

DISCOVERY AND UNDERSTANDING WITH THE SKA

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OCTOBER 3, 2006
VERSION 1.03

EXECUTIVE SUMMARY

The Square Kilometre Array will be a premier instrument for discovery owing to its continuous coverage of a wide range of radio frequencies combined with unprecedented high sensitivity, wide field of view, multiple-scale angular resolution, and highly flexible sampling of the time domain. In this document we summarize the planned capabilities of the SKA as defined by key science areas that drive the specifications. We characterize the SKA as a discovery instrument, both for known and unknown classes of astrophysical sources. Finally we summarize the unique and complementary aspects of the SKA with respect to other large-scale instruments that are being planned across the electromagnetic spectrum and also for non-photonic detection.

INTRODUCTION

The SKA will transform our understanding of the universe on all scales of space and time. Science goals envisioned for it target fundamental aspects of our universe, such as the nature of the mysterious dark energy that is accelerating the universe's expansion, and the properties of gravity around black holes. The rich complexity we see all around us — a cosmic web of galaxy clusters, each containing hundreds of billions of stars around many of which planets have formed as prospective venues for life — is also awaiting study and understanding with the SKA working in concert with other instruments. Known classes of sources, such as gamma-ray burst afterglows, will be detected in such large numbers that they will become routine tools for studying the intergalactic and interstellar media (ISM, IGM). And there is the discovery of the as-yet unknown in the universe. The SKA will open up new realms of parameter space in which entirely new classes of sources will be discovered. In this document, we highlight the SKA as a platform for discovery and a tool for understanding the universe and the complex phenomena we find within it.

In the following we summarize the broad science areas that the SKA will address in § I and the requirements on the SKA that are needed to achieve the science goals. In § II we discuss the capabilities of the SKA from a parameter space point of view and in § III we outline summarize the types of discovery that are relevant to the SKA, with some emphasis on sources of transient radio emission. We point out in § IV the importance of data management protocols and systems that will be needed to enable the discovery process. Finally, in § V we discuss aspects in which the SKA is entirely unique or complementary with other instruments in achieving its science goals.

I. KEY SCIENCE AREAS AND EXPLORATION OF THE UNKNOWN

Five primary science areas have been defined by the internationally constituted Science Working Group that address fundamental questions on the forefront of physics, astrophysics and astrobiology.¹ Much of the science entails massive sky surveys that will be challenging both technologically and logistically. Together they drive the specifications for the SKA². A provisional Reference Design³ suggests a possible implementation of these specifications with aperture (phased) arrays at low frequencies and an array consisting of a large number of small diameter dishes (LNSD) at higher frequencies. Figure 1 shows schematically the frequency ranges demanded by the key projects.

The Dark Ages: The structure of the universe prior to and during the formation of galaxies can be probed uniquely at radio wavelengths. The 21cm line from hydrogen will be used to map cosmic structure both in space and time (via the redshift) and is a powerful complement to the cosmic microwave background (CMB), which provides a single snapshot of the universe when it was about 300,000 yr old. The 21 cm line, observed at redshifted frequencies above and possibly below the FM band, will sample structures that were in the process of forming clusters of galaxies at redshifts of 6 to 15 or even higher, culminating in the Epoch of Reionization when the formerly atomic universe became the plasma universe. The agents of ionization — the first stars and black holes — will also be probed with the SKA through mapping of redshifted carbon monoxide and through high-resolution mapping of active galactic nuclei at high redshifts. Figure 2 shows simulated temperature fluctuations in hydrogen emission and absorption associated with the turning on of ionizing sources.

Galaxy Evolution/Dark Energy: The unparalleled sensitivity of the SKA, combined with its extremely large instantaneous field of view, permits ground-breaking cosmic surveys. Reasonable models indicate that, in a year of operation, the SKA can map $\sim 10^9$ HI galaxies across the entire visible sky to redshift $z \approx 1.5$, providing

¹ The SKA science case is presented in *Science with the Square Kilometre Array*, eds: C. Carilli and S. Rawlings, New Astronomy Reviews, Vol. 48, Elsevier, 2004

² SKA Memo 45, *SKA Science Requirements: Version 2*, 2004 http://www.skatelescope.org/pages/page_astronom.htm

³ SKA Memo 69, *Reference Design for the SKA*, 2006

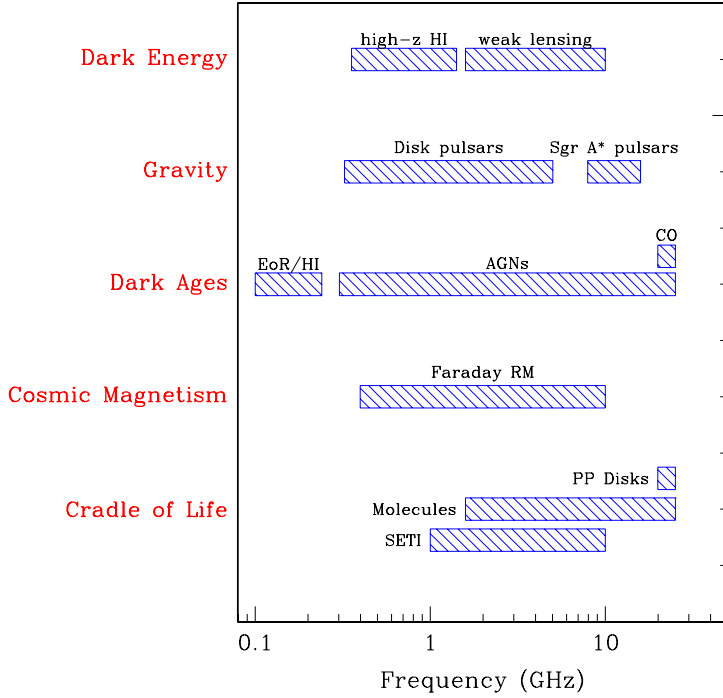


FIG. 1.— Frequency ranges associated with the five science areas identified for the Square Kilometre Array, demonstrating the nominal 0.1 to 25 GHz range specified in the Reference Design (see text).

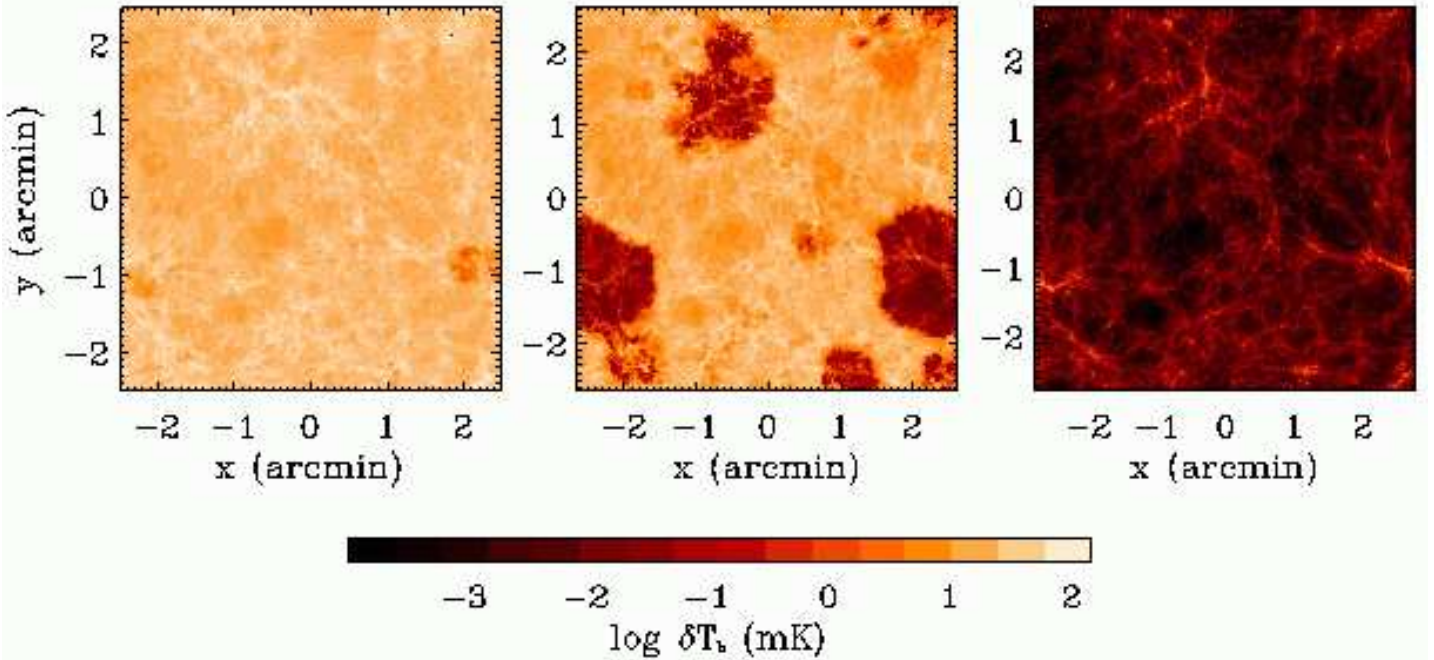


FIG. 2.— Simulations of 21 cm hyperfine radiation at high redshifts, showing temperature fluctuations and the growth of structures (Furlanetto & Briggs 2004).

the premier measurement of the clustering power spectrum: accurately delineating acoustic oscillations and the ‘turnover’. HI detections provide full 3D positional information without separate spectroscopy observations, as with optical surveys. In addition, a radio continuum survey will quantify the cosmic shear distortion of $\sim 10^{10}$ galaxies with a precisely-known point-spread function, determining the power spectrum of dark matter and its

growth as a function of cosmic epoch. These experiments will provide exquisite information on the properties of dark energy. Furthermore, additional cosmological constraints will follow from the late-time Integrated Sachs Wolfe effect, and precise geometrical measurements of the distance scale using strong gravitational lensing and studies of extragalactic water masers.

