THE SQUARE KILOMETRE ARRAY: A SCIENCE OVERVIEW

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Over the past several years an international effort has been developing to solve the technical challenges required to construct a giant radio telescope with a collecting area of one square kilometre. The Square Kilometre Array (SKA) will have a hundred times more collecting area than our most powerful existing radio telescopes, providing sensitivity of a few tens of nano-Jansky in the centimetre/decimetre wavelength continuum. With a spatial resolution better than the Hubble Space Telescope, a field of view larger than the full moon, and the ability to simultaneously image a wide range of red shift, the SKA will be the world’s premier spectroscopic imaging telescope. The Square Kilometre Array will be able to detect emission from the atomic and molecular gas at extreme redshifts, allowing study of the "Dark Ages" of the Universe before, and during, the transition phase when the initial stars formed and reionisation occurred. The wavelength range of the SKA spans the transition from emission dominated by non-thermal processes at long wavelengths to thermal radiation processes at the short wavelengths. With the combination of sensitivity, wide field of view and high angular resolution, the SKA will image the interstellar media and magnetic fields of galaxies to high redshift. Measurements of atomic hydrogen emission and continuum emission from galaxies will trace the star formation history of the Universe from primordial galaxies to the present. In our own Galaxy star formation processes and phenomena in the gaseous ISM will be studied on linear scales down to a few A.U. Millions of stars will be detected as radio sources, allowing, for example, imaging of protostellar and protoplanetary disk on sub AU scales, the initial mass function of massive stars in our own and other galaxies to be measured, the surfaces of red giant stars to be directly imaged, and solar-type phenomena to be studied on hundreds of nearby stars.

1 The Square Kilometre Array

New developments in all fields of astronomy have brought the current generation of astronomers to the brink of understanding the origin and evolution of the Universe. The next major step, to explore the earliest epochs of the evolution of the Universe, before the dawn of first light and the creation of stars and galaxies, and trace the subsequent formation and evolution of primordial galaxies will require a giant telescope operating at radio wavelengths. An international community of scientists and engineers has emerged with a common goal to develop a new radio telescope with a total collecting area of one million square meters, 100 times the collecting area of the Very Large Array, and 30 times larger than the largest telescope ever constructed. Technological advances promise to make it possible for such a telescope to be built within the next decade. This telescope, called the Square Kilometre Array, would engender profound advances in virtually all areas of modern astrophysics.

The design goals for the Square Kilometre Array, listed in Table 1, were established at a technical workshop held in Sydney, Australia in 1997. The SKA will be an interferometric array operating at wavelengths from about 2 metres to 1.5 cm, with baselines up to about a thousand kilometres. Very high brightness temperature sensitivity at arc-second to arcminute scale resolution, to study faint spectral line emission from the early Universe will be achieved by concentrating approximately 80% of the baselines within a few tens of kilometres. At the highest frequencies and the full resolution of the array brightness sensitivity of a few 10’s of K at milliarcsecond-scale resolution will allow studies of faint synchrotron and free-free radiation from the interstellar media of distant galaxies and ultra-high spatial resolution studies of stellar and interstellar processes in our own Galaxy. By combining
interferometry and phase-array receiver technology, the SKA will provide 0.1″ resolution images over a field of view of 1° at 21 cm (see Figure 1.). The Square Kilometre Array will be the world’s premier astronomical imaging instrument. No other telescope, existing or planned, operating at any wavelength regime will provide simultaneously: a spatial resolution better than the Hubble Space Telescope (0.1 arcsecond), a field of view significantly larger than the full moon (1 square degree), and spectral coverage to instantaneously observe a large range of redshift. The implications of this wide-field spectral imaging capability are truly profound. The sky will become accessible in a way that is difficult for us now to fully appreciate. In this paper I very briefly summarize a few of the major science goals of the SKA that have emerged from initial discussions.

