA and the SKA are shown. The LIGO and LISA sensitivities are taken from the literature. The SKA limit is compared to those of two other pulsar timing array experiments: that of Kaspi, Taylor & Ryba (1994), and the on-going Parkes Pulsar Timing Array (PPTA) experiment. This Figure was prepared by members of the PPTA collaboration; see <http://www.atnf.csiro.au/research/pulsar/ppta>.

can be timed with sufficient precision to make a detection possible. Binary supermassive black holes in the cores of galaxies are the most likely astrophysical sources, but relic gravitational waves from the inflation era and oscillations of cosmic super-strings in the early Universe may also be detected. Current timing array projects such as the Parkes Pulsar Timing Array (PPTA) may have sufficient sensitivity to detect gravitational waves from these sources in 5–10 years. With its huge sensitivity and ability to monitor a large number of pulsars, after five years or so the SKA will either detect gravitational waves from these sources or rule out all current models for their origin.

5.2 Black Hole Spin Measurement

Within general relativity (GR), black holes are the simplest possible objects, with all properties determined by their mass and spin. The measurement of the spin of a black hole would allow us to test GR descriptions such as the Cosmic Censorship Conjecture, which postulates the existence of an event horizon to hide the singularity.

The SKA, through timing measurements of a pulsar orbiting a black hole, will provide the most likely means of detecting this effect. The timing measurements of a pulsar in a neutron star-neutron star binary have already been analyzed to determine the deformation of space-time within the binary. In a similar fashion, the signals from a pulsar in a neutron star-black hole binary should also contain information about the black hole spin, among other effects. Possible targets for an SKA observing program include a pulsar/stellar-mass black hole binary in the Galaxy, a pulsar orbiting an intermediate black hole in the center of a globular cluster, or pulsars in orbit around Sgr A*, the supermassive black hole in the Galactic center.

In principle, LISA could derive the spin of supermassive black holes from observations of the EMRI events, while LIGO-type detectors may be able to achieve this for stellar-sized black holes if the deformation of the merging object can be understood astrophysically.

5.3 Theories of Gravity

Both Solar system measurements and pulsar timing have contributed to stringent constraints on deviations from GR in the weak-field limit. Any physics beyond GR is therefore expected to be detected in the strong-field limit. Typically theories of gravity can be probed using the so-called Parameterized Post-Newtonian formalism, the parameters of which should have specific values for specific theories of gravity.

A key aspect of comparison of various science cases usually starts with the discussion of the definition of “strong-field” effects. Gravitational wave physicists tend to define strong-field as the regime where Post-Newtonian approximations to the field equations (in orders of v^2/c^2) break down. In contrast, a more general definition classifies a strong-field experiment as one where self-field effects need to be taken into account. The latter is clearly the case for the study of binary pulsars and their companions, and the measurement of black hole properties also should be classified as a truly strong-field experiment.

The SKA, LISA and Gaia will provide the best chance for detecting departures from the predictions of GR. The SKA and LISA will provide tests in the strong-field regime, while Gaia’s tests will be obtained by combining the sheer volume of data with high precision, in order to probe the weak-field regime at unparalleled limits, and to apply various tests related to the Strong Equivalence Principle.

Unlike measurements in the radio band, gravitational wave detectors have the advantage of being able to directly measure the distance of a gravitational wave source, although they are likely to be somewhat imprecise in their mass measurements. Conversely, the SKA can determine the masses of pulsars and their companions with high precision, but distances will be difficult to obtain, except in cases where interferometric parallax measurements are feasible. Hence, a joint study of the same binary pulsars with LISA and the SKA will not only be highly complementary, but may be essential in revealing deviations from GR that could not be achieved with either instrument individually.

The gravitational wave detectors will also provide an exciting extension of the classical electromagnetic windows probed by telescopes like the SKA or Gaia. As such, any source newly discovered in one window can be followed up with the other instruments in other windows. Because of the enormous volume of data generated both by the SKA and by Gaia, they also have the potential to discover signals that cannot be explained by known objects. Such possibilities include quark stars and boson stars.

6 THE CRADLE OF LIFE

The focus of this KSP is to probe the full range of astrobiology, from the formation of prebiotic molecules in the interstellar medium to the emergence of technological civilizations on habitable planets (Lazio, Tarter & Wilner 2004). This KSP has three observational aspects, which we discuss separately.