CO surveys with the SKA can measure gas at redshifts $z > 3.6$ providing an important counterpart to high-redshift hydrogen at and before the Epoch of Reionization. Figure 3 shows the detectability of CO and of continuum emission with the SKA and ALMA.

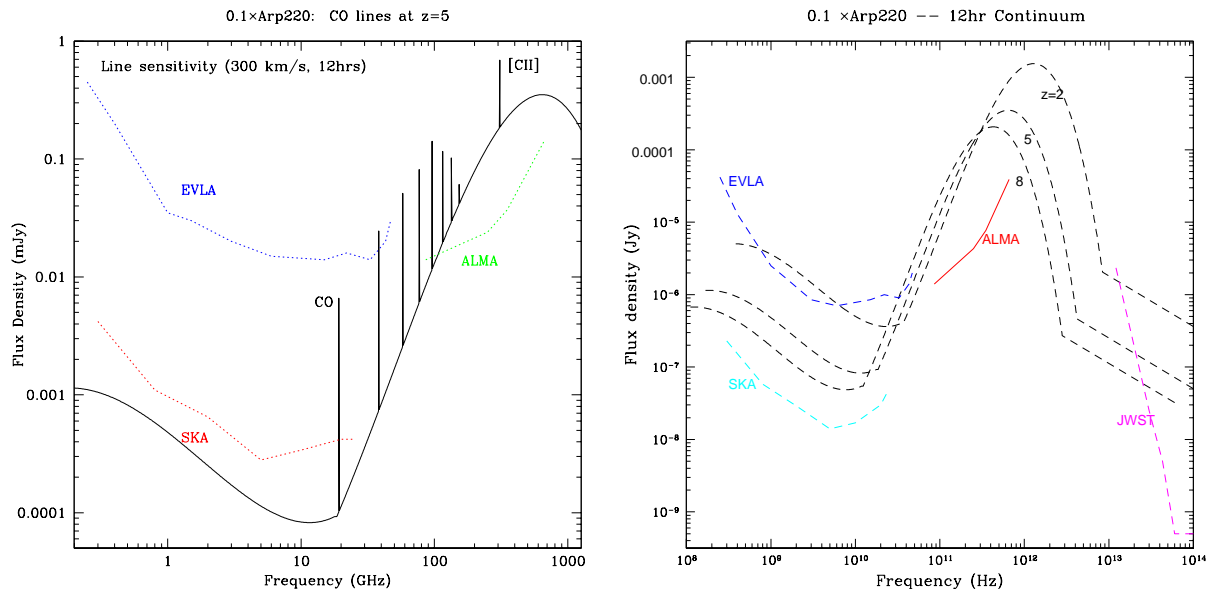


FIG. 3.— Plots — one for line (left) and one for continuum (right) sensitivity versus the expected SED of a high z star forming galaxy with a luminosity $1/10$ that of arp 220 — this would be typical of Lyman break galaxies or Lyman alpha galaxies.

The Magnetic Universe: The structure and evolution of magnetic fields are topics that thread many of the most important issues in astrophysics today, from galaxy formation to star and planet formation. However, our knowledge of dynamo mechanisms and the cosmic evolution of magnetic fields is at best cursory. The SKA can rectify this by allowing Faraday tomography of polarized synchrotron radiation in our Galaxy and in other galaxies and clusters and large scale surveys of the Faraday rotation of sources at cosmological distances. Variations in sign of the Faraday rotation will reveal model-independent magnetic topologies in galaxies and in the IGM. As an inverse problem, the electron density and magnetic field can be deconvolved with more model dependence to gain a three dimensional picture of the magnetic field as a function of redshift.

Probing Strong-Field Gravity with Pulsars and Black Holes: Pulsars are exquisite clocks — owing to their spins — that can be used for space-time cartography around massive objects, such as other neutron stars and black holes. They also serve as test masses that respond to very long wavelength gravitational waves. Thirdly, their pulses are excellent probes of the gas and magnetic fields through which they must propagate to reach us. The SKA will yield a (nearly) complete census of pulsars in the Milky Way, from which the Galaxy’s spiral structure can be defined and turbulence in the magnetized plasma will be mapped on scales from parsecs to hundreds of kilometres. Of greater importance is the guaranteed discovery of rare binary systems — pulsars with other neutron stars and black holes as companions — that serve as laboratories for gravity. The most prominent target is the center of our galaxy, where a dense star cluster orbits the massive black hole, Sgr A* ($3 \times 10^6 M_{\odot}$). The SKA’s sensitivity at high frequencies is required to combat the intense radio-wave scattering that quenches the pulsed emission from pulsars in the star cluster. Discovered pulsars will be monitored as they orbit Sgr A*; those with favorable alignments will probe the space-time around the black hole arbitrarily closely to the last stable orbit and thus provide quantitative measures of the gravity in the strong field regime. Many of the millisecond pulsars found with the SKA will comprise a pulsar timing array for detection of low-frequency gravitational waves (nHz). Successful detection of gravitational waves will complement terrestrial and space-based detectors — such as LIGO, VIRGO and LISA — by covering a much lower-frequency band of gravitational waves. Finally, pulsars in other galaxies will be detectable with the SKA: out to a few Mpc in periodicity searches and perhaps as far as the Virgo cluster for detection of giant pulses like those from the Crab pulsar.

The Cradle of Life: Based on a sample of one (the Earth, its biosphere, and ourselves) we know that planets can provide the constituents for life and the environments needed to jump start and evolve life. However, we have only an incomplete inventory of organic molecules in the interstellar medium that may be important for triggering

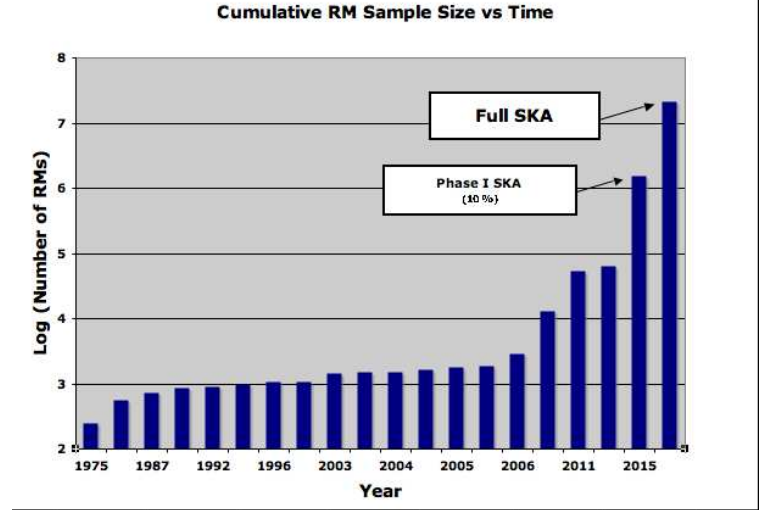
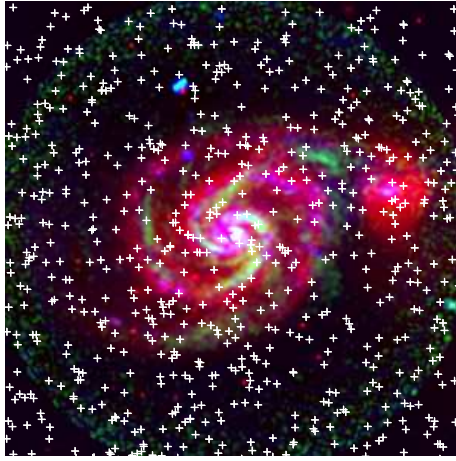


FIG. 4.— Left: An image of M51 that is a superposition of optical (red), radio continuum (blue) and polarization (green) with + symbols corresponding to SKA-detectable background point sources that follow a standard $\log N - \log S$ distribution and would provide a rotation-measure grid for probing the magnetic field coexistent with thermal, ionized gas in the galaxy. RM-grid results can be combined with polarization imaging of synchrotron radiation to further model the magnetic field in M51. Right: Cumulative Rotation Measures vs. time, showing the huge increase in lines of sight measured with the 10% SKA and with the full SKA.

