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on the pathway to the SKA
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Future H i Surveys on the road to the SKA

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Abstract. In this short contribution we consider what types of surveys might be optimally pursued with path-finding instruments of 1%, 10% and finally 100% of the projected SKA sensitivity from the perspective of scientific applications that utilize the red-shifted λ21 cm emission line. Achieving interesting H i galaxy sample sizes with 1% SKA surveys requires very substantial survey durations, of about 1000 days. Good sampling (log(N)$\sim$5 down to below M^*_{HI}) can then be achieved out to z = 0.2 over 8000 deg^2 of survey area or even to z = 0.5 over 800 deg^2. The same surveys will permit the resolved imaging of order 1000 galaxies in each of several red-shift bins as well as detection of faint neutral filaments in the vicinity of galaxies with a column density of about 10^{18}cm^{-2}. Once 10% SKA sensitivities are achieved, then ground-breaking surveys are possible with only 100 day duration. Sample sizes of log(N)$\sim$6 extending below M^*_{HI} are possible over 800 deg^2 out to z = 0.5 and over 80 deg^2 out to z = 1. Such surveys will permit very competitive measurement of acoustic oscillations in the galaxy power spectrum. One can then envision a series of 10% SKA surveys probing different depths. The diffuse H i sensitivity would be such ($\sim10^{17}$cm^{-2}) that the next factor of three in sky area will become accessible to imaged detection and kinematic study of the H i cosmic web. With the 100% SKA sensitivity the capabilities are truly phenomenal. Survey sample sizes in the range log(N) = 7–8 are feasible over the red-shift range of 0.2 to about 5. Precise tracking of potential time evolution of dark energy (via the baryonic acoustic oscillation signature) should be possible out to z $\sim$ 3. The local cosmic web will be imaged down to $N_{HI} = 10^{16}$cm^{-2}. What exactly will be seen at z > 3? This will depend crucially on the SKA sensitivity in the critical frequency window of 350 to 200 MHz.

1. Introduction

One of the original (and still most compelling) motivations for building the SKA was realizing the ability to study the evolving neutral gas content of galaxies throughout cosmic time. The distribution and kinematics of H i as traced by the red-shifted λ21 cm emission line provide unique insights into galaxy formation and evolution. In addition to permitting direct assessment of the atomic and dynamical mass, H i imagery retains the signature of galaxy interactions from the previous Gyr, rather than only providing a snap-shot of gas content. However, current instrumentation permits H i detection and imaging in only the very local universe. It will require some two orders of magnitude greater instantaneous sensitivity to push back the H i frontier to the early universe.

Realization of the complete SKA is envisioned to take place by about 2020. However, a series of path-finding instruments will become available as early as 2009, and these should pave the way for a 10% SKA by about 2015. What exactly might these instruments make possible and what types of surveys might be optimally pursued with each? In this short contribution we will consider this question from the perspective of H i surveys.

2. Surveys

The complete SKA is currently specified as providing 20000 m^2/K of effective sensitivity (between at least 0.5 and 5 GHz) with an instantaneous FOV significantly exceeding 1 deg^2 at low frequencies. About 25% of the collecting area is envisaged to be within a region of 1 km diameter, 50% within 5 km, and 75% within 150 km. For simplicity, we will assume that the effective sensitivity of the complete SKA for H i galaxy surveys will be about 10000 m^2/K at all frequencies, while applications requiring the highest brightness sensitivity will have 5000 m^2/K. This should be accurate out to at least z = 3, since at lower frequencies it will be possible to use longer baselines without over-resolving targets, but will certainly no longer apply at z = 6, without a higher sensitivity than currently envisaged between 200 and 300 MHz.

The currently funded path-finder instruments: APERTIF (APERture Tile In Focus) in the Netherlands, xNTD (the eXtended New Technology Demonstrator) in Australia and KAT (Karoo Array Telescope) in South Africa each amount to about a 1% SKA in terms of their surveying power. APERTIF, by placing Focal Plane Array (FPA) receivers in each of the 14 dishes of 25 m diameter that make up the WSRT array will provide 100 m^2/K sensitivity over a 8 deg^2 FOV; while each of xNTD and KAT is planned to provide about 50 m^2/K sensitivity over a 22 deg^2 FOV. Since survey speed scales as BW×FOV×Sens^2, all three of these systems will provide similar survey performance, given a similar instantaneous bandwidth of about 300 MHz and frequency tuning range of at least 850 to 1700 MHz.