Table 1. Scientific Specification for the Square Kilometre Array

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Goal</th>
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<tbody>
<tr>
<td>$A_{	ext{eff}}/T_{\text{sys}}$</td>
<td>$2 \times 10^4 \text{ m}^2/\text{K}$</td>
</tr>
<tr>
<td>Frequency range</td>
<td>0.15 – 20 GHz</td>
</tr>
<tr>
<td>Imaging Field of view</td>
<td>1° at 1.4 GHz</td>
</tr>
<tr>
<td>Number of instantaneous beams</td>
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</tr>
<tr>
<td>Maximum primary beam separation</td>
<td></td>
</tr>
<tr>
<td>Low Frequency</td>
<td>100°</td>
</tr>
<tr>
<td>High Frequency</td>
<td>1° at 1.4 GHz</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>0.1″ at 1.4 GHz</td>
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<tr>
<td>Brightness sensitivity</td>
<td>1 K at 1.4 GHz</td>
</tr>
<tr>
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</tr>
<tr>
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</tr>
<tr>
<td>Image dynamic range</td>
<td>$10^6$ at 1.4 GHz</td>
</tr>
<tr>
<td>Polarisation Purity</td>
<td>–40 db</td>
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Figure 1. Instantaneous field of view of the Square Kilometre Array relative to the size of the Hubble Deep Field and the field of view of the Atacama Large Millimeter Array.
2 The High Redshift Universe

2.1 Probing the Dark Ages: before the Dawn of Galaxies

Figure 2 shows the radiation wavelength of line radiation from transitions of astrophysically important species as a function of redshift over the proposed wavelength range of the SKA. The epoch of initial formation of galaxy and QSO’s and the first generation of stars is not known. Galaxies have been detected to redshifts greater than 5 [1]. In a CDM universe the first objects may begin to form at $z > 10$, initiating the reionisation process. Before the dawn of galaxies and the re-ionisation of the primordial gaseous medium, the structure of the Universe and the nature of the first energy sources can be investigated using the 21-cm line of neutral atomic hydrogen. Several processes render the neutral hydrogen gas visible, including Ly$\alpha$ coupling of the hydrogen spin temperature to the kinetic temperature of the gas, preheating of the primordial medium by soft x-rays from collapsing objects, and preheating by ambient Ly$\alpha$ photons [2]. Questions central to understanding this important evolutionary era are: When did the first stars form? What are the first energy sources, stars or QSO’s? What is the size and velocity distribution of mass perturbations? How do collapsing mass perturbations evolve and perhaps influence the ongoing collapse of galaxies and stars? Simulations indicated that the Square Kilometre Array will measuring the structure and kinematics of the primordial HI gas at wavelengths about 2m in integration times of order 10 to 100 hours, revealing the epoch of first light and the sources of energy generation [2].

The epoch of the first generation of stars begins the chemical evolution of the Universe, and the enrichment of metals, leading to production of molecules and galaxies rich in CO. The CO (1-0) line is shifted into the SKA wavelength band at $z > 4$, and CO (2-1) at $z > 8$. Emission from the CO (1-0) line has been detected out to red shift 2.4 [3]. The sensitivity of the SKA will allow the CO content of an average spiral galaxy to be detected to redshift greater than 20. Whatever the epoch of the initial star formation, the creation of the first metal enriched galaxies should be observable with the SKA.

![Figure 2. Wavelengths of important astrophysical lines within the SKA wavelength range, as a function of redshift.](image-url)
3 Large Scale Structure

One of the major undertakings with the SKA will be HI redshift surveys, to map the distribution of galaxy distribution to high redshifts, and chart the large scale structure of the Universe. In the local Universe, detectable HI emission is associated with galaxies, albeit HI emission extends will beyond the optical disk of late-type galaxies and samples the mass distribution of galactic haloes. HI is also often present between interacting galaxies, tracing the history of interaction. The HI luminosity of late-type galaxies increases as optical luminosity decreases [4]. Redshift surveys in atomic hydrogen will thus be critical to obtaining a complete picture of the distribution of galaxies and the matter structure of the Universe on large scales.

The wide field of view and high sensitivity of the SKA will make it a magnificent instrument for these studies, allowing study of the large-scale structure of the universe to greater depths than now possible and over a large area of the sky. In 12 months of observations the SKA could observe over 1000 square degrees and detect $L_*$ galaxies out to $z = 2$. Unlike optical redshift surveys, where a galaxy must first be identified and then followed-up with spectroscopy, this entire volume of the universe will be sampled to the surveyed flux limit. Assuming no evolution of HI properties with redshift, more than $10^7$ galaxies would be detected, over an order of magnitude more than the largest optical surveys [5,6] (see figure 3). The structure of the universe would be sampled over scales of 10’s of Mpc to several Gpc. The ability to trace the distribution of late-type galaxies to large redshift, will allow us not only to measure the large-scale structure, but also to determine the evolution the structure over a large fraction of the age of the universe.

![Figure 3. The number of detected galaxies and volume sampled for a number of resent large galaxy redshift surveys. Optical surveys are shown as filled circles.](image)
From rotation velocities derived from HI line widths, the Tully-Fisher relationship can provide independent distance determinations, allowing measurements of peculiar velocities of spiral galaxies relative to the expansion flow. The dynamics of large structures and the mass density field could be studied.

4 Evolution of Galaxies

4.1 Mass and Kinematics of Galaxies

Studies of the HST Deep field show significant evolution in the stellar content of galaxies back to redshifts of 1 \cite{7}. Very rapid evolution in the comoving star formation rate appears between redshifts of 1 and 3. These results imply vigorous evolution in the properties of galaxies during this epoch, and rapid processing of the interstellar media. HI observations provide a direct measure of the mass distribution of a galaxy within and beyond the stellar disk. When combined with optical spectroscopy HI rotation data yields the mass to light ratio and the stellar mass fraction with radius. The HI properties of galaxies at high redshift are currently, however, unobservable. A few hundred hours of integration on a deep HI field with the SKA will detect galaxy masses of a few $10^9 \, M_\odot$ out to $z = 4$. Within a single 1-degree field, $10^6$ galaxies will be detected.

The angular resolution of the SKA will be sufficient to resolve a large fraction of the galaxies out to $z = 2$, providing rotation curves and mass distributions, including dark matter, of over $10^5$ galaxies well into the era of strong star formation. The observations select for HI content independent of stellar content and optical brightness. The rate of star formation with galaxy mass, environment and dark matter content could be studied for a very large number of galaxies over look back time of more than 5 Gyr.

![Figure 4](image-url)

Figure 4. The HI mass distribution of galaxies detected in a deep SKA HI field. The thin line in the upper panel is the sensitivity of the survey. The solid curve is a Schechter mass function with the parameters given \cite{8}.
4.2 Star Formation History of the Universe

Atomic hydrogen surveys with the SKA will reveal redshifts, neutral gas content and masses distributions for millions of galaxies to high redshift. In combination with SKA radio continuum images, these data promise to trace the history of star formation back to the early stages of galaxy formation and evolution.

Optical identification of radio source catalogues show that almost all sources stronger than a few mJy are strong radio galaxies and quasars, powered by energy from active galactic nuclei. A very small fraction are nearby, lower luminosity normal galaxies detected by radio emission from the galactic disks. Below 1 mJy, and down to a few 10’s of µJy, the radio source population becomes dominated by disk emission from starburst and normal galaxies [9]. The integrated radio emission is tightly correlated to the 60 micron radiation [10], since both are linked to massive star formation activity in galactic disks. The SKA will probe the radio continuum sky to the nanoJy level, allowing detection of disk emission from starburst galaxies to very large redshift; thereby probing the star formation activity of the early universe (Figure 5).

Figure 5. Simulated radio continuum spectra of the spiral galaxy M101 over a frequency range of $10^8$ to $10^{14}$ Hz. Spectra are plotted for redshifts of 0.5, 2, 8 and 32. The 1σ sensitivity for an integration time of 8 hours is shown for several existing and planned instruments. The SKA will routinely measure the continuum properties of galaxies beyond redshift of 8. A schematic deconvolution of the “low frequency” radio continuum into synchrotron, free-free and dust continua is shown at bottom.

At frequencies of a few GHz, 80–90% of the emission from disk galaxies is due to synchrotron radiation [11]. The remainder is free-free emission from diffuse ionised gas and HII complexes
associated with newly formed massive stars. At higher frequencies the fraction of free-free emission rises, and it dominates the total radiation above about 20 GHz. At redshifts of a few, this transition will be observed in the 10 GHz range. Free-free radiation from normal galaxies outside our local group is largely unexplored, requiring a telescope like the SKA that combines simultaneously very high sensitivity, high angular resolution and wide field of view. Whereas the synchrotron luminosity is mediated by the magnetic field strength and geometry within the disk of a galaxy, the free-free luminosity relates directly to the luminosity of ionising UV photons, and thus the current population of young massive stars, independent of obscuration by dust. The free-free luminosity will be the most direct and reliable measure of the massive star formation rate in primordial starburst galaxies. By coupling the massive star content to the synchrotron luminosity, deconvolution of the thermal and non-thermal emission from early galaxies provides a means to measure the evolving role of magnetic fields.

The radio source density on the sky at nanoJy levels is not known. Preliminary simulations, based on simple extrapolation from known populations, suggested source densities greater than $5 \times 10^9$ sr$^{-1}$ in a single 8-hour integration at 20 cm wavelength [12]. This is similar to the source density in the Hubble Deep Field. Deep SKA integrations will require angular resolution better than the NGST to avoid confusion from overlapping galaxy disks on the line of sight. At its short wavelength limit the sensitivity of the SKA will allow the disks of normal galaxies at cosmological distances to be imaged with resolution far superior to that of any other telescope existing or planned.

5 Star Formation

In our own Milky Way galaxy, the SKA will revolutionize the study of stars. Radio emission allows investigation of processes and phenomena associated with stars that are not detected by any other means. With the present generation of radio telescopes, emission at radio wavelengths has been detected from several hundred stars, representing all stages of stellar evolution. The SKA will increase the number of radio detected stars by four orders of magnitude to at least $10^6$ [13].

An interesting example is emission from the late stages of star formation. This area, particular the formation of low mass stars and associated protoplanetary disks is one of the important precursors to the formation of planets and life, and has become a central investigations of modern stellar evolution studies. Observations are approaching the point where studies of the formation of individual stars and planetary systems will become feasible. The circumstellar disks around protostars are typically 100 AU in radius and a few tens of AU thick. Probing the structure of circumstellar disks at AU scales requires angular resolution at mas scales combined with brightness temperature sensitivities at 10$^5$ Kelvin, a combination is not provided by any existing facility. Figure 6 shows the parameter space of brightness temperature sensitivity and angular resolution that will be opened up by the SKA. The diagonal dashed lines show the angular size required to produce flux densities of 1 mJy, 1 mJy and 1 nJy at a frequency of 20 GHz for a source with a given angular diameter. The dark solid lines show the sensitivities (diagonal portion) and maximum resolution (horizontal portion) of the world’s most powerful existing interferometric arrays. For a radio sources with a given angular dimension and brightness temperature to be detected and resolved by an array it must lie above the solid line. (The photosphere of the supergiant star Betelgeuse, for example, can be just resolved with the Very Large Array and MERLIN [14].) Below $10^4$ K brightness temperature, the upper limit for photo-ionised gas, no current instrument can provide resolution better than about 70 mas. The SKA will allow for the first time mas scale imaging at brightness temperatures of a few K, opening up a vast range of thermal phenomena that have hitherto been hidden from view.
Several regions of low mass star formation exist within a few 100 pc of the Sun. At 100 pc, 3 mas corresponds to a linear dimension of 0.3 AU, sufficient to resolve the internal structure of protostellar and protoplanetary disks. Little is known about the conditions and processes within such disks. Although jets of free-free mission are seen on scales of 10’s of AU in a large fraction [15], the dusty disks have been traditionally studied via emission in the dust continuum at millimetre and submillimetre wavelengths. Observations with the SKA at cm wavelengths may provide the only means to probe protostellar disks at AU scales, where dust opacity may hide the final stages of star and planet formation. The optical depth of a dust cloud can be expressed in terms of the dust properties,

$$\tau = \kappa_o \cdot \sigma \cdot \left( \frac{\lambda}{\lambda_o} \right)^{-\beta},$$

where $\kappa_o$ is the mass absorption coefficient ($cm^2 gm^{-1}$) at wavelength $\lambda_o$, $\sigma$ is the dust mass column density and $\beta$ is the power law coefficient. Typical values for diffuse ISM dust are $\kappa_o=0.1$, $\lambda_o=250 \, \mu m$, and $\beta=2$. Figure 7 shows a simple calculation of the wavelength at which a collapsing spherical cloud with dust mass of 0.01 $M_\odot$ becomes optically thick as a function of radius. For ISM dust properties, a spherical cloud of diameter 35 AU is optically thick at wavelength of 1 mm and shorter. It has been suggested that evolution of dust properties as dust condenses into dense, cold cores a few 10’s of AU in size may lead to much larger opacity [16].
Dust emission from young class O protostars accounts for a significant fraction of the emission at 20 GHz [17]. Older class I protostars have steep cm wavelength spectral indices that must be dominated by long wavelength dust emission. The SKA will easily detect the dust emission from even the most evolve class III protostars having well evolved disks within which advanced and planet formation may be well advanced.

![Figure 7](image.png)

Figure 7. The wavelength for dust optical depth of unity as a function of diameter for a spherical cloud of total mass $1 \, M_\odot$ (dust mass $0.01 \, M_\odot$). Typical interstellar dust parameters have been assumed ($\kappa = 0.1 \, \text{cm}^2 \, \text{g}^{-1}$, $\lambda_o = 250$ and $\beta = 2$). The cloud becomes opaque at wavelengths shorter than 1 mm for diameters below 35 AU.

6 Summary

The structures that existed in the Universe before the dawn of stars and galaxies and the re-ionisation of matter can only be observed directly by the radio waves. Mapping the properties of these over a large part of the sky with the SKA will provide definitive tests of cosmological models and, in concert with next generation optical telescopes like the NGST, will reveal the process by which the first galaxies formed. The cosmic rays produced by the death of the first generation of stars will illuminate the magnetic fields in the early Universe. The SKA will trace the origin of cosmic magnetic fields and their role in the subsequent evolution of galaxies, and reveal the star formation history of the evolving Universe. In our own Galaxy, the sensitivity and resolving power of the SKA at its shortest wavelengths will provide a unique view of the birth process of stars. At 1.5 cm wavelength the SKA will probe protostellar clouds on dimensions of order the Earth-Sun separation, where the high density of dust currently hides the final details of the star formation process, and the emergence of planetary bodies.

Through these, and many other investigations, the SKA will engender major advances in those areas of modern astrophysics considered today to be fundamental to our understanding of the Universe about us. At the same time history has taught us that the most profound discoveries will by their nature be impossible to foresee. A leap of this magnitude in sensitivity and wide field imaging power will provide access to the universe in new ways, revealing unexpected object classes and unpredicted physical phenomena. The fundamental problems of today are often not resolved, but instead evolve into a new set of fundamental questions for tomorrow.
References