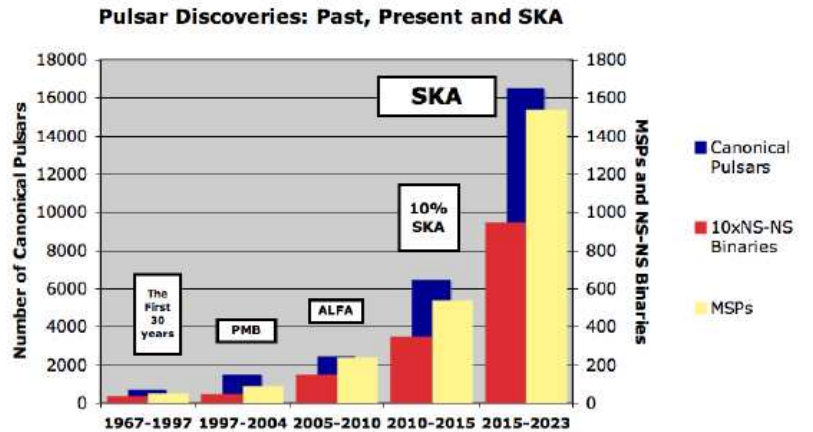
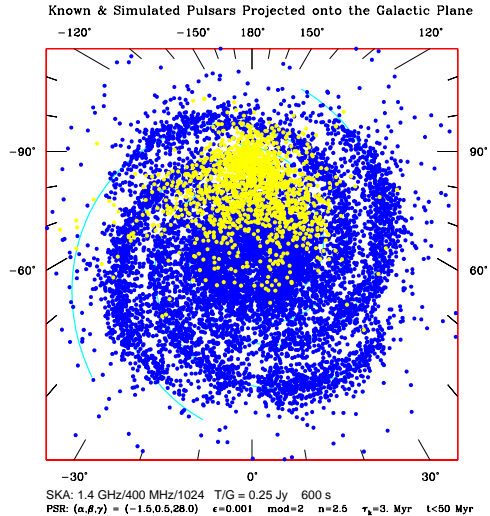


FIG. 5.— Left: Simulated pulsar survey results for the SKA, assuming it has all-sky coverage at 1 to 2 GHz. In practice, the SKA may have $\sim 80\%$ sky coverage. Blue points represent the $\sim 10^4$ pulsar detections. Yellow symbols represent the 1604 known pulsars in the ATNF/Jodrell pulsar catalog with distance estimates. The survey yield is based on a 600-s dwell time per sky position and a standard search analysis for dispersed and periodic signals. The simulation does not include the recently discovered “rotating radio transients” whose numbers might double those seen here. Right: survey yield for canonical pulsars (blue), those with periods from 30 ms to 5 s with magnetic fields $\sim 10^{12}$ G, millisecond pulsars (red) and relativistic binaries (yellow). Note that the left-hand scale applies to canonical pulsars and the right-hand scale to MSPs and binaries; the number of binary pulsars has been multiplied by 10. MSPs and NS-NS binaries provide extraordinary opportunities for measuring low-frequency gravitational waves and for testing General Relativity, respectively. The importance of Large scale surveys therefore lies in the discovery of such objects for their role as gravitational laboratories and as new tools for astrophysics.

the first stages of life. The SKA will provide such an inventory through its broad frequency coverage and its ability to survey large regions of the sky at high sensitivity. Many stages lie between the initial collapse of molecular cloud regions and the formation of stable planetary systems that include planets in habitable zones around stars: formation of massive dust and gas disks, agglomeration of planetesimals, growth of planets from the planetesimals, and a final clearing of the debris disks left behind. With the SKA’s planned high-frequency and high-angular resolution (0.1 mas), specific protoplanetary disks can be observed as Earth-sized protoplanets carve paths in their feeding zones in the disk. Movies of this process can be made using the SKA’s high-resolution imaging capability. Finally, the enormous sensitivity of the SKA provides the means for plausible detection of deliberate or leakage signals from other civilizations. Television from civilizations on planets orbiting nearby stars is detectable, should complex life be prolific in the Milky Way. Other signals, such as those from powerful, monochromatic radars that

we use for planetary studies, are detectable across a significant portion of the Milky Way.

The beauty of the SKA is that, while it addresses specific key science areas and thus will answer important questions that we pose now, it will have the flexibility to address evolved versions of these questions in the future and entirely new questions that are spawned by the old ones. Very importantly, the SKA will increase the coverage of parameter or phase space by many orders of magnitude, making it a powerful instrument for the discovery of objects and phenomena that we do not yet know. This leads to a sixth key science area:

Exploration of the Unknown: As an instrument that will better probe the domains of astrophysical and astrobiological sources by many orders of magnitude, the SKA will discover entirely new *kinds* of objects. The chapter “The Exploration of the Unknown” in the SKA science book (Wilkinson et al. 2004) identifies the key variables that underlie each of the long list of fundamental discoveries that have been made in radio astronomy. One might think that all of the key variables have been identified and probed with existing telescopes. This is far from being the case because the so-defined parameter space has been investigated only in very compartmentalized subvolumes. What the SKA offers is a chance for a much more thorough sampling of parameter space combined with incredible sensitivity. An obvious *axis of discovery* is the time domain and the prospects for detecting counterparts to classes of sources we already know about (e.g. Gamma-ray bursts, flare stars, AGNs) but also surprise discoveries such as unexpected signals from other civilizations, evaporating black holes, etc.

II. INCREASING DISCOVERY SPACE BY MANY ORDERS OF MAGNITUDE

The current Reference Design for the SKA specifies coverage of the 0.1 to 25 GHz frequency range with three kinds of receptors to cover three bands: 0.1 to 0.3 GHz with dipoles, parabolic dishes and focal plane arrays in the mid-range 0.3 to about 2 GHz, and dishes with broadband, single-pixel feeds in the high band from 1 to 25 GHz (the implied overlap with the mid-range is intentional because the implementation may be different for the two bands).

The revolutionary aspect of the SKA is the combination of a huge boost in sensitivity across all three bands, wide field of view (FoV) for survey throughput, and the ability to sample with high resolutions the time, frequency and spatial domains.

Many of the high priority science areas for the SKA require high-throughput surveys, leading to array configuration and FoV requirements as given in the specifications document (SKA Memo 45). In the mid-range band, massive surveys will be conducted for galaxies using the HI hyperfine line at 21 cm and in the continuum for studies of dark energy, dark matter, and Faraday rotation measurements. High-yield surveys of L^* galaxies will be made to redshifts of up to about 2. These require both high sensitivity and also wide field of view in the 0.5 to 1.4 GHz range. Sampling the time domain to employ pulsars as tools for studying gravity and to discover transients, including orphan gamma-ray burst afterglows to levels 100 times fainter than at present, also requires wide FoV to provide long dwell times on large swaths of solid angle. A more detailed inventory of the tremendous survey capability will be given later.

The diverse requirements for sampling the sky with high time and frequency resolutions are depicted in Figures 6-8, which also delineate how astrophysical sources and processes fill the “phase space” defined by these resolution parameters.

The Angular Domain: Angular scales include the sizes of AGNs, which are as small as $100 \mu\text{as}$ in direct interferometry but also include compact intra-day variable (IDV) sources that are inferred to be just a few $\times \mu\text{as}$ in size using the resolving power of interstellar scintillation. Pulsar magnetospheres can be probed in similar ways to the sub- μas level. A deep survey for 21-cm HI in $10^8 - 10^9$ galaxies requires the combination of ~ 1 arc resolution and very wide survey FoV, 40 to 100 deg². On larger scales, studies of magnetic fields in the Galaxy and in the IGM require a broad range of angular resolution. The Epoch of Reionization signal in HI provides the means for measuring structure evolution prior to and during early galaxy formation. The relevant scales are depicted in Figure 6.

The Time Domain: The time domain is shown in Figure 7. Under close scrutiny, most compact sources are time variable. Radio techniques have been used to discover emission events down to nano-second scales and exploit transient emissions to study the energetics of sources (GRB afterglows) and use interstellar scintillation to probe source sizes of compact sources (pulsars and GRB afterglows). From the standpoint of populations of transient sources, however, it is also clear that the time-variable radio sky is very poorly characterized. This owes to the fact that existing large radio telescopes have small FoV so that blind surveys for transients have covered only a small fraction of the overall parameter space. To adequately characterize the transient sky, the product $P = A\Omega T$ must be large enough to detect a fair sample given the intensity, sky density, and event rate, where A is the collecting area, Ω is the instantaneous solid angle, and T is the dwell time. With a single pixel instrument, $A\Omega = \lambda^2$, so $P = \lambda^2 T$. At cm wavelengths, multiple-pixel systems have been used with $N_{\text{pix}} = 13$ (Parkes multibeam surveys) and $N_{\text{pix}} = 7$ (ALFA at Arecibo). Subarrays that analyze different sky regions do not alter P . The SKA is proposed to have N_{pix} in the hundreds at about 1 GHz and below, thus increasing the throughput for transient searches enormously.

The Frequency Domain: Natural sources demand spectral resolution as small as a few hundred Hz over a spectral domain of many GHz. For SETI, the search for extraterrestrial intelligence, signals of Hz bandwidth or less are often sought.

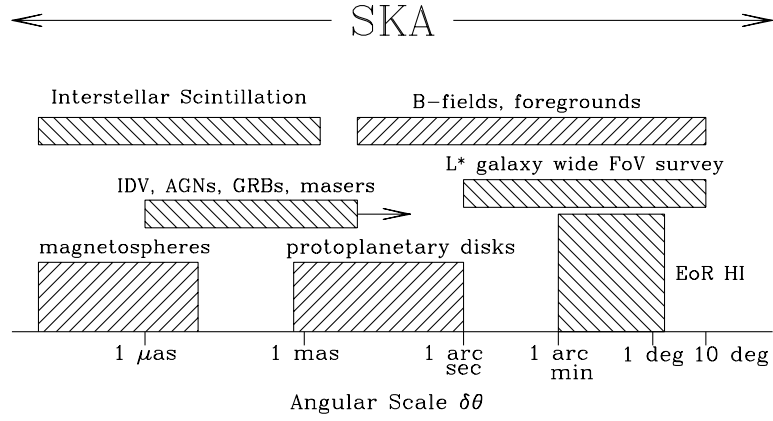


FIG. 6.— Angular scales relevant to sources, surveys and scintillation that will be probed with the SKA. Coherent radiation from pulsar magnetospheres and hyper-compact AGNs can be probed using the high sensitivity and time-frequency sampling of the SKA combined with the resolving power of interstellar scintillation.

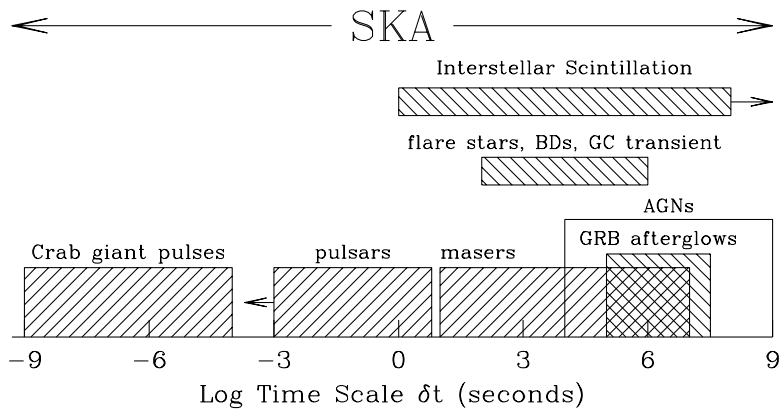


FIG. 7.— Time scales relevant to sources, surveys and scintillation.

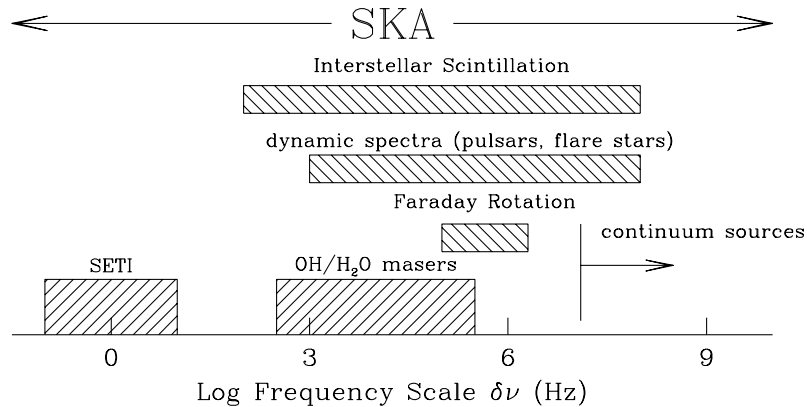


FIG. 8.— Frequency resolutions relevant to sources, surveys and scintillation.

III. TYPES OF DISCOVERY

As we know, there are known knowns. There are things we know we know. We also know there are known unknowns. That is to say we know there are some things we do not know. But there are also unknown unknowns, the ones we don't know we don't know — D. Rumsfeld (2002)

The SKA will be a discovery instrument of both known classes of objects and new objects in new classes. Many aspects of the key science projects involve large-scale surveys of known types of objects that primarily are used as tracers of cosmic evolution, of their environments or of intervening media, or of spacetime itself. However, at one time, most of these objects were themselves unknown. A conservative stance, consistent with the Copernican principle,⁴ is to expect discoveries of new classes of object.

New objects in known classes: With known classes of objects, the payoff from the SKA is a combination of the large survey yields and the likelihood that rare members of that yield will be especially useful. Examples include:

1. Near-Earth asteroids approaching from the sunward direction and Kuiper-belt objects with low albedo.
2. HI in galaxies to $z \lesssim 2$ for studies of dark energy and dark matter and of galaxy evolution.
3. Giant relic galaxies that emit at low frequencies with low-surface brightness and provide information on the evolution of supermassive black holes in galactic nuclei.
4. Magnetized Galactic objects
5. Pulsars in the Galactic disk and globular clusters to identify millisecond pulsars and relativistic binary pulsars to probe gravity.
6. Pulsars in the Galactic center that can be used to probe the environment and space time around the massive black hole, Sgr A*.
7. Faraday rotation measures (RMs) toward distant galaxies (active or star-forming) to allow tomographic delineation of cosmic magnetic fields and to exploit galaxies seen as Faraday silhouettes against polarized backgrounds.
8. High- z CO in transitions and redshifts that complement ALMA in quantifying star and element formation vs. cosmological epoch.
9. Giant pulses from extragalactic pulsars analogous to those seen from the Crab pulsar and a handful of other young and millisecond pulsars; these can probe the nearby IGM through propagation effects that alter the pulses (dispersion, scattering and Faraday rotation).

Targeted known phenomena: Similarly, there are processes that occur or have occurred that we can detect and analyze through appropriate imaging, spectroscopic and time-domain measurements:

1. The EoR signal from structure formation as it appears both spatially and in the spectral domain.
2. Magnetic fields and dynamo action in the first galaxies and clusters.
3. Weak magnetic fields in galaxy halos, in clusters and in the Cosmic Web, including primordial magnetic fields.
4. Detecting protoplanets in disks as they evolve during the planet formation process.
5. Detecting coherent radio emission from extrasolar planets analogous to radiation seen from solar-system objects.

New Classes of Sources and Phenomena Based on Known Physics, Biology, etc:

1. Transient sources of many kinds have been identified (e.g. Figure 10). Mild extrapolations from the physics of known sources suggests that plausible detections may be made from extrasolar planets (through mechanisms other than solar-system type), extraterrestrial intelligence (at minimum, leakage signals analogous to what we transmit), prompt GRB emission that is coherent similar to that seen from pulsars (for both hypernovae and mergers of compact stars), and black hole evaporation.
2. Coherent sources tend to be prominent at low frequencies and thus may emerge as new classes.
3. Radio-loud, gamma-ray quiet GRBs: orphan afterglows seen in the radio without corresponding high-energy radiation would better our understanding of relativistic beaming and environmental effects in cosmic explosions.
4. Reconnection regions in the ISM and magnetic fields in the IGM, including large magnetic filaments in the Cosmic Web.
5. Sources with high circular polarization.
6. ETI (non-transient).

The Totally Unexpected! Finally, we can expect the truly unexpected, some categories of which are:

1. Clusters of magnetic monopoles, probed with Faraday rotation and distinguished through consistency with $\nabla \cdot \mathbf{B} \neq 0$.
2. Spectral lines from dark-energy/dark-matter particles.
3. New kinds of stars (strange, quark).
4. Manifestations of higher dimensions.
5. New physics.
6. ETI technological activity (not signals).

⁴ I.e., we do not live at a special time with respect to our study of the universe.

Survey Figure of Merit

High sensitivity and wide field of view together boost the SKA’s survey capabilities by many orders of magnitude compared to existing instruments. In Appendix A we derive a figure of merit that is related to the volume surveyed. The survey volume is proportional to the FoM taken to some power that depends on how the survey is conducted.⁵ We define $\text{FoM} \propto \Omega B (A_e/T_{\text{sys}})^2$ where Ω = total instantaneous solid angle, B = bandwidth, A_e = total effective area of array, and T_{sys} = system temperature. We use $\Omega A_e = N_{\text{FoV}} N_A \lambda^2 \propto N_{\text{FoV}} N_A \nu^{-2}$ to arrive at the expression (Eq. A4) given in the Appendix; implicitly assumed is that signal processing and survey analysis is of the full primary beam of an individual reflector (which we call the FoV). Table 1 lists the FoM at 1.4 GHz along with input data for the SKA and a number of other telescopes. Figure 9 shows the figure of merit plotted against frequency for the SKA as compared to other radio telescopes.