6.1 Imaging Protoplanetary Disks

It is now clear that accretion disks are both the means by which the late stages of stellar accretion proceed and the environment in which planets form. Their study forms an integral part of essentially all major instruments operating at wavelengths from the visible to the radio. We use an optical ELT, the JWST, ALMA, and the SKA to illustrate protoplanetary disk studies. The focus of these studies will be two-fold: the spectral properties of the disks and direct imaging of them.

The composition of a protoplanetary disk is dominated by molecular hydrogen, meaning that most observations of protoplanetary disks target either trace molecules (with typical abundances no greater than 10^{-4}) or dust grains, observing either their thermal emission or scattered starlight from them. A key aspect of the SKA is that it will observe at wavelengths near 1 cm, so that it will be sensitive to the thermal emission from dust

grains of a comparable size. Planet formation can be generally understood as a hierarchical process, in which smaller particles accrete to form larger objects which in turn accrete to form even larger objects (dust grains → “pebbles” → “boulders” → “planetesimals”). A major uncertainty in our current understanding is how particles of order 1 cm in size (“pebbles”) accrete to form larger objects. The typical kinetic energies of pebbles is such that they should collide destructively rather than accrete to form larger objects. By observing disks at centimeter wavelengths, the SKA will be probing them at a stage in the planet assembly process for which our uncertainty is the largest.

The second aspect, and the major advance provided by next-generation instruments, will be the imaging of protoplanetary disks. The nearest star forming regions (the dark clouds in Taurus, Ophiuchus and Chamaeleon) are at distances of order 150 pc, meaning that planets having semi-major axes of 1–5 AU around a solar-mass star have orbits that are approximately 10 to 100 milliarcseconds in diameter. All of the major next-generation instruments (ELT, JWST, ALMA, and SKA) will have resolutions of this order, although at different wavelengths and with different risks. Both an ELT and the JWST aim for diffraction-limited imaging in the near infrared ($\approx 2 \mu\text{m}$), which would produce angular resolutions in the range of 5–50 mas. This will be suitable for imaging debris disks and planets, corresponding to the late stages of planetary formation. However, these instruments will not be capable of penetrating dusty disks with large optical depths at visible and near-IR wavelengths. Also, both telescopes require the construction of quite large mirrors. In the case of the JWST, the risk is that a sufficiently large aperture will not be cost-effective to launch, while for a ground-based telescope, adaptive optics are required to obtain diffraction-limited imaging.

ALMA, on its longest baselines, will also obtain angular resolutions of approximately 6–60 mas. Operating at longer wavelengths than either an ELT or the JWST, ALMA will be able to probe deeper into dusty (i.e., younger) disks. At its highest frequencies, ALMA will begin to approach the peak of the dust spectral energy distribution. Concomitantly, the contrast between the larger dust disk and the gap opened by the planet will decrease at ALMA’s highest frequencies. Moreover, obtaining the highest angular resolutions with ALMA will require accurate phase compensation for atmospheric water vapor, even at ALMA’s high altitude site.

The SKA will obtain higher angular resolutions (≈ 1 mas) than any of these other instruments. With this resolution, and at frequencies for which disks will be optically thin, the SKA will be able to resolve the spectral energy distribution of the disk, thereby showing the locations at which on-going planet assembly is occurring. Just as for ALMA, the SKA will obtain this angular resolution at its highest operational frequencies (≈ 25 GHz) and longest baselines. Like ALMA, obtaining the required angular resolution will require accurate phase compensation for water vapor fluctuations, but this procedure has been demonstrated already with very long baseline interferometric observations with existing telescopes.

6.2 Prebiotic Molecules

Astrobiology undoubtedly begins with the formation of biomolecules in interstellar clouds from which new solar systems eventually form. Approximately 140 different interstellar compounds have now been identified, ranging in size from two to 13 constituent atoms. The more complex species have six or more atoms and all are organic since each of these molecules contains carbon. Because many of the complex molecules found in space are also found in laboratory experiments specifically designed to produce prebiotic molecules under assumed primordial Earth-like conditions, this suggests that a universal prebiotic chemistry is at work in space. Thus, the study of prebiotic chemical evolution in interstellar clouds will be an ever increasing area of research to determine exactly how amino acids, complex sugars, and other important biomarkers are formed in space.