The distinguishing features of these SKA path-finders are: (1) simultaneous, wide-field, wide-band data acquisition, followed by (2) parallel multi-topical astrophysical analysis. Specialized science teams (continuum, polarimetry, spectral line, transients, etc.) will capitalize on the full survey potential and maximize the scientific return on these instrument investments. This should permit world-class science to be carried out in the decade preceding full SKA deployment.

Some of the major scientific themes that drive H I science to higher sensitivities are:

1. Quantifying the evolving gas content as well as the baryonic power spectrum of galaxies by detecting statistical samples spanning the widest possible range of red-shifts.
2. Witnessing galaxy formation and evolution via resolved imaging studies at the highest possible look-back times.
3. Imaging the local cosmic web by pushing back the N_{HI} frontier into the optically thin (to ionizing photons) regime below 10^{18}cm^{-2}.

We have assessed the types of H I surveys which might be carried out to address these three science themes by instruments having 1, 10 and 100% of the full SKA sensitivity (taken to be 10000 m^2/K for galaxy surveys and 5000 m^2/K for the low N_{HI} application) in order to determine their relative and absolute utility. We have assumed an unevolved HIPASS HIMF (Zwaan et al. 2003) at all red-shifts to allow a conservative prediction of galaxy detection rates. We further assume that the effective line-width of the H I signal is given by $\Delta V(M_{HI}) = 0.105 M_{HI}^{1/3}$ in statistical agreement with local galaxy populations. The assumed cosmological parameters are $H_0 = 73$ km/s/Mpc, $\Omega_m = 0.24$ and $\Omega_\Lambda = 0.76$. We also assume that the facility has a instantaneous FOV of 8 deg^2 independent of frequency (as will be the case for APERTIF) and then consider surveys which cover a total area on the sky of 8000, 800, 80 and 8 deg^2. The total observing time for each survey was 1000 days for the 1% SKA cases and 100 days for 10 and 100% SKA cases. As will be seen below, these appear to be realistic survey durations to reach interesting depths.

The galaxy results are summarized in Tables 1 and 2, where we have assumed a 7σ threshold (at a velocity resolution matched to the line-width) for simple detection and a 100σ threshold for imaging. This second criterion stems from allowing for some 10's of high significance resolution elements across each source. We tabulate the (base 10) logarithm of the number of detections (rounded to the nearest integer) of each survey in a sequence of red-shift bins.

Several of the detection surveys are illustrated in more detail in Fig. 1. The number of detections per half dex H I mass bin are plotted in the figure. Separate curves are drawn for each of the red-shift intervals to permit assessment of the achieved mass depth in each interval. The dotted vertical line near $M_{HI} = 10^{10}$ $M_\odot$ is M^*_{HI} of the HIMF. Good sampling of a red-shift interval demands a significant detection rate down to below M^*_{HI}.

The results for low column density surveys are summarized in Table 3 where the 1σ column density sensitivity is indicated over a 20 km s^{-1} line-width for a beam size of 60 arcsec. This beam size corresponds roughly to that of the central km of an array configuration. Such a beam size might reasonably be expected to be filled with diffuse H I emission out to distances of about 30 Mpc where it subtends less than 10 kpc. At larger distances, the effective column density sensitivity will likely be diminished due to beam dilution.