TABLE 1
FIGURE OF MERIT AT 1.4 GHz FOR NOMINAL PARAMETERS

Instrument	N_{FoV}	N_A	B (GHz)	T_{sys} (K)	$\log_{10}(A_e)$ (m ²)	$\log_{10}(\text{FoM})$ (m ² K ⁻² GHz ⁻¹)
SKA	1	5000	0.2	30	5.74	5.7
SKA + FPA	48	5000	0.2	30	5.74	6.7
SKA Phase I	1	500	0.2	30	4.74	3.6
Arecibo	1	1	0.4	27	4.46	0.92
Arecibo+ALFA	7	1	0.3	30	4.46	1.5
EVLA	1	27	0.2	20	3.97	2.1
GBT	1	1	0.8	20	3.74	0.67
Parkes+MB	13	1	0.3	21	3.28	0.91

The Transient Radio Sky: The SKA as A Radio Synoptic Survey Telescope

Unlike the high-energy sky that has been probed with wide-field detectors in X-rays and γ -rays, leading to discoveries of gamma-ray bursts and afterglows and bursters of various kinds, the transient radio sky is unexplored in any systematic way. In spite of this, a wide variety of radio transients has been identified, as shown in Figure 10, which shows a two-dimensional phase space for the transient radio sky. The SKA can cover unprecedentedly large areas of sky while also probing the full domain defined in the figure.

Figure 10 has axes chosen because they allow lines of constant brightness temperature to be plotted. Further details can be seen in the chapter “The Dynamic Radio Sky” in the SKA science case (Cordes et al. 2004) Two main points emerge from considering this figure:

1. *Known* transients already cover a huge range of parameter space, indicating that natural sources populate a large volume.
2. There are also empty areas in the plot; do these signify the patchiness in the way nature populates the phase space or do they signify a proportionate number of new source classes that remain to be discovered? Nature appears to abhor a vacuum, even in phase space, so we expect the latter case to apply: many new discoveries await!

Using this subspace as an example, we could approach the question “How many new source classes are there?” in two ways. First, we could simply scale up from the portion of phase space that has been probed to the total volume available. Alternatively, we could list types of objects that exist or are thought to exist and then speculate on whether they ever would be detectable in some part of the phase space. The occurrence of several source classes relies on the generation of coherent radiation. If not for that, very compact sources would never be detectable. Fortunately they do generate coherent radiation and thus are detectable. Are there other objects that might emit coherent radiation? In this way we might generate a list of possible discoveries to be made.

To illustrate the large return to be expected with wide-field sampling over a wide-range of time scales, three recent discoveries come to mind. First is a transient in the Galactic center, GCRT J1745–3009 which appeared in images made with the VLA with approximately hour-like variability. Its nature is not yet known. Pulsar-related discoveries include the *rotating radio transients* (“RRATs”), which are most likely radio-pulsar-like neutron stars that are triggered through processes we have not yet identified, and the *quasi-periodic bursting pulsar*, B1931+24, which has a quasi-period of 40 days and is in the on state for only 20% of the time. Recently, a magnetar discovered in 2003 with the X-ray Timing Explorer was identified as a very strong periodic source (5.54 s) about one year after a large burst increased its X-ray flux by a factor of one hundred.

⁵ While different survey strategies lead to different volumes, they involve the same *combination* of parameters.

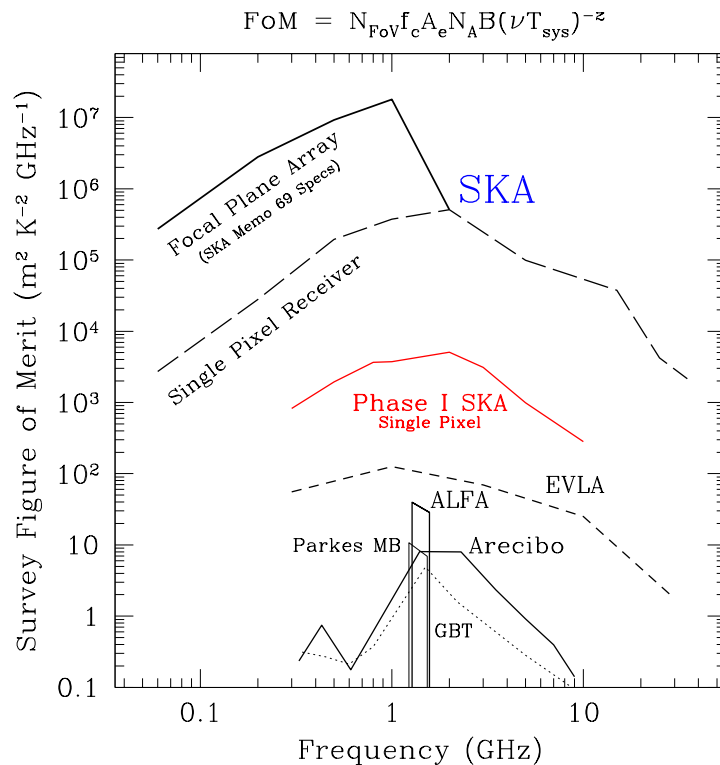


FIG. 9.— Survey figure of merit for the SKA with and without multiple-pixel receivers. Also shown is a curve for the “Phase I” SKA, which is assumed here to have 10% of both the sensitivity and number of antennas and to extend from 0.3 to 10 GHz. The curve applies to a single-pixel system; for clarity we do not show a Phase I curve with focal plane array, but the enhancement would be similar to that shown for the full SKA. For other telescopes, single pixel systems are considered except for the 7-beam ALFA system at Arecibo and the 13-beam system on the Parkes telescope. The figure of merit is related to the spatial volume that can be surveyed in a fixed amount of time, as described in Appendix A. The huge increase in figure of merit for the SKA results from the assumed combination of large collecting area and wide field of view. Note that if only a fraction $f_c \leq 1$ of the collecting area is used for a survey, the figure of merit is reduced proportionately. Alternatively, if each antenna is outfitted with a multiple pixel focal-plane-array receiver, the figure of merit increases substantially, as shown. The focal plane array specifications were obtained from SKA Memo 69, referred to earlier, which assumes a frequency range of 0.1 to 25 GHz for the SKA, possibly extended down to 0.06 GHz, as shown here.

The time scales associated with these discoveries — variability time scales that range from tens of milliseconds to months — are very difficult to sample with low sensitivity, single-pixel instruments.

A measure of phase space coverage for transients is the number of “cells” that cover the angular, frequency and time domains. In general the search domain is a total solid angle Ω , a frequency range $B = \nu_{\max} - \nu_{\min}$ and a time range $T = t_{\max} - t_{\min}$. If a source emits only one event with characteristic time and frequency scales δt and $\delta \nu$ with unity time-bandwidth product, $\delta \nu \delta t = 1$, the number of cells to be searched is $N_{\text{cells}} \propto \Omega B T$ with cell sizes $\Omega_b \delta t \delta \nu$ in order to identify the event and assuming there is adequate sensitivity. For sources that emit multiple events with event rate, R_t , fewer cells are needed to *detect* the source. For continuum sources — those that have smooth spectra and are not strongly modulated in time — the number of cells to be surveyed is

$$N_{\text{cells,cont}} = \frac{\Omega}{\Omega_b}, \quad (1)$$

where Ω_b is the resolution in solid angle. For sources with natural spectral lines that are time invariant, we have $\delta \nu / \nu = \Delta V / c$, where ΔV is the effective range of Doppler velocities (which will be smaller than the actual range for, e.g., maser sources) and if we are searching for spectral lines with a flat prior over a frequency range $[\nu_{\min}, \nu_{\max}]$, the number of cells is

$$N_{\text{cells,line}} = \left(\frac{\Omega}{\Omega_b} \right) \left(\frac{c}{\Delta V} \right) \ln \frac{\nu_{\max}}{\nu_{\min}}. \quad (2)$$

For pulsars, which are continuum sources with characteristic time durations δt that repeat periodically in many cases but are sporadic in others (RRATs), the number of required cells is

$$N_{\text{cells,PSR}} = \left(\frac{\Omega}{\Omega_b} \right) \frac{1}{R_t \delta t}. \quad (3)$$

Finally, ETI sources that may be both narrowband and pulsed require

$$N_{\text{cells,ETI}} = \left(\frac{\Omega}{\Omega_b} \right) \frac{1}{R_t \delta t} \left(\frac{\nu_{\max} - \nu_{\min}}{\delta \nu} \right) \quad (4)$$

