RADIO ASTRONOMICAL CONNECTIONS TO QUARKS AND THE COSMOS:
A Perspective for the NSF from the U.S. SKA Consortium

July 2003
Radio astronomy provides important methods for exploring fundamental physics. We discuss particular ways in which the next generation radio telescope — the Square Kilometer Array (SKA) — can provide answers to some of the eleven questions about fundamental physics posed in the recent report by the National Academy of Sciences, Connecting Quarks with the Cosmos. This document summarizes briefly how answers from radio astronomy will emerge from the SKA and a complementary telescope, the Low Frequency Array (LOFAR). These new instruments will provide enormous jumps in sensitivity in their respective, complementary frequency bands and new ways to explore observational phase space. In addition to providing answers to fundamental questions in physics, the SKA and LOFAR will provide the means for exploring many new frontiers in space science, astrophysics, and astrobiology.

Radio astronomy has a notable track record in probing issues of fundamental physics. Partial evidence for this success is manifested in the awarding of three Nobel prizes (for six awardees) in Physics for radio-astronomical discoveries. Particular accomplishments include:

- The discovery of the Cosmic Microwave Background (CMB);
- The discovery of neutron stars;
- Using binary pulsars to demonstrate the existence of gravitational waves in accordance with General Relativity;
- Constraining the variation of physical constants over cosmic epochs;
- Identifying the physical processes responsible for the acceleration and collimation of matter near black holes into relativistic jets.
- The discovery of gravitational lensing;
- Providing definitive evidence for massive black holes; and
- Analyzing fluctuations in the CMB to determine the properties of the Big Bang and spacetime (precision cosmology).

Current and future radio facilities will advance our knowledge of basic physics. Key elements are large increases in sensitivity resulting from greater bandwidths and collecting areas combined with new modes of operation enabled by the revolution in digital signal processing. Accordingly, the suite of existing national radio facilities (Arecibo, GBT, VLA and VLBA), near-future instruments (ATA, EVLA, LOFAR and ALMA) and next-decade telescopes (SKA) will broaden the horizons of the physical (and biological) universe.

In this document we focus primarily on the role expected for the SKA, as requested by the NSF. The SKA will will provide a huge increase in sensitivity combined with new operational modes that will enable new science in the targeted frequency range, roughly 0.15 to 25 GHz. (The final section
of this document provides more information about specifications and development of the SKA. The SKA will complement the LOFAR instrument, whose design includes frequency coverage from 10 to 240 MHz. While there is some thematic overlap of science enabled by LOFAR and SKA and they share an array concept comprising large aggregate collecting areas, there are fundamental differences in their overall scientific thrusts so that they will probe different fundamental aspects of radio science, space science, astrophysics and astrobiology.

Science cases for LOFAR and for SKA are available elsewhere and are still evolving, as to be expected from facilities that are designed to target a number of forefront science areas. They will also be discovery instruments through their enlargening of observational phase space in key ways (solid angle, time resolution and modes of operation). Here we focus specifically on the areas of fundamental questions that are posed as the “eleven questions” in *Connecting Quarks with the Cosmos*. Radio astronomy will provide detailed answers to four of the questions and less direct, though important information, for several additional questions.

The questions for which the SKA will play central roles in providing answers are as follows.

**What is Dark Energy and What is Dark Matter?**

What we know so far about dark energy has emerged from studies of Type Ia supernovae at high redshift, from the characterization of CMB fluctuations, and from the statistics of large-scale structure as probed by galaxy surveys. Taken together, these methods provide complementary measures in precision cosmology and constraints on the equation of state of dark energy. The study of large-scale structure (LSS) through massive surveys of galaxies is highly recommended in *Connecting Quarks to the Cosmos* as a continuing source of information on dark energy. The report emphasizes the importance of wide-field-of-view imaging in conducting such surveys and specifically endorses two optical/infrared telescopes, a ground based instrument, the Large-aperture Synoptic Survey Telescope (LSST), and a space-based telescope, the Supernova Acceleration Probe (SNAP).