Table 3. Survey Size and Cosmic Web Depth

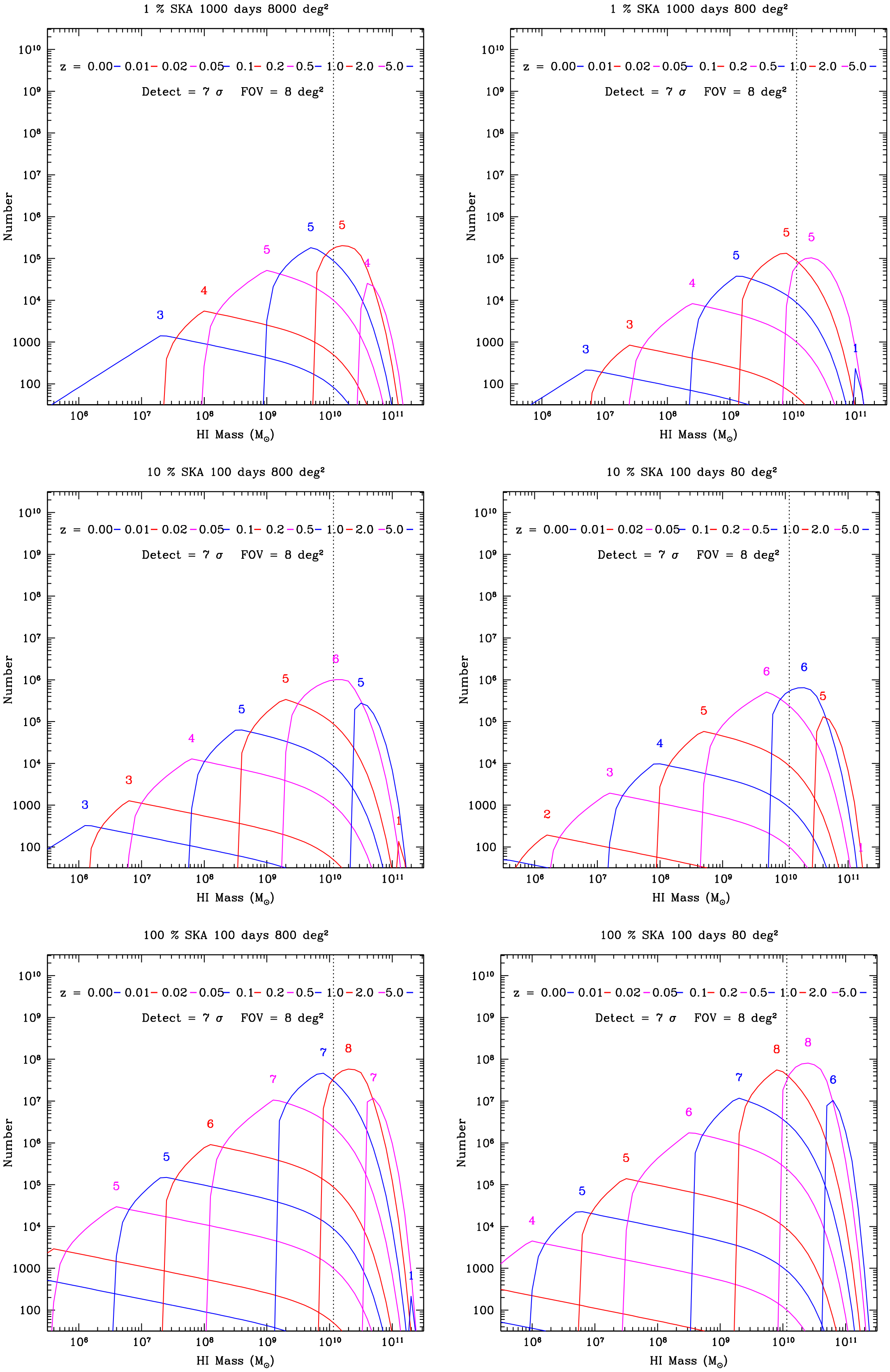
Sensitivity (% SKA)	Time (Days)	Area (deg^2)	log(ΔN_{HI}) (θ=60", ΔV=20 km/s)
1	1000	8000	18.5
1	1000	800	18
1	1000	80	17.5
1	1000	8	17
10	100	8000	18
10	100	800	17.5
10	100	80	17
10	100	8	16.5
100	100	8000	17
100	100	800	16.5
100	100	80	16
100	100	8	15.5

3. Conclusions

Achieving interesting H I galaxy sample sizes with 1% SKA surveys requires very substantial survey durations, of about 1000 days. Good sampling (log(N)$\sim$5 down to below M^*_{HI}) can then be achieved out to z = 0.2 over 8000 deg^2 or even to z = 0.5 over 800 deg^2 as shown in Table 1. The same surveys would permit the resolved imaging of order 1000 galaxies in each of several red-shift bins as can be seen from Table 2 as well as detection of faint neutral filaments in the vicinity of galaxies with a logarithmic column density RMS of 18.5 or 18 (from Table 3). This should be compared with the current detection threshold in all but the deepest H I imaging surveys of about 10^{19}cm^{-2} over ΔV = 20 km s^{-1}. Since the surface area of diffuse H I is known to increase by a factor of three for each decade of column density in this regime (from the statistics of QSO absorption lines, cf. Braun & Thilker 2004) it is clear that the first step towards systematic mapping of the diffuse H I filament distribution will be achieved in such surveys. Simultaneous with the various H I, OH and other spectral line applications that would be served by these surveys are the continuum, polarimetric and variability applications that other members of a survey science team would exploit.

The very long survey durations, underline the great utility of having several of such 1% SKA path-finders operational in the same timeframe; APERTIF in the North and xNTD and KAT in the South. Complimentary surveys could then be carried out by the different facilities to maximize the total scientific return.