ALMA is designed to be a powerful high spatial resolution, short-wavelength probe of molecules in interstellar clouds, particularly of the relatively warm gas-phase molecules in compact hot cores, having diameters of a few arcseconds or less. However, within the last few years, it has become apparent that a number of complex interstellar molecules of prebiotic interest also are distributed on arcminute scales, vastly larger than typical hot core dimensions (e.g., Chengalur & Kanekar 2003); these molecules have been detected by means of their low-energy transitions and have been determined to reside in cold halo regions more suitable to the better beam-coupling capability and longer wavelength observing range of the SKA (Hollis et al. 2006). Thus, the SKA

and ALMA will complement each other in the study of interstellar clouds, since the SKA will be able to observe low-energy rotational transitions of complex molecules, obtaining critical spatial information that ALMA will miss entirely by over-resolution. For instance, a recent detection of glycolaldehyde (CH_2OHCHO) with the Green Bank Telescope (GBT) resulted from observations of transitions at frequencies ranging from 13 to 22 GHz (Hollis et al. 2004).

Furthermore, at longer wavelengths (i.e., at frequencies covered by the SKA but not by ALMA), *spectral line confusion* is also less problematic. The sheer number of molecules and transitions means that separating individual lines above 100 GHz can become difficult. In contrast, below 30 GHz the abundances and separations of molecular transitions means that spectral line confusion will be less of an issue for the SKA as compared to ALMA. This capability is particularly important for low abundance species, for which multiple transitions must be identified.

6.3 Technological Civilizations: The Search for Extraterrestrial Life

Detecting the presence of another technological civilization would be *prima facie* evidence that the entire range of astrobiological processes — from planet formation to the origin of life to development of intelligence — are universal. With its sensitivity, the SKA will be without peer in Search for Extra-Terrestrial Intelligence (SETI) programs because it will be able to search for *unintended* emissions. By contrast all SETI programs to date have only been sensitive to beacons, i.e., powerful broadcasts intended to be detected by other civilizations.

The sensitivity of the SKA is such that its nominal detection threshold will be approximately two orders of magnitude better than that of previous searches at radio wavelengths. The SKA's detection threshold should be approximately $10^{-28} \text{ W m}^{-2}$, sufficiently sensitive that it could detect a typical airport radar out to 30 pc, comparable to the distances for many of the currently known planets (although these planets are unlikely to have any transmitters on them). Modest improvements in signal processing afforded by additional computing power suggest that perhaps as much as another order of magnitude improvement in sensitivity could be obtained. With this sensitivity, leakage radiation from transmitters with power only at the level of current broadcast television stations could be detected over interstellar distances.

While the details of SETI programs at optical wavelengths differ — searching for nanosecond optical pulses — the motivation for optical SETI programs requires that they also search for directed transmissions. The motivation behind optical SETI programs is that, even with current technology, our civilization is capable of outshining a main-sequence star, albeit only on nanosecond time scales. Obtaining such a luminosity requires a relatively powerful laser focused into a 10-m class telescope. The point spread function of such a telescope means that, in order for a detection to occur, the telescope must be pointed in the direction of any receiving civilization, i.e., any other civilization must know that we exist and transmit in our direction in order for us to detect their optical pulses. We thus anticipate that only with the SKA will we have the capability to detect untargeted transmissions.

Finally, there is the possibility that the first detection of an extraterrestrial signal will be obtained not by a dedicated SETI program, but serendipitously as the result of another observing program, potentially not even in the radio band. While it is clearly difficult to predict in which wavelength band such a detection will occur, expanding the available parameter space at any wavelength band will increase the odds of such a detection. In this regard, the SKA's sensitivity, bandwidth and field of view will open up a large range of parameter space for discoveries, whether they be extraterrestrial civilizations or some other phenomenon.

7 CONCLUSIONS

The 20th century saw astronomy progress from observations of only thermally-emitting stars, nebulae, and galaxies over a limited wavelength range to a vast range of astrophysical investigations, using telescopes operating across the entire electromagnetic spectrum, along with cosmic ray, neutrino and gravitational wave detectors. These advances have allowed us to formulate incredibly ambitious questions relating to the structure and evolution of the Universe, the formation of galaxies, and the origin of life. The Square Kilometre Array is one of the future large facilities essential for addressing these questions. The unquestioned strengths of the SKA will

be its ability to detect radio emission from neutral hydrogen, from pulsars, and from magnetized plasmas. This will allow us to understand how gas has assembled into stars and galaxies over the last 14 billion years of cosmic history, to test theories of gravitation, and to determine what role magnetism has played in the evolving Universe. In combination with other facilities, the SKA will play a crucial role in studying planet formation, detecting gravitational radiation, measuring the properties of dark energy, and finding the first supermassive black holes. Finally, the SKA is the only current or future facility capable of detecting undirected transmissions from extraterrestrial intelligence. The SKA will thus be uniquely positioned to identify sentient life on other worlds, a discovery which would forever change humanity's view of the cosmos.

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