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Low Frequency Science with the Square Kilometre Array

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Abstract. Over the past several years an international community of scientists and engineers has emerged with a common goal to solve the technical challenge 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 nanoJy 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 worlds premier spectroscopic imaging telescope at any waveband.

At long wavelengths the SKA will be able to detect emission from atomic hydrogen 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 reionization occurred. The combination of sensitivity, wide field of view and high angular resolution, will allow high resolution imaging of the interstellar media and magnetic field of a vast number of galaxies to high redshift. Measurements of atomic hydrogen emission and continuum emission will trace the star formation history of the Universe from primordial galaxies to the present.

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.

The GMRT will make a significant step forward and, in the next decade, promises to be the premier facility for low-frequency radio astronomy. However, within the next 10 years there will be a pressing need for a much larger radio telescope that can bring to bear the power of radio wavelength observations on the high redshift universe. An international community of scientists and engineers has emerged with a common goal to develop a 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 every 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 are listed in Table 1. The SKA will be an interferometric array operating at wavelengths from about 2 metres to 1.4 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 . 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 at frequencies of 1.4 GHz and below that have emerged from initial discussions.

Table 1. Design Specifications for the Square Kilometre Array

Parameter	**Goal**
A_{eff}/T_{sys}	2×10^4 m^2/K
Total Frequency Range	0.03 - 20 GHz
Imaging Field of View	1 square deg. @ 1.4 GHz
Number of Instantaneous Pencil Beams	100
Maximum Primary Beam Separation	
low frequency	100 deg.
high frequency	1 deg. @ 1.4 GHz
Angular Resolution	0.1 arcsec @ 1.4 GHz
Continuum Brightness Sensitivity	1 K @ 0.1 arcsec
Number of Spectral Channels	10^4
Number of Simultaneous Frequency Bands	2
Image Dynamic Range	10^6 @ 1.4 GHz
Polarization Purity	−40 dB

2. Probing the Dark Ages: Before the Dawn of Galaxies

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 (Day et al. 1998). 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 Lya 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 Lya photons.

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, the structure of the intergalactic medium at this epoch, and the sources of energy generation (Tozzi et al. 1999).

3. Large Scale Structure of the Universe

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 halos. HI is also often present between interacting galaxies, tracing the history of interaction. Since the HI luminosity of late-type galaxies increases as optical luminosity decreases (Briggs 1990), redshift surveys in atomic hydrogen will 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 measurement 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 in this area out to $z \sim 2$.

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 (Gunn et al. 1995; Lahav 1995), 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

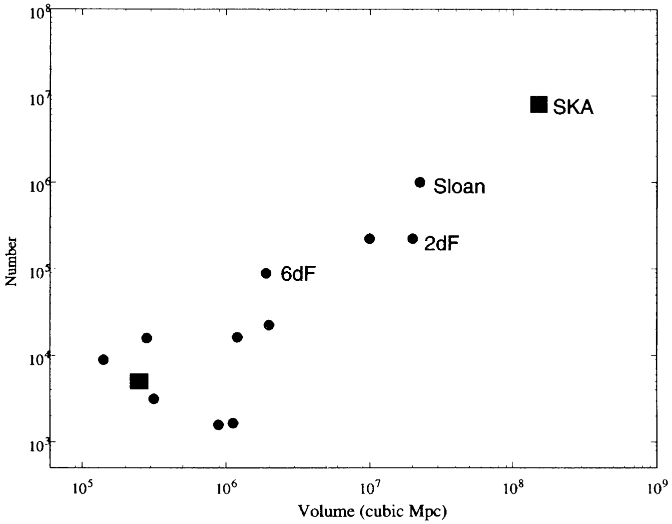

Figure 1. The number of detected galaxies and volume sampled for a number of resent large galaxy redshift surveys. Optical surveys are shown as filled circles. A parameters for a 12-month survey with the SKA is shown at upper right

to determine the evolution the structure over a large fraction of the age of the universe.

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 within 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 (Madau 1998). Very rapid evolution in the co-moving 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 the HI content and 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

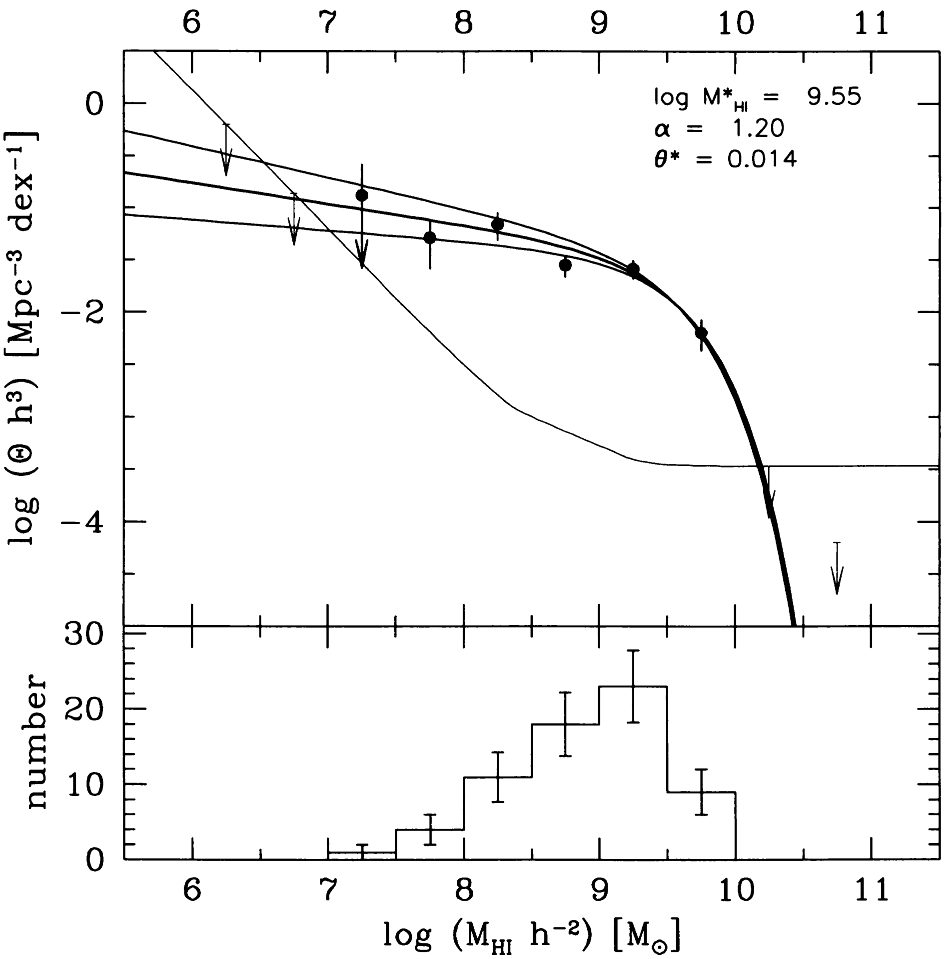

Figure 2. The HI mass distribution of galaxies detected in a deep SKA HI field. The thin line in the upper panel is the sensitivity of the survey. The solid curve is a Schechter mass function with the parameters given. From Zwaan et al. (1997)

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, within a single field of view, rotation curves and mass distributions, including dark matter, of over 10^5 galaxies well into the era of strong star formation. These 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.

4.2. The Star Formation History of the Universe

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

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. Large area surveys down to a mJy (Condon et al. 1998), see through the entire population of powerful AGN. Below 1 mJy, and down to the current limit of a few 10's of μJy, the radio source population becomes dominated by disk emission from starburst and normal galaxies (Wall & Jackson 1997). The integrated radio emission of normal galaxies is tightly correlated to the 60 micron radiation (Condon et al. 1991), since both are linked to massive star formation activity in galactic disks. At current sensitivity levels only a very small number (seven) of the HST galaxies are detectable as radio sources (Richards et al. 1998). 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. The radio source density on the sky at nanoJy levels is not known. Simulations based on simple extrapolation from known populations (Hopkins 2000), suggest source densities greater than 5×10^9 sr^{-1} in a single 8-hour integration at 20 cm wavelength – similar to the source density in the Hubble Deep Field. Deeper SKA integrations will require angular resolution better than the NGST to avoid confusion from overlapping galaxy disks on the line of sight.

At frequencies of a few GHz, 80-90% of the emission from disk galaxies is due to synchrotron radiation (Duric et al. 1998). 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 begins to dominate the total radiation above about 20 GHz (Figure 3). Above a few 10's of GHz, radiation from dust dominates, reaching a peak luminosity at a few hundred GHz. Carilli & Yun (1999) have shown that the spectral index between 1.4 and 350 GHz can be used to measure of redshift. The Atacama Large Millimeter Array (ALMA) will detect the radiation 350 GHz at levels of ~10 μJy in 8 hours, sufficient to detect the dust emission from starburst galaxies at very high redshift (see figure 3). All these galaxies will be detectable by the SKA at nanoJy levels allowing redshift determinations by the radio/mm colours. For galaxies with independent redshift from HI, the radio/mm flux ratio provides a sensitive measure of nuclear activity.

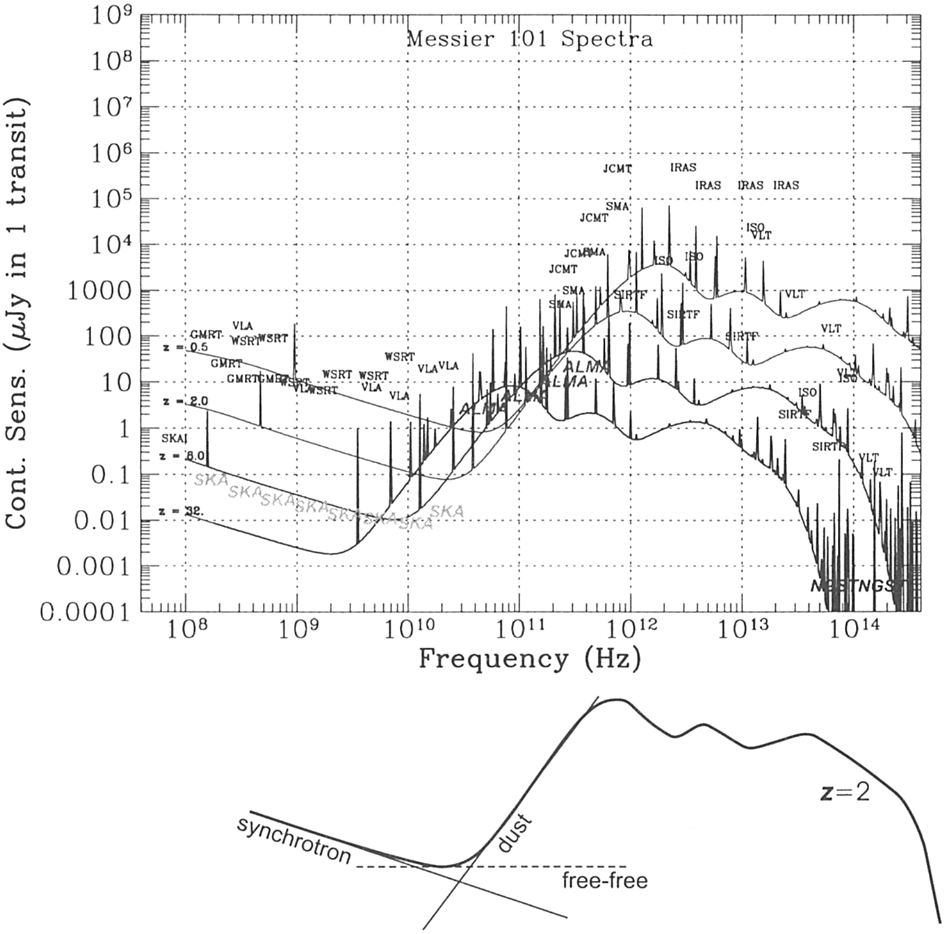

Figure 3. Simulated continuum spectra of the spiral galaxy M101 over a frequency range of 10^8 to 10^{14} Hz. Spectra are plotted for redshifts of 0.5, 2, 8 and 32. The 1σ sensitivity for an integration time of 8 hours is shown for several existing and planned instruments. The SKA will routinely measure the continuum properties of galaxies beyond redshift 8. A schematic deconvolution of the radio continuum into synchrotron, free-free and dust continua is shown at bottom. Adapted from Taylor and Braun (1999).

5. 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.

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.

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