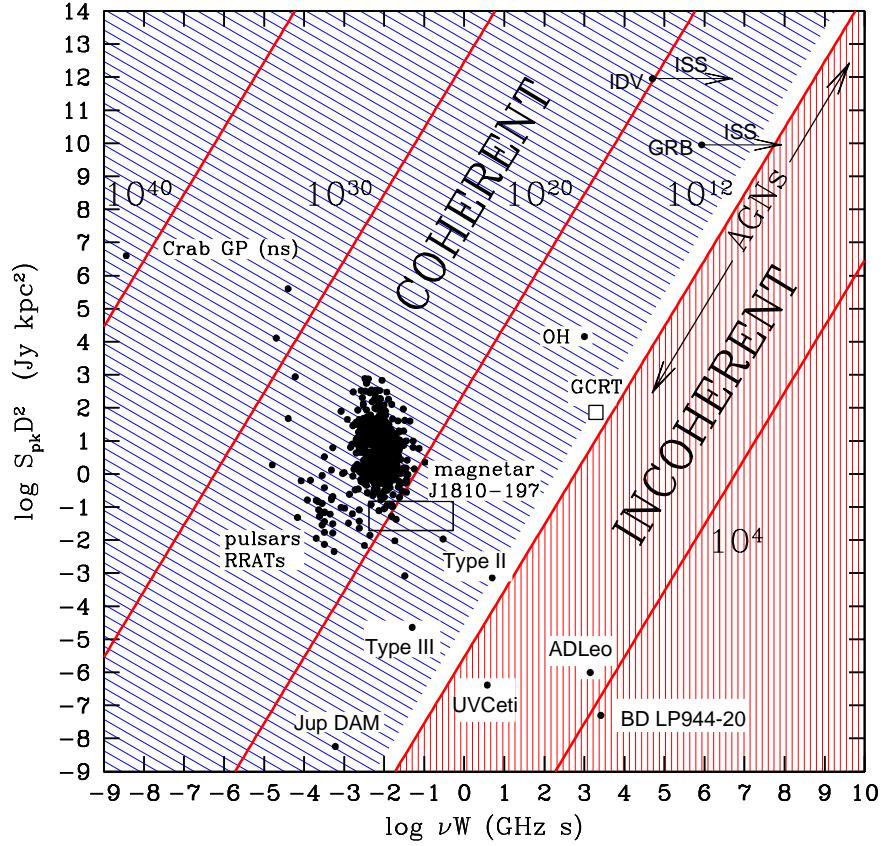


FIG. 10.— The time-luminosity phase space for radio transients. A log-log plot of the product of peak flux S in Jy and the square of the distance D in kpc vs. the product of frequency ν in GHz and pulse width W in s. Lines of constant brightness temperature $T = SD^2/2k(\nu W)^2$ are shown, where k is Boltzmann’s constant. Points are shown for the ‘nano-giant’ pulses detected from the Crab (Hankins et al. 2003), giant pulses detected from the Crab pulsar and a few millisecond pulsars, and single pulses from other pulsars. Several of the recently discovered “rotating radio transients” (RRATs; McLaughlin et al. 2006) are shown, along with the Galactic center transient source, GCRT J1745-3009 (Hyman et al. 2006) and the recently reported strong bursting from the magnetar XTE J1810-197 (Camilo et al. 2006), illustrating the fact that empty regions of the $\nu W - S_{\text{pk}}D^2$ plane may be populated with sources not yet discovered. Points are also shown for Jovian and solar bursts, flares from stars, a brown dwarf, OH masers, and AGNs. The regions labeled ‘coherent’ and ‘incoherent’ are separated by the canonical 10^{12}K limit from the inverse Compton effect. Arrows pointing to the right for the GRB and IDV points indicate that interstellar scintillation (ISS) implies smaller brightness temperatures than if characteristic variation times are used to estimate the brightness temperature.

Transient Blind Survey Speed and Sensitivity

Detailed aspects of sky surveys are presented elsewhere. Basically, the duration of transient signals along with the distribution of source populations determines whether a *staring* or a *scanning* strategy should be used. To emphasize the tremendous survey capacity for the SKA, we consider here a raster-scanning approach, which is also proposed for the Large Synoptic Survey Telescope that will operate at optical wavelengths and will survey the sky every few days.

For the SKA operating with N_{FoV} independent fields of view and N_{sa} subarrays (i.e. the collecting area divided into subarrays that each survey an independent part of the sky), the survey rate is

$$\dot{\Omega} = \frac{N_{\text{FoV}}N_{\text{sa}}\Omega_{\text{FoV}}}{T_1} \approx 10^{-1.65} \text{ deg}^2 \text{ s}^{-1} \frac{N_{\text{FoV}}N_{\text{sa}}}{T_{1,100}(\nu_{\text{GHz}}D_{12})^2}, \quad (5)$$

where $T_1/10^2T_{1,100}$ is the integration time per sky position in seconds and $D = 12 \text{ m } D_{12}$ is the antenna diameter in meters. The time to survey a sky area Ω_{total} is then, if a fraction f_{sky} is surveyed,

$$T_{\text{survey}} = \frac{T_1\Omega_{\text{survey}}}{N_{\text{FoV}}N_{\text{sa}}\Omega_{\text{FoV}}} \approx 17.2 \text{ days} \frac{T_{1,100}(f_{\text{sky}}/0.8)}{N_{\text{FoV}}N_{\text{sa}}(\nu_{\text{GHz}}D_{12})^2}. \quad (6)$$

With a nominal 100 s integration per sky position, the minimum detectable flux density, taking into account only radiometer noise but requiring detections at the $m = 10\sigma$ level, is

$$S_{\text{min}} \approx 5.5 \mu\text{Jy } T_{\text{sys},30} N_{\text{sa}} D_{12}^2 (B_{\text{GHz}} T_{1,100})^{-1/2} \left(\frac{m}{10}\right) \left(\frac{f_c N_A}{5000}\right)^{-1}. \quad (7)$$

The coefficient in this expression is for 5000 antennas, a 30K system temperature, and 1 GHz bandwidth. As is evident, a deep survey of the visible sky (80% of the total) can be done about every two weeks using nominal parameters at $\nu = 1$ GHz and can be done even faster at lower frequencies or if multiple fields of view are employed. The detection level $\sim 6 \mu\text{s}$ is sufficient to detect GRB afterglows at levels that are about $\times 20$ fainter than at present with the VLA. More importantly, GRB afterglows will be detected in *blind* SKA surveys rather than being triggered by detections with high energy satellites. And, of course, an SKA survey will be unbiased and complete with respect to *all* classes of transient sources.

An SKA transient survey will parallel that proposed for the LSST. However, the classes of transients that will be detected in the radio and optical bands are already known to be different in many ways, particularly given the prominence of sources of coherent radiation at low frequencies. Nonetheless there are areas of overlap (e.g. supernovae) and the LSST and SKA surveys can be cross-compared for both coincidences and anti-coincidences. Such comparisons can be done contemporaneously for the portion of the SKA that has been built during LSST’s lifetime and also after the fact for sources that display both quiescent and bursting states.

IV. ENABLING DISCOVERY: VIRTUAL OBSERVATORY TOOLS

The SKA will provide data products at a rate that will dwarf those seen for telescopes today and of other telescopes now in the planning process, such as the Large Synoptic Survey Telescope (LSST) that will operate at optical wavelengths. As such, processing for particular key science goals needs to be efficient and robust. At the same time, however, tools are needed that allow *exploration* of the data for as-yet unidentified signal classes from celestial sources. These tools must also sift through the myriad of interference generated both at electromagnetic frequencies and by instrumentation. Data adaptive methods must clearly play a role.

V. UNIQUE AND COMPLEMENTARY ASPECTS OF THE SKA

Essentially all telescopes are built for discovery. Their construction is also motivated to follow up on discoveries through various analyses that lead to a better understanding of the universe we live in. In this regard the SKA provides unique capabilities that surpass those operating in other wavelength regimes for some target areas. For other science goals, the SKA plays a complementary role that is needed in order to fully understand what is going on. Finally, there are areas where the primary survey or observation is in a non-radio band but for which the SKA plays an important supporting role.

Table 2 summarizes how the SKA addresses key science questions or activities and compares the SKA with other telescopes now being planned.

A more complete discussion of SKA complementarity and uniqueness is in the document “Science with the Square Kilometre Array: Uniqueness and Complementarity.” Some brief comments follow on particular key science areas for the SKA:

1. **Epoch of Reionization:** LOFAR and MWA will pave the way by providing, hopefully, first detections of the EoR/HI signal which will inform follow-on work with the SKA and its design. HI Imaging of EoR structure will provide unique information about the first ionizing structures via the mapping of epoch into redshift. Complementary information about the EoR will be provided by WMAP, Planck, and spectroscopy of high- z AGNs.
2. **CO and Star Formation at High Z :** IR and sub-mm surveys of high- z galaxies. JWST. ALMA together with the SKA will provide a complete picture of the CO universe and its implications for element formation vs. cosmic epoch. The SKA will detect low-level, redshifted CO lines that are out of ALMA’s frequency range.
3. **Dark Energy:** As the report of the Dark Energy Task Force describes⁶, the SKA can play a major role in studies of dark energy in the fourth stage of program of studies that has already begun: “Stage IV comprises a Large Survey Telescope (LST), and/or the Square Kilometer Array (SKA), and/or a Joint Dark Energy (Space) Mission (JDEM).” Characterization of dark energy includes estimation of the equation of state parameter, $w = P/\rho$, which is -1 for a cosmological constant. Large-scale surveys of N sources will yield determinations of w and its derivative dw/dz with precisions proportional to $N^{-1/2}$. While programs in the optical and radio play out, it also seems likely that a thorough understanding of DE will require the full arsenal of pan-chromatic surveys. An SKA survey has a particular advantage over an optical survey with LST in that radio redshifts will be provided for all $\sim 10^9$ galaxies detected.
4. **Magnetic Universe:** There is no real competitor for measurements of polarized synchrotron radiation and its Faraday rotation. Synchrotron emission dominates the radio continuum from cosmic sources and thus provides a signal detectable to very high redshift. Degrees of polarization are much higher at radio wavelengths than in any other spectral range. Faraday rotation, being an integral effect, allows detection of very weak magnetic fields. Planck and Auger will provide important supporting roles in mapping the Faraday-free polarized sky and in measuring magnetic fields in the local IGM, respectively.

⁶ <http://www-astro-theory.fnal.gov/events/detf.pdf>

TABLE 2
SKA SCIENCE AND COMPLEMENTARITY WITH OTHER VENTURES

Fundamental Question Or Activity	SKA	SKA Advantage	Complement	Comment
What is Dark Energy?	massive galaxy survey standard rod	10^9 sources $\implies \delta w \sim 1\%$	LSST, SNAP laboratory experiments	
What is Dark Matter?	weak lensing survey, rotation curves of large sample	10^{10} sources, 10^8 sources	LSST laboratory experiments	
Was Einstein Right? about Gravity?	compact star binaries (100s), compact orbits around Sgr A*	sustained precision timing, strong field lensing	IR orbits around Sgr A* (ELT/GMT/TMT) LISA NS plunge into BH + ringdown LIGO II merger detection, GAIA	
Reionization: when and how?	tomography of neutral IGM ($15 > z \gtrsim 6$) first stars: high-z CO first AGNs	direct observation of IGM prior to and at birth of first OIR luminous objects	CMB: Planck ALMA (CO) JWST (senses first luminous objects)	LOFAR, PaST, MWA = pathfinders
Structure formation	massive surveys of galaxies, AGNs	high angular resolution (no confusion)	LSST	
Evolution of Cosmic Magnetism	RM grid (10^7 sources), Faraday tomography, B in first galaxies and in IGM; polarization imaging, high-z synchr. sources	direction and strength of B, no extinction sensitivity to small $B \times$ electron density	Planck, Auger, NeXT, ALMA, XEUS, Constellation-X SDSS, JWST	X-rays provide n_e
Using Gravitation Waves as tools	millisecond pulsar timing array SMBH mergers, cosmic strings	$10^{-9} \rightarrow 10^{-6}$ Hz gravitational waves	LIGO/LISA: 10^{-5} Hz $\lesssim f \lesssim 1$ kHz	
Black Hole Masses and Spins	timing of Sgr A* pulsars masers around AGNs	high-f mitigates scattering, long time-frame (decades) 3D velocities	LISA	
Matter in Extreme States	submillisecond NS detection or limits masses of 100s of NS, possibly BH extreme magnetic fields	strong statistical significance delineate mass range of NS vs. spin massive survey	GLAST and follow-ons	
Acceleration mechanisms	high-energy cosmic rays: atmospheric coherent bursts, lunar neutrinos	large sampling area	GLAST	LOFAR, LWA, MWA = pathfinders
How do Planets Form?	synoptic images of gaps in disks	high-resolution imaging (mas)	ALMA, CCAT, ELT/GMT/TMT JWST	
Molecules for Life	deep survey of massive molecules	broad frequency coverage, sensitivity	ALMA	
Search for Extraterrestrial Intelligence (SETI)	targeted and blind surveys	full coverage of water hole TV from nearest stars, strongest radars across Milky Way	ATA	
The Transient Sky	inventory of transient radio sky, GRB afterglows in blind surveys, local IGM from giant pulses, extrasolar planet flares	wide field of view, long dwells	LOFAR, LWA, MWA, LSST GLAST	

5. **Gravity and Pulsars:** Pulsar studies with SKA will be highly complementary with an all-sky survey with GLAST, which will provide complementary studies of beaming in rotation-driven pulsars and complete Galactic censuses of pulsars and other manifestations of neutron stars, such as magnetars. SKA may provide the first direct detection of gravitational waves. Whether it or LIGO-II does, SKA studies will provide unique information about the gravitational-wave background at nano-Hz frequencies. It also will provide opportunities for testing gravity in the strong field regime through timing measurements of compact relativistic binaries and also of pulsars orbiting the Galaxy's central black hole, Sgr A*. The extent of strong gravity can be arbitrarily large for ray paths that approach the last stable photon orbit around a black hole companion. LISA and perhaps LIGO-II in the end will supplant the SKA in using gravitational waves as astrophysical tools for studying the plunge and ringdown of neutron stars falling into black holes. However, LISA may not come on line until well after the SKA comes on line.
6. **Protoplanetary and Debris Disks:** Other instruments — JWST, the ELTs and ALMA — are needed along with the SKA to develop a thorough understanding of disk types, jets produced by disks and their co-evolution with planet formation.
7. **SETI:** Historically, SETI has largely been done in the radio but recent work explores pulsed laser signals in the optical and the IR. However, exploration of radio bands is a reasonable path to take because SKA will be able to detect “leakage” signals like those our civilization transmits at distances that encompass a large number of solar-type stars.
8. **The Transient Universe:** Blind surveys are a main goal of LSST to explore the *optical* transient sky. As discussed previously, the SKA can provide an equally rich and exciting view of the radio transient sky on time scales similar to those probed by LSST. The radio sky is known to be rich on sub-second time scales that correspond uniquely to coherent radio emissions from compact sources, including relativistic stellar objects, planets, and stellar flare emission. Gamma-ray burst afterglows with the SKA can be detected in all-sky surveys without a high-energy trigger 100 times fainter than with the VLA.
9. **Near Earth Objects:** Discovery of NEOs is a primary goal for LSST and related instruments. Orbit determination is far better with the SKA in concert with a radar transmitter than with optical or infrared monitoring.

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APPENDIX

A. METRICS

Etendue: Often the “etendue” — the product $A\Omega$ — is used as a figure of merit for a telescope, a large value signifying that the field of view of the telescope exceeds the diffraction limit associated with a single pixel, for which $A\Omega_{\text{pix}} \equiv \lambda^2$. While informative for comparing telescopes that measure the same emission process from a class of sources, this metric is not useful for comparing surveys made with telescopes operating at different wavelengths that may sample the same population of sources but with different tracers. For example, the etendue values for radio arrays such as the EVLA, $A\Omega = 10^{4.1} \text{ m}^2 \text{ deg}^2$, or the SKA, $A\Omega = 10^6 \text{ m}^2 \text{ deg}^2$, are enormously larger than that of an optical survey telescope, such as the Large Synoptic Survey Telescope (LSST), $A\Omega = 10^{2.5} \text{ m}^2 \text{ deg}^2$. However, a far better metric is the number of sources detected in a given sky region. The bottom-line metric for a survey is the rate at which members of a particular source population are detected. This rate depends on the depth (distance reached) of a survey, the time needed to detect an object with a given luminosity, and instantaneous sky coverage.

Detection rates of known sources: In large-scale surveys, the source detection rate is a clear figure of merit because the larger the number, the more successful the survey. For a given luminosity density L_ν , distance, emission solid angle, and detection threshold, $I_{\nu,\text{min}}$, the integration time for detection is τ . With a field of view Ω_{FOV} and source number density n_s , the number of sources detected per unit time is

$$\dot{N}_d = \frac{n_s V_{\text{max}}}{\tau} \propto n_s L_\nu^{3/2} \frac{\Omega_{\text{FOV}} B^{3/4}}{\tau^{1/4} S_{\text{sys}}^{3/2}}. \quad (\text{A1})$$

where B is the bandwidth and S_{sys} is the SEFD. For a source population with a wide range of luminosities, $n_s L_\nu^{3/2}$ would be replaced by an appropriate integral. This figure of merit emphasizes the importance of having a large instantaneous field of view and we can compare different telescopes by taking the ratio of \dot{N}_d , in which case the source properties scale out.

Another approach is to consider two broad types of survey. For **fixed total solid angle and fixed total time for the survey**, the maximum distance D_{max} reached depends on the integration time per pointing and thus depends on the FoV; the volume surveyed is

$$V_{\text{survey}} \propto (N_{\text{FoV}} f_c N_A A_e B)^{3/4} / T_{\text{sys}}^{3/2}, \quad (\text{A2})$$

where N_{FoV} is the number of independent fields of view and $f_c N_A$ is the number of antennas (out of a total N_A) that can be used in a particular survey (owing to baseline constraints). A fundamental assumption here is that the survey is done over the entire FoV of an individual antenna, for which $\Omega_{\text{FoV}} A_{e1} = \lambda^2$, where A_{e1} is the effective area of a single antenna. If, instead, we hold **the total time fixed and D_{max} fixed**, we obtain a different expression,

$$V_{\text{survey}} \propto N_{\text{FoV}} f_c N_A A_e B / T_{\text{sys}}^2. \quad (\text{A3})$$

In both of these cases and for Eq. A1, the same *combination* of parameters appears (but taken to different powers). Therefore we take as a figure of merit,

$$\text{FoM} = \frac{N_{\text{FoV}} f_c N_A A_e B}{\nu^2 T_{\text{sys}}^2}. \quad (\text{A4})$$

This same figure of merit follows by simply defining it as proportional to the *survey speed*, Ω_i/τ , where $\Omega_i = N_{\text{FoV}}\Omega_{\text{FoV}}$ is the instantaneous solid angle that is sampled and τ is the integration time needed to reach a minimum detectable flux density. SKA Memo 66 presents a comparison of survey speeds for the SKA and other instruments.⁷

For clarity, we note that survey volume is not necessarily proportional to the chosen figure of merit, but in general is proportional to FoM^x . For the two cases considered above, we have $x = 2/3$ or 1.

Phase-space volumes surveyed: To date, surveys have covered little of the phase space, Φ . The SKA will increase the volume surveyed by orders of magnitude. Where are the sweet spots in Φ that are likely to yield the greatest payoffs? Or are all volumes equally populated? Do we quantify the volume linearly or (as Harwit did) logarithmically? This metric is useful for comparing the coverage of phase space by different radio telescopes.

Sampling of specific source populations: This metric assesses performance based on how a given instrument samples members of a source class with known properties (e.g. canonical pulsars, HI in L* galaxies, etc.).

⁷ SKA Memo 66, *Relative Sensitivities of the SKA and Other Current or Near-Future Instruments*, 2005, D. Jones, http://www.skatelescope.org/pages/page_astronom.htm

B. AXES OF DISCOVERY: DELINEATING PARAMETER SPACE

The goal is to identify the axes and extent of an appropriate parameter space and then to define metrics for coverage of the space. We can then demonstrate how the SKA will drastically increase our coverage. A key issue is how *nature* populates the parameter space. We have partial knowledge of this but the greatest interest is in those things not yet discovered: a chicken and egg problem. Harwit in *Cosmic Discovery* estimated the fraction of objects discovered by considering the rate of rediscovery when new instruments were built that pushed on one or more axes. His analysis was therefore multiwavelength in nature and also considered non-electromagnetic information carriers (e.g. cosmic rays, neutrinos and gravitational waves). Our approach will focus on radio discovery space while keeping in mind multidisciplinary aspects of source populations.

We take an approach that is similar to but diverges from that of Harwit. His Table 1.2 lists parameters that characterize an elementary astronomical observation. We extend the dimensionality of the phase space according to *measurements* that are under our control. To define the phase or parameter space, we need to consider both the resolution and the extent of each axis. The properties of astrophysical sources of course map into this measurement space.

Let the Stokes parameter vector be

$$\mathbf{S} = \text{col}(I, Q, U, V). \quad (\text{B1})$$

Then define measurement space as the set

$$\mathbf{P} = \{t, \nu, \Omega, \delta t, \delta \nu, \delta \Omega\}, \quad (\text{B2})$$

where the first three elements are axes for time, frequency, and direction (solid angle) and the following three are the corresponding resolutions.⁸ The Stokes vector is a function of \mathbf{P} :

$$\mathbf{S} = \mathbf{S}(\mathbf{P}). \quad (\text{B3})$$

We define observational phase space as

$$\Phi = \{\mathbf{S}(\mathbf{P}), \mathbf{P}\}.$$

Sources in the universe have complex dependences on the various parameters and thus show structure in parameter space. E.g. the luminosity function, spectrum and spatial distribution of a source population link I, ν , and Ω .

Time axis: Transients define how the time axis needs to be covered. The fastest known events are the “nano-giant” pulses from the Crab pulsar which are up to ~ 1 Mjy in amplitude with $\sim \delta t \sim 1$ ns widths. Event rates per source, the density of sources on the sky, and the luminosity distribution all determine how the time axis should be covered.

Frequency axis: Spectral lines (with widths determined by velocity spreads and, where applicable, maser gain) need to be resolved. Frequency coverage needs to be continuous though not necessarily simultaneously. A blind survey for spectral lines has not yet been done. Spectral line transients might include maser transients (examples known) and ETI signals.

Angular coverage: The angular axis (which is itself two-dimensional) covers the entire sky but with a pixelization that accomodates the dynamic range of source sizes, which is large. The most compact sources are

1. common AGNs: $\sim 0.1 - 1$ mas; accessible through VLBI techniques.
2. IDV sources: $\sim 1 - 10 \mu\text{as}$; accessible through scintillation techniques.
3. GRB afterglow sources: $\sim 1 \mu\text{as}$; scintillation.
4. pulsar magnetospheres: $\lesssim 0.1 \mu\text{as}$; scintillation.

The SKA will need to map angular scales from a few tenths of a mas on up and, through appropriate sampling of the frequency-time plane, allow the angular resolving power of interstellar scintillations to be exploited.

Astrometry requires VLB resolution for extragalactic maser studies and pulsar parallaxes, among other projects. In survey mode, the SKA will be used to cover either the entire sky or the Galactic plane, depending on survey goals.

Sensitivity and Phase Space Coverage: The luminosities of sources tie together most of the other axes. Let L_ν = luminosity density ($\text{erg s}^{-1} \text{Hz}^{-1}$) for a source assuming isotropic emission. The maximum distance that the source could be detected is

$$D_{\text{max}} = \left(\frac{L_\nu}{4\pi S_{\nu, \text{min}}} \right)^{1/2}, \quad (\text{B4})$$

⁸ We might also have included the position vector \mathbf{x} of the observer; we leave this implicit. Multiple site measurements for interferometry, coincidence tests, and excision of radio frequency interference require consideration of \mathbf{x} , but these are really just details of how we operationally characterize the sky in terms of the phase space.

where $S_{\nu, \min}$ is the minimum detectable flux density, which is strongly dependent on \mathbf{P} as well as on telescope size and on source properties. For other Stokes parameters, equivalent expressions may be written down. To assess coverage of phase space, we need to compare D_{\max} with the distance range for the target population of objects and take into account the luminosity function of the population. Equivalently, we can consider the maximum volume surveyed, $V_{\max} = \frac{1}{3}D_{\max}^3$, and the volume occupied by the population. These quantities of course are dependent on time, frequency, location on the sky, etc.

Astrophysical source properties that map into phase space: Source attributes are:

1. luminosity density (L_{ν}),
2. beaming of the radiation, expressed as a solid angle into which L_{ν} is radiated, Ω_s , with no preferred beaming direction.
3. spatial distribution expressed as a number density vs. Ω and distance (or redshift);
4. polarization state (which we could characterize through a luminosity density Stokes vector, but for now let's just include polarization as here);
5. characteristic time scale W and event rate R for repetitive sources. E.g. GRBs have $W \sim$ seconds and $R \rightarrow 0$. Pulsars have $R = P^{-1}$ and $RW \sim 0.03$. Steady sources correspond to $RW = 1$.

We therefore define the set of astrophysical source parameters as

$$\mathbf{A} = \{L_{\nu}, \Omega_s, n(\Omega, D), \text{pol}, R, W\}. \quad (\text{B5})$$

For some populations, D might be sensibly replaced with redshift, z . Other source attributes could be included, such as space velocity, which can contribute to the discovery process via the proper motion of asteroids and comets, but these aren't particularly relevant for a discussion of radio discovery.

The mapping from source parameters to observational phase space is thus

$$\boxed{\mathbf{A} \longleftrightarrow \Phi}$$

Propagation Effects: Radio waves are strongly affected by plasma propagation effects, including dispersion, refraction, and multipath scattering, which alter the distribution of \mathbf{S} in the frequency-time plane (dispersive arrival times, pulse broadening, spectral broadening, intensity scintillations) and broaden sources in angle. Gravitational lensing affects all sources through weak and strong lensing, which are time variable but frequency independent (except in instances where plasma and gravitational effects are coupled). Propagation effects may be subsumed in source properties \mathbf{A} .

Priors: To assess the prospects for discovery, we need to consider how source populations are distributed in \mathbf{P} and whether currently empty subvolumes in \mathbf{P} of equal importance.

Coverage: What coverage of \mathbf{P} has been done and can be done with the SKA? Radio surveys to date have covered the entire sky (or nearly so), but only for steady — not transient — sources. Transients have been searched over small solid-angle ranges or towards specific targets. The large-scale sky surveys that have been done have been rather shallow, down to ~ 1 mJy whereas deep field studies reveal the existence of sources a thousand times fainter. Existing telescopes have covered sub-regions of \mathbf{P} but only very sparsely and with low sensitivity. The innovation of the SKA lies in two primary axes: sensitivity a factor of 10 to 100 greater than with existing instruments and wide field of view. These two factors will allow significant coverage of the parameter space that has been neglected so far, especially for the transient radio sky, and it will allow very sensitive, massive surveys of both the polarized and the unpolarized universe.