Large scale surveys of atomic hydrogen from galaxies are a key enterprise for the SKA. Like LSST and SNAP, high-throughput surveys with the SKA are enabled by the large field of view (∼ 5 deg² for z = 2 and larger at higher redshifts owing to diffraction limited optics). For H I surveys, the sensitivity specification for SKA (2 × 10⁴ m² K⁻¹) is essential. Substantial regions of the sky can be surveyed, yielding a total > 10⁷ galaxies and rotation curves on about 10% of these. The SKA yield of galaxies for LSS is comparable to or larger than those expected from LSST and from SNAP, and thus will be important in future studies of dark energy and dark matter. In particular, SKA detections will sample the large volume needed to reduce cosmic variance in estimating the equation of state for dark energy; the corresponding high redshifts (z ≤ 1 to 2) are necessary in order to probe the linear clustering regime, where acoustic peaks in the matter power spectrum can be measured. Identification of these peaks in the matter spectrum are highly complementary to those measured in CMB fluctuations. Furthermore, radio detections of H I are unimpaired by extinction and trace the underlying
gravitational potential without galaxy bias.

Radio continuum surveys, conducted concurrently with the HI observations, will yield large samples of strong and weak gravitational lensing (and microlensing), which will probe the spatial distribution of dark matter on a wide range of scales (stars to clusters of galaxies). Identification of clusters through lensing complements other constraints on cosmology and probes dark energy through the cosmological evolution of clusters. The SKA’s design will include a high degree of multiplexing, so that time-dependent lensing events can be captured through monitoring of the sky. The large radio continuum samples also provide important information on the star formation rate and the magnetic fields of individual galaxies as a function of $z$. The origins of magnetic fields are not understood and understanding them may lead to connections to fundamental aspects of the early universe.

Are there new states of matter at exceedingly high density and temperature?

Radio pulsars are the most numerous of the known classes of neutron stars, which include accreting binary neutron stars (seen in X-rays) and hypermagnetic objects — magnetars — seen in X- and $\gamma$-rays. Particular objects are occasionally recharacterized as quark or strange stars. Though such claims are not overly compelling at present, they underscore the possibility that new kinds of stellar objects will be discovered or ruled out in such a way as to probe the equation of state of nuclear matter and the possible existence of exotic states of matter. Any new classes of compact objects are evidently either rare or manifest themselves in regions of observational phase space that have not yet been probed to the necessary degree of completeness. The SKA will provide huge leaps in sensitivity and coverage of the frequency and time domains over large solid angles. New surveys will lead to a deep, nearly-complete census of radio pulsars in the Galaxy and thus to discoveries of rare objects, such as those rotating at or near the breakup limit of a neutron star ($\sim 0.5$ ms) or those more rapidly rotating objects that might require alternative equations of state.

The distribution of neutron star magnetic fields is not well understood, particularly on the high end that spans the quantum critical field, $B_q = 4.4 \times 10^{13}$ Gauss. Deep radio surveys leading to the Galactic census, in concert with high-energy observations with future X-and-$\gamma$-ray satellites, will better determine the demographics of high magnetic fields and hopefully will lead to a physical understanding of high fields and the way they are manifested in the population of neutron stars.

Mergers of compact objects, in particular neutron stars and black holes, lead to states that are likely to include black holes and neutron stars, but also perhaps to transient states of extreme magnetic fields and density. Deep censuses leading to large numbers of objects may also yield observational opportunities for probing spacetime, such as an active pulsar orbiting a stellar or supermassive black hole. Spacetime probes are part of the answer for the following question, where we also clarify the complementary roles of LOFAR and the SKA.

Did Einstein Have the Last Word on Gravity?

General Relativity has not been tested in the strong gravity regime and it has not been
modified to include quantum mechanical effects. Laboratory experiments and high-energy astronomy investigations are mentioned in *Connecting Quarks with the Cosmos* as particular ways to make progress on this question. Radio astronomy has the potential for great progress in this area that builds upon the past successes of the technique of pulsar timing. Massive pulsar surveys are likely to yield pulsar-black-hole binaries that can be monitored in exquisite detail to probe relativistic effects and spacetime around blackholes. Considerations of stellar evolution and pulsar phenomenology suggest that there may be only a few such binaries in the Milky Way, so the high sensitivity of the SKA is likely required to find them.

The high sensitivity and wide field of view of SKA are necessary for the massive Galactic census that will identify rare objects. Monitoring of pulse arrival times on large pulsar samples is enabled by the multiplexing capability of SKA that will allow multiple simultaneous uses of the telescope with which many pulsars can be sampled simultaneously.

LOFAR’s frequency range is too low to allow direct discovery of many Galactic pulsars as periodic sources, owing to propagation effects in intervening plasmas that smear the pulses. However, imaging surveys with LOFAR will identify steep spectrum sources as pulsar candidates that can be followed-up with SKA. It is significant that many of the rare objects expected in pulsar surveys are ‘recycled’ pulsars, which tend to have steep radio spectra in samples obtained to date.

Another research direction that demands the multiplexing capability of SKA along with the need to discover and monitor rotationally stable pulsars is the usage of pulse timing to detect or place limits on low-frequency gravitational waves. The frequency range is related to the reciprocal of the data span of the timing data (\(\sim\) years\(^{-1}\)) and the sensitivity to gravitational waves is related to the timing precision. The relevant gravitational wave backgrounds include those produced by merging massive black holes and are thus tied to this question about gravity.

**How do cosmic accelerators work and what are they accelerating?**

Radio astronomy shares with gamma-ray astronomy sensitivity to high-energy cosmic rays. While cosmic rays less energetic than about \(10^{15}\) eV are generally considered to be accelerated by supernovae in the Galaxy, the acceleration of cosmic rays with energies extending to \(\sim 10^{20}\) eV is enigmatic. Also, several classes of sources produce coherent emission in the radio band and these involve, especially in the case of pulsars, acceleration processes that are not well understood.

LOFAR and SKA are important for probing the forefront of cosmic acceleration. The frequency range of LOFAR, combined with high-time resolution sampling over wide areas, make it ideal for detecting radio pulses produced in air showers from \(\gtrsim 10^{16}\) eV cosmic rays. In essence, LOFAR exploits the atmosphere as a huge particle detector. Results from LOFAR are expected to complement those from optical Cerenkov detectors such as the Southern Auger facility and anticipated space detectors of atmospheric events. Neutrino events on the Moon can be probed with high efficiency with SKA because the entire visible surface can be
sampled in the field of view of SKA.

A unique capability of the SKA will be its ability to probe sources on micro-arcsecond scales and smaller. This capability arises by using the high sensitivity of SKA to exploit the high spatial sensitivity of the interstellar scintillation phenomenon. Working together, the SKA and diffractive scintillations provide a virtual telescope with effective diameter the size of Earth’s orbit. Techniques have been developed using existing telescopes, but application of this method requires high sensitivity along with high time and frequency resolution. Among known kinds of sources, the sub-microarcsecond regime includes the magnetospheres of pulsars and the inner regions of AGNs, where acceleration processes are poorly understood. If additional classes of compact astrophysical sources are found, they are likely to involve coherent emission processes and will also show the scintillation effect and be amenable to this method of angular resolution.

Relativistic jets in AGNs are powerful accelerators of cosmic rays. The SKA will allow multi-scale mapping of jets down to sub-milliarcsecond scales with a factor of 100 greater sensitivity than currently possible. Outcomes of SKA studies will include an understanding of the jet collimation zone and constraints on the kinds of particles constituting the jets (electron-positron pairs vs. electrons and ions).

**Is a New Theory of Matter and Light Needed at the Highest Energies?**

As mentioned in *Connecting Quarks with the Cosmos* and in our discussion above, neutron stars serve as cosmic laboratories for high magnetic fields. At present it is not understood how the quantum critical field $B_q$ plays a role in the electron-positron cascades that are thought to be required in the production of pulsar radio emission. Perhaps the apparent radio quietness of the known magnetars, discovered in $\gamma$-rays, is a consequence of the superhigh magnetic fields and suppression of pair production. However, some radio pulsars appear to have surface fields in excess of $B_q$. Because known samples with superhigh fields are small in number (less than two dozen, at present), larger pulsar samples and deeper searches are needed for radio emission from the known magnetars and from those found in the future. Through surveys and analyses of particular objects, the electrodynamics of magnetospheres in the superhigh field regime will perhaps open a window for answering this question.

Mapping of neutron stars’ magnetic fields is highlighted as an outcome of future X-ray polarimeters. Such mapping has been conducted for many years on radio pulsars using polarimetric techniques. It is fair to say, however, that comprehensive, three-dimensional mapping of magnetic fields yet to be done. Arguments are often made that different radio frequencies arise from different altitudes in pulsar magnetospheres. Alternative pictures apply as well, but it is plausible that different frequencies sample different parts of the magnetosphere. With existing telescopes, sufficient sensitivity has not been available to measure polarization over a large dynamic range in frequency. With the SKA, large samples can be studied over at least a factor of 100 in frequency. On nearby objects, LOFAR will be able to extend the range by another factor of 10 or so. The interpretation of such measurements is undoubtedly
complicated but is surely rich in possibilities for mapping the magnetic fields. A byproduct of such analyses may also be contraints on neutron star radii, because the radius sets the scale of the dipolar component of the magnetic field.

The discussion of the above questions demonstrate that radio astronomy will be central to providing answers and LOFAR and the SKA are the next-generation instruments needed.

Radio astronomy will also play a role, though perhaps not a central one, in discussions of two additional questions:

**Are There Other Spacetime Dimensions?**
Radio astronomical observations have already placed stringent limits on the possible variation of physical constants such as the fine structure constant $\alpha$ and the gravitational constant $G$. Pulsar observations with the SKA will enlarge greatly the sample size for testing possible variations of $G$ while SKA and LOFAR observations will increase both the number of systems and redshift range over which spectral transitions can be probed for variations in $\alpha$.

**How were the elements from Iron to Uranium Made?**
The question as posed and discussed in *Connecting Quarks with the Cosmos* centers on r-process nucleosynthesis in Type II supernovae and perhaps in mergers of neutron stars and gamma-ray bursts. Much of the anticipated new information will derive from X- and $\gamma$-ray spectroscopy of young supernova. However, radio observations, while not allowing direct probes of particular heavy elements, will provide significant information about the rates by which candidate r-process objects occur. For example, gamma-ray bursts are known to be highly beamed and it is probable that there is a preponderance of radio-loud, X-and-$\gamma$-ray quiet bursts. Mergers of neutron stars or neutron-star/black-hole binaries may yet underlie short-duration gamma-ray bursts and it is conceivable that they too provide radio transients that will be discovered with LOFAR and the SKA.

How element formation varies with cosmological epoch is a topic of great interest because the capabilities for probing the time evolution will be coming on line with GLAST and JWST, for example. The SKA, allied with ALMA, will permit probing of early element formation out to redshifts $\sim 20$ through detection of redshifted carbon monoxide.
Synopsis of the Square Kilometer Array Project

The SKA is a project for the next-generation radio telescope that will increase sensitivity by more than a factor of 10 over Arecibo and by nearly a factor of 100 over the largest existing array telescope. It will provide enormous increases in capability along multiple parameter axes with fewer tradeoffs than ever before. These include sensitivity, sky and frequency coverage and imaging fidelity, while maintaining high resolution in time, frequency and direction.

The SKA has been an international concept from the start (1994) and it will continue to be so through the development, construction and operational phases. Seven concept designs were recently submitted (July 2002) to the ISSC by the different participating countries:

<table>
<thead>
<tr>
<th>Table 1: SKA DESIGN CONCEPTS AS OF 2002 JULY</th>
</tr>
</thead>
<tbody>
<tr>
<td>A large-N array of small parabolic antennas</td>
</tr>
<tr>
<td>Planar phased-arrays</td>
</tr>
<tr>
<td>Spherical radio (Luneburg) lenses</td>
</tr>
<tr>
<td>Cylindrical paraboloids</td>
</tr>
<tr>
<td>Nearly flat reflectors with balloon suspended receivers</td>
</tr>
<tr>
<td>Very large Arecibo-like dishes</td>
</tr>
<tr>
<td>Large, low-cost parabolic antennas</td>
</tr>
</tbody>
</table>

Concept design documents can be found at http://www.ras.ucalgary.ca/SKA/ska_memos.shtml (Memos 17-23). These concepts are under review by the International SKA Steering Committee. Various technologies important to all of these designs are being investigated around the world including imaging simulations, signal processing, interference reduction, and operations.

