HI Science with MeerKAT

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1. Introduction

The evolution of HI in the universe is one of the key science drivers for the effort to build the Karoo Array Telescope (MeerKAT) and subsequently the Square Kilometer Array (SKA). Ultimately, we want to understand its evolution over cosmic times and the star-formation cycle within galaxies themselves. The HI science drivers can be divided into:

- Obtain the HI mass function in the nearby and distant Universe (up to $z \sim 0.5$).
- Find the HI content of the Universe, Ω_{HI} out to high redshift ($z \sim 1$).
- Identify and quantify gas inflow into galaxies; the "cold accretion".
- Group dynamics of galaxies and faint member statistics and properties.
- Search for the markers of CDM in the HI distribution of nearby galaxies; their dynamics and starformation cycle.
- Map parts of the Cosmic Web in HI.
- Identify the Great Attractor in the Zone of Avoidance.

Following is a brief sketch of projects that could be undertaken with MeerKAT to address these drivers. These descriptions are not meant to be exhaustive, but hopefully give a good idea of the kind of HI science at which MeerKAT will excel, and should form the basis of a set of concrete proposals involving the international community.

2. Galaxies, Star Formation and the Cosmic Web

The proposed configuration of MeerKAT enables studies of galaxies in the Local Volume both at the high resolution needed to investigate the links between gas and star formation, as well as the high sensitivity needed to study the outer parts of disks, the presence of accreting gas, and the possible link with the cosmic web. We define the Local Volume as a volume within 20 Mpc of the Milky Way. This is the practical limit of stellar population studies with the James Webb Space Telescope.

Detailed, high-resolution (sub-kiloparsec) and high-sensitivity observations of the Interstellar Medium (ISM) in Local Volume galaxies are crucial for understanding the internal dynamics of galaxies and their link with predictions resulting from Lambda Cold Dark Matter cosmology. There is currently disagreement between the predictions of CDM simulations and observations and tracing the source of these discrepancies requires a detailed knowledge of the dynamics of galaxies over a wide range of galaxy properties.

Star-formation processes regulate the conversion of gas to stars and so ultimately link the inflow of gas from the cosmic web to the stellar distribution in galaxies. Understanding them is central to a complete picture of galaxy evolution. Sensitive, high-resolution, high-fidelity observations of the HI 21-cm line are the best way to trace the distribution and kinematics of the neutral ISM in galaxies.

Last year saw the completion of THINGS (The HI Nearby Galaxy Survey; Walter et al. 2008), which obtained 21-cm line maps of 34 nearby galaxies that were also targets of the Spitzer Legacy program SINGS and the GALEX Nearby Galaxy Survey. THINGS, uniquely, included the VLA B-array in its observations, thus yielding angular resolutions of $6''$ to $10''$.

Its results clearly demonstrated the power of obtaining these high-resolution 21-cm observations and combining them with multi-wavelength (particularly infrared and UV) data to probe galaxy evolution and physical processes in the ISM (see Figure 1). THINGS, however, observed and analysed only 34 galaxies, which were specifically selected to be non-interacting, late-type, and known to have an extended HI disk. For a more complete census of the properties of local galaxies this work needs to be extended to more galaxies over a larger range of properties and environments. This is particularly relevant with the advent of future surveys, such as will be produced by the Herschel Space Telescope, JWST, SkyMapper and LSST, to name but a few. The presence of major optical, IR and sub-mm telescopes in the southern hemisphere also make MeerKAT an ideal telescope to provide a catalog of detailed HI observations of nearby galaxies.

Lower resolution observations (but correspondingly better column density sensitivity) enable us to explore the low column density universe. The structure of the outer parts of galaxy disks, the nature of their stellar populations and the kinematics of their gaseous component are central to understanding the formation and evolution of galaxies. It is well known that the outer HI envelopes of galaxies are easily affected by galaxy interactions, which result in the removal, distortion, and/or reaccretion of the outermost gas. The infall of this this, possibly in combination with primordial, unprocessed gas clouds is a process known as "cold accretion" (Sancisi et al. 2008).

Galaxies are not "island universes". They do not exist in isolation, but are found aligned in a three-dimensional large scale structure web of filaments, knots, groups and clusters. It is now reasonably certain that the majority of the baryons do in fact not reside in galaxies, but are found outside galaxies spread along this so-called "Cosmic Web". The material is however tenuous, the neutral fraction is small. It has been seen in a few lines of sight as absorption features against background sources. A direct detection of the Cosmic web would significantly improve our understanding of the baryon content of the universