The Square Kilometer Array

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Abstract. The Square Kilometer Array is intended to be the centimeter- and meter-wavelength telescope for the 21st century. Originally proposed as the “hydrogen telescope,” the 21-cm hyperfine transition of neutral hydrogen continues to play a significant role in the Key Science Projects envisioned for the SKA. The 21-cm emission from galaxies will be used both as a means of tracking galaxy evolution over a significant era in the Universe’s history as well as a tracer of mass for cosmological studies. The 21-cm emission and absorption from the intergalactic medium itself at the time of the Epoch of Reionization will be traced to follow the evolution of this crucial phase of the Universe’s history. A number of telescopes both those currently in operation and under construction, and notably including Arecibo, will provide crucial pathfinding developments, technically, algorithmically, and scientifically.

Keywords: instrumentation: interferometers—surveys—galaxies: ISM—cosmology: observations

PACS: 95.45.+i,95.55.Jz,98.62.-g,98.65.-r,98.80.-k

INTRODUCTION

The Square Kilometer 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 [21]. 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.

The concept for the SKA grew out of multiple, independent suggestions in the early 1990s for a “large hydrogen telescope.” With the notable exception of the 305-m diameter Arecibo telescope, radio telescopes and telescope arrays have been limited for several decades to apertures of no more than about \(10^4\) m\(^2\), constraining, for instance, studies of the 21-centimeter hydrogen emission from galaxies to the nearby Universe (\(z < 0.2\)). It was recognized that tracing the primary gas component of galaxies—hydrogen—to much larger redshifts would require a substantial increase in collecting area. The International Astronomical Union first established a working group in 1993 to begin a worldwide study of the next generation radio observatory. Since that time, the effort has grown to comprise 17 countries and 55 institutes, including about 200 scientists and engineers. Further fueling interest in the SKA have been the technological developments in the latter half of the 20th century that offer a path to substantial improvements in future astronomical measurements at radio wavelengths.

\(^1\) http://www.skatelescope.org/
In the past decade, there have been a number of significant milestones in the development of the SKA, including the identification of 5 Key Science Projects, the establishment of an international program office, a set of scientific specifications and a reference design, and identification of a short-list of suitable sites. The Key Science Projects were identified through a series of international workshops, with the aim of selecting projects that represent 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 [9]. As identified by the international community, the SKA Key Science Projects are [3]

- The Cradle of Life and astrobiology [19]—including imaging the thermal emission from centimeter-sized particles in protoplanetary disks, detecting biomolecules, and searches for extraterrestrial intelligence (SETI);
- Strong Field Tests of Gravity Using Pulsars and Black Holes [17]—including constructing a gravitational wave observatory by precise timing of millisecond pulsars, studying theories of gravity in ultra-relativistic binaries, and using neutron stars as probes of nuclear physics;
- The Origin and Evolution of Cosmic Magnetism [10]—including establishing an all-sky Faraday rotation measure (RM) grid to track the evolution of magnetic field strength and structure through cosmic time;
- Galaxy Evolution, Cosmology, and Dark Energy [20]—to be discussed further below, but focussing on H\textsubscript{I} as both a probe of galaxy evolution and a cosmological probe; and
- Probing the Dark Ages [2]—also to be discussed further below, but focussing on tracking the evolution of the intergalactic medium from a neutral to ionized state during the Epoch of Reionization.

Consistent with the original concept for the SKA, the 21-cm line of neutral hydrogen continues to play a prominent role in the Key Science Projects, which help guide the design and development of the telescope.

**KEY SCIENCE AND REFERENCE SCIENCE MISSION**

In this section we summarize the goals of the Key Science Projects, with a focus on the role of observations of neutral hydrogen. Also, currently being developed is the SKA “Reference Science Mission,” which attempts to describe how the observations required for obtaining the Key Science Project goals will actually be conducted. Thus, we also discuss the kind of observations, though with the recognition that the actual observations conducted by the SKA will be informed by pathfinders (see below).

**Galaxy Evolution, Cosmology, and Dark Energy**

This Key Science Project has the complementary goals of following the primary baryonic component of the Universe and its role in the formation and evolution of
galaxies while also using the 21-cm emission from galaxies as a tracer of mass and cosmological probe.

Examples of current uncertainties in galaxy formation and evolution, as discussed elsewhere in this volume, include whether large galaxies accrete exclusively through mergers with satellites or whether cooling of hot gas in their halos plays a role and the extent of the last vestiges of galaxy accretion in the form of extremely low mass clouds/filaments of neutral gas surrounding galaxies (at column densities around $10^{17}$ cm$^{-2}$). The very assembly process itself requires that gas dissipate energy and angular momentum. While simulations are making progress in reproducing the galaxy assembly process, the dynamic ranges required are still large and cannot be handled without approximation. All of these necessitate observations that trace the gas in the range of environments and over the epochs relevant for galaxy assembly and evolution.

It is now well established that the star formation rate in the Universe has evolved dramatically since a redshift $z \approx 1$ [lookback time $\approx 7$ Gyr, e.g., 14], decreasing by about an order of magnitude. Strikingly, over the same epoch that the star formation rate has decreased so dramatically, there has been little evolution in the H I content of the Universe [i.e., $\Omega_{H I}$, 18]. Given that the H I gas represents the raw material from which stars form, this apparent contradiction in evolutionary histories indicates significant uncertainties in our understanding of the assembly of galaxies.

The SKA will provide detailed measurements of the kinematics of the H I line on 20–100 kpc scales, to $z > 1$, helping to establish how fresh hydrogen gas is brought in from the dark matter halo. In conjunction with ALMA observations of molecular lines, optical/infrared observations of the stellar populations of galaxies, and star formation tracers such as the far-infrared and radio continua, there will be a direct link from the baryonic component of a galaxy to the dark matter halo in which it is embedded. Moreover, in many instances, the H I emission surrounding apparently morphologically normal galaxies indicates that interactions have played a crucial role in the evolution of galaxies [e.g., 24]. With its resolution and sensitivity, the SKA will illuminate the history of galaxy interactions at higher redshifts than is currently possible.

Complementing its role for tracing galaxy evolution, the 21-cm H I line emission from galaxies has been proposed as a cosmological probe. The primary focus of the proposed observations has been baryon acoustic oscillations (BAOs), the fluctuations in the baryon distribution imprinted by acoustic modes in the plasma near the time of recombination. The BAOs are expected to impose a characteristic scale of order 150 Mpc in the galaxy correlation function, a scale which can then serve as a standard ruler. Finally, BAOs also are recognized as the probe of dark energy that is least likely to be affected by systematic uncertainties [6].

With a sensitivity to reach to $z \approx 1$ and surveying a large fraction of the sky, the SKA will conduct a 21-cm “Billion Galaxy Survey.” Because 21-cm observations are intrinsically spectroscopic, high-precision redshifts will be obtained as a natural part of the survey. Such a sample of galaxies will not only allow BAOs to be detected using 21-cm emission as the mass tracer, but there will be ample galaxies to probe the evolution of BAOs over a significant redshift range and detect or constrain the effects of dark energy. Further, while BAOs have already been detected in the luminous red galaxy sample from the SDSS [8], a 21-cm sample ultimately will be required in order to provide consistency
checks with large-scale optical/infrared surveys.

More recently, Guzzo et al. [12] have discussed the role of galaxy redshifts as tracers of the growth of large-scale structure. As large-scale structure grows, an increasing radial anisotropy is imprinted in galaxy redshifts. The rate at which large-scale structure grows is, in turn, influenced by dark energy. Thus, galaxy redshift surveys, including those at $z \sim 1$, can provide a measure of dark energy, complementary to the more common measures such as BAOs and Type Ia supernovae.

The Reference Science Mission will likely include both a Deep Field component and a Wide Area component. The former will target galaxy assembly and evolution over cosmic time, in a manner similar to the Hubble Deep Fields. The latter will enable the “Billion Galaxy Survey.”

Galaxy evolution can be studied at even higher redshifts via H$\text{I}$ absorption. Unaffected by dust obscuration, these observations can search in an unbiased manner for H$\text{I}$-rich structures. While clearly limited only to those lines of sight for which suitable background sources exist, H$\text{I}$ absorption is already probing galaxies at $z \approx 3$ [15] and can be used to probe galaxy kinematics and formation at redshifts at which detecting H$\text{I}$ emission is impractical.

**Probing the Dark Ages**

This Key Science Project has the goal of tracking the transition in the Universe from a neutral state to its current, largely ionized state. As is well known, following recombination ($z \approx 1100$), the intergalactic medium (IGM) consisted essentially of neutral hydrogen. This situation persisted until the Epoch of Reionization (EoR), during which the first luminous objects began to form and the IGM transitioned from neutral to its current, nearly fully ionized state. Observations of high-redshift quasars and the cosmic microwave background indicate that the EoR was underway by $z \approx 10$ and largely concluded by $z \approx 6$ [1, 7, 16].

The goal for the SKA is to be able to conduct “tomographic” observations of the H$\text{I}$ emission during the EoR. As the first sources begin to illuminate and ionize their surroundings, they carve out Strömgren spheres. In turn, this patchwork of H$\text{II}$ regions produces spatial fluctuations in the H$\text{I}$ brightness temperature (i.e., because there are regions where there is no H$\text{I}$). When these H$\text{II}$ regions form and how they grow provide crucial information about the nature and growth rate of the first sources.

In addition to emission from the IGM, the SKA will search for the “21-cm forest” against any extremely high redshift radio sources [4]. Much like the Ly-$\alpha$ forest at lower redshifts, modest overdensities of H$\text{I}$ seen along the line of sight to radio sources at $z \gtrsim 8$ will produce absorption that can be used to track the growth of structure.

Both of these observations focus on the H$\text{I}$ line. A complementary technique will be to observe the low-order transitions of CO, to trace the growth of molecular gas in the first galaxies [23]. At $z \approx 6$, the low-order transitions are shifted to centimeter wavelengths, at the short end (blue end) of the SKA wavelength range.

Combined with ALMA observations of molecular emission from the first galaxies and JWST observations of the first starlight, the SKA will enable the complete history of the
FIGURE 1. An artist’s illustration of part of the SKA Reference Design. A large number of antennas with diameters of approximately 10 m is likely to comprise a substantial fraction of the collecting area for the SKA. This part of the SKA would target, among other goals, H I emission and absorption at redshifts $z \lesssim 3$. Not shown is the longer wavelength/lower frequency component of the SKA that is essential for probing the 21-cm H I emission and absorption from the intergalactic medium during the Epoch of Reionization.

EoR to be followed. Indeed, much like the 21-cm galaxy surveys at lower redshifts, both the ALMA and SKA observations will be intrinsically spectroscopic, allowing the evolution of the EoR and the first galaxies to be tracked.

SKA REFERENCE DESIGN

Over the past several years, initial design and prototyping efforts have focussed the design [13] and have led to a Reference Design. The Reference Design comprises both a set of specifications, informed by the Key Science Projects, as well as a concept for realizing those specifications (Figure 1).

The range of science programs to be conducted by the SKA demands essentially continuous wavelength coverage at least over the range 1 cm to 3 m (0.1—25 GHz). This wavelength range is sufficiently large that different technologies will be required for the antennas. The different technologies effectively define three bands, which are
nominally

**Low** \(0.1 \text{ GHz} \lesssim \nu \lesssim 0.3 \text{ GHz}\) \((1 \text{ m} \lesssim \lambda \lesssim 3 \text{ m})\); this portion of the SKA will make use of broad-band dipoles similar to those developed for the Murchison Wide-field Array (MWA), the Long Wavelength Array (LWA), and the Low Frequency Array (LOFAR).

**Mid** \(0.3 \text{ GHz} \lesssim \nu \lesssim 3 \text{ GHz}\) \((10 \text{ cm} \lesssim \lambda \lesssim 100 \text{ cm})\); multiple possible technical implementations for this portion of the SKA exist, including an array of small-diameter \((\approx 10 \text{ m})\) antennas, possibly outfitted with phased arrays in the focal planes, or aperture arrays.

**High** \(3 \text{ GHz} \lesssim \nu \lesssim 25 \text{ GHz}\) \((1 \text{ cm} \lesssim \lambda \lesssim 10 \text{ cm})\); this portion of the SKA will most likely be implemented by small-diameter \((\approx 10 \text{ m})\) antennas outfitted with wide-bandwidth feeds.

Considerable international effort is devoted to understanding and improving relevant technologies, both in the form of major design studies such as the U.S.-led Technical Development Program and the European-led PrepSKA and in the Pathfinders.

**PATHFINDERS**

The scientific interest in the SKA goals, including but not limited to H\(_1\) observations, has spurred the design, development, and construction of telescopes worldwide. Moreover, many existing telescopes are being enhanced in ways that will enable crucial demonstration observations or provide critical data for refining the SKA Reference Science Mission.

A prime example are the H\(_1\) observations being conducted with the Arecibo telescope. For example, the ALFA surveys, and notably the ALFALFA survey [11], will provide crucial information on the H\(_1\) mass function, which in turn is needed to make predictions about how to conduct the SKA “Billion Galaxy Survey.” In addition, the Arecibo telescope has been used to detect the H\(_1\) emission from galaxies at \(z \approx 0.3\), the most distant detections to date [5].

Other examples of pathfinding scientific observations relevant to the SKA Key Science Projects include detecting H\(_1\) emission with the WSRT from galaxies in the cluster Abell 2192 and a group behind the cluster Abell 963, both at redshifts \(z \approx 0.2\) [22] and H\(_1\) absorption with the GMRT at \(z \approx 3\) [15]. In the former case, the search strategy was to target two clusters, with different dynamical states and apparent star formation properties, and the detections hint at the range of outcomes for galaxies in diverse environments. Also important will be future observations with the EVLA, which will provide higher angular resolution than either Arecibo or WSRT can obtain.

Pathfinders also provide important technical information. Both the EVLA and the Allen Telescope Array (ATA) have helped illuminate the design and construction of wide-band feeds. The H\(_1\) observations—with Arecibo, EVLA, and WSRT—are important for algorithmic development and survey design, i.e., handling large volumes of data, identification and excision of radio frequency interference (RFI), etc. Also in the design and development phase are the Australian SKA Pathfinder (ASKAP) and South African Karoo Array Telescope (MeerKAT). While their capabilities have not yet been finalized,
both telescopes have H\text{I} observations as key science goals and both are located in the southern hemisphere, complementary to the existing northern hemisphere instruments.

At longer wavelengths, the already referenced MWA, LWA, and LOFAR are providing crucial technical understanding of the design and construction of a long-wavelength array targeting the EoR. Moreover, both MWA and LOFAR have as key science goals detecting the H\text{I} emission fluctuations from the EoR in a statistical sense, and the techniques they develop for dealing with the (strong) foreground emission are likely to be essential for the SKA.

ACKNOWLEDGMENTS

Basic research in astronomy at the NRL is supported by 6.1 Base funding. I thank M. Haynes, P. Henning, J. van Gorkom, and E. Wilcots for many illuminating discussions.

REFERENCES

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