Once 10% SKA sensitivities are achieved, then ground-breaking surveys are possible with only 100 day duration.


1 % SKA 1000 days 8000 deg²

1 % SKA 1000 days 800 deg²

10 % SKA 100 days 800 deg²

10 % SKA 100 days 80 deg²

100 % SKA 100 days 800 deg²

100 % SKA 100 days 80 deg²

Fig. 1. Detected numbers of galaxies as a function of their H I mass for representative surveys. The different curves correspond to the red-shift intervals indicated at the top of the plots. The logarithm of the integrated number of detections in a red-shift interval is indicated by the integer above the peak of each curve. A detection threshold of 7σ is assumed and an instantaneous FOV of 8 deg^2. The dotted vertical line is M^*_{HI}. The label above each panel gives the survey sensitivity, duration and total area.

Table 1. Survey Size and Detection Results

Sensitivity (% SKA)	Time (Days)	Area (deg^2)	log(Number Detections) in z-range $> 7\sigma$ 0–0.01	0.01–0.02	0.02-0.05	0.05–0.1	0.1–0.2	0.2–0.5	0.5–1	1–2	2–5	>5
1	1000	8000	3	4	5	5	5	4	-	-	-	-
1	1000	800	3	3	4	5	5	5	1	-	-	-
1	1000	80	2	2	3	4	4	5	4	-	-	-
1	1000	8	1	1	2	3	4	5	5	4	-	-
10	100	8000	4	4	5	6	6	6	2	-	-	-
10	100	800	3	3	4	5	5	6	5	1	-	-
10	100	80	2	2	3	4	5	6	6	5	1	-
10	100	8	1	2	3	3	4	5	5	6	5	-
100	100	8000	4	4	5	6	7	8	8	7	3	-
100	100	800	3	4	5	5	6	7	7	8	7	1
100	100	80	2	3	4	5	5	6	7	8	8	6
100	100	8	1	2	3	4	5	6	6	7	8	8

Table 2. Survey Size and Imaging Results

Sensitivity (% SKA)	Time (Days)	Area (deg^2)	log(Number Detections) in z-range $> 100\sigma$ 0–0.01	0.01–0.02	0.02-0.05	0.05–0.1	0.1–0.2	0.2–0.5	0.5–1	1–2	2–5	>5
1	1000	8000	3	3	3	2	-	-	-	-	-	-
1	1000	800	2	2	3	3	2	-	-	-	-	-
1	1000	80	1	2	3	3	3	1	-	-	-	-
1	1000	8	1	1	2	2	3	2	-	-	-	-
10	100	8000	3	3	4	4	3	-	-	-	-	-
10	100	800	2	3	4	4	4	2	-	-	-	-
10	100	80	2	2	3	3	4	3	-	-	-	-
10	100	8	1	1	2	3	3	4	2	-	-	-
100	100	8000	4	4	5	5	6	5	-	-	-	-
100	100	800	3	3	4	5	5	6	4	-	-	-
100	100	80	2	2	3	4	5	5	5	4	-	-
100	100	8	1	2	3	3	4	5	5	5	3	-

Sample sizes of log(N)$\sim$6 extending below M^*_{HI} are possible over 800 deg^2 out to z = 0.5 and over 80 deg^2 out to z = 1. Such surveys will permit very competitive measurement of acoustic oscillations in the galaxy power spectrum (e.g. Blake & Glazebrook 2003). Given the more modest survey duration (relative to the 1% SKA case), one can envision a series of surveys probing different depths. The diffuse H I sensitivity is such ($\sim 10^{17}$cm^{-2}) that the next factor of three in sky area will become accessible to imaged detection and kinematic study of the cosmic web.

With the 100% SKA sensitivity the capabilities are truly phenomenal. Survey sample sizes in the range log(N) = 7–8 are feasible over the red-shift range of 0.2 to about 5. The SKA will easily be the most productive redshift engine in astronomy. This finally brings H I imaging into completely new terrain. Precise tracking of potential time evolution of dark energy (via the baryonic acoustic oscillation signature) should be possible out to z $\sim$ 3. The local cosmic web will be imaged down to $N_{HI} = 10^{16}$cm^{-2}. What exactly will be seen at z >3? This will depend crucially on the SKA sensitivity in the critical frequency window of 350 to 200 MHz. If this can be maintained at the level of 10000 m^2/K, then the prospects are extremely good for detecting large populations of early universe objects. Given the very low cost of collecting area in this frequency range, this seems to be a very worthwhile area for investment.

References

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