Science: The extraordinary range of astronomical targets and topics envisioned for the SKA is discussed in Science with The Square Kilometer Array: A Next Generation World Radio Observatory.1 The science case is being re-worked to take into account evolution of the research forefront in astronomy and astrophysics and changes in technological capability. A new science document will be produced by mid-2004. The SKA will allow exploration of unique aspects of the radio universe on solar-system to cosmological scales. The SKA will also allow radio science to be conducted on par with innovations expected across the entire electromagnetic spectrum in the next two decades. With its specified sensitivity, angular resolution, and frequency coverage, the SKA concept will provide centimeter wavelength complementarity to telescopes such as ALMA at mm wavelengths, the NGST in the optical and infrared, the VLT, the GSMT, and CELT operating in the optical/IR, the LSST (Large-aperture Synoptic Survey Telescope), SNAP (Supernova Acceleration Probe) and its descendants, Con-X in X-rays, and follow-ups to GLAST in the gamma-ray range.

Last, but perhaps foremost, the greatest value of the SKA will be in the new, unanticipated

discoveries made with it, which will unfold new questions. This process has happened repeatedly in the past\textsuperscript{2} when new regions of observational phase space are explored\textsuperscript{3}.

A set of provisional design goals has emerged over the last 5 years from a series of international meetings and workshops. These are presented in broad terms in Table 2. The sensitivity \((2 \times 10^4 \text{ m}^2/\text{K})\), frequency range \((0.15 \text{ to } 22 \text{ GHz})\), and imaging dynamic range \((10^6:1)\) of the SKA are required for faint-source science, particularly sources at high redshift. The higher frequencies are also demanded by solar system science (surveys of Kuiper-belt objects), the detection of thermal radiation from nearby stars, and to obtain the greatest resolution. The physical collecting area will be utilized interferometrically over large bandwidths using fully digital techniques. The challenge for developing the SKA is to build it cost effectively.

Table 2: Provisional International SKA Specification Goals

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity</td>
<td>(A_{\text{eff}}/T_{\text{sys}} = 2 \times 10^4 \text{ m}^2/\text{K})</td>
</tr>
<tr>
<td>Surface brightness sensitivity</td>
<td>1K at 0.1 arcsec (continuum)</td>
</tr>
<tr>
<td>Frequency range†</td>
<td>0.15-22 GHz</td>
</tr>
<tr>
<td>Redshift coverage</td>
<td>(z &lt; 8.5 \text{ HI, } z &gt; 4.2 \text{ CO(1\rightarrow 0)})</td>
</tr>
<tr>
<td>Detectability of Milky Way in HI (CO)</td>
<td>(z_{\text{max}} \sim 2 (20))</td>
</tr>
<tr>
<td>Imaging field of view</td>
<td>1-10 deg(^2) at 1.4 GHz</td>
</tr>
<tr>
<td>Multibeam capability</td>
<td>(N_{\text{beams}} &gt; 100)</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>&lt; 0.04 arcsec at 1.4 GHz</td>
</tr>
<tr>
<td>Number of spatial pixels</td>
<td>(&gt; 10^8)</td>
</tr>
<tr>
<td>Instantaneous bandwidth</td>
<td>(\sim 20% \text{ at high frequency})</td>
</tr>
<tr>
<td>Number of spectral channels</td>
<td>(&gt; 10^4)</td>
</tr>
<tr>
<td>Image dynamic range</td>
<td>(10^6) at 1.4 GHz</td>
</tr>
</tbody>
</table>

† The US SKA Consortium will consider extending the frequency range to \(\gtrsim 32 \text{ GHz}\).

The US SKA Consortium is considering \textquote{large-N\textquoteright} designs that exploit the economies-of-scale for replicated antennas and digital electronics, where \(N\) is the number of individual antennas or stations of antennas, depending on the detailed configuration that emerges. \(N\) will be determined by the cost equation, science requirements, and logistics. Our strawman design includes a central core array comprising \(\gtrsim 50\%\) of the overall collecting area that would allow near-optimal baseline coverage in imaging applications while also providing sensitivity to low-surface brightness emission and allowing phasing of all antennas into multiple beams for time-domain science and spectroscopy.

The time line for SKA development includes a decision on site in 2005, a decision on design concept in 2007, and presentation to appropriate review panels and funding agencies at the end of this decade and the beginning of the next.

\textsuperscript{2}Serendipitous Discoveries in Radio Astronomy, NRAO Proceedings, Eds. K. Kellerman & B. Sheets., 1983

\textsuperscript{3}M. O. Harwit, Cosmic Discovery, Basic Books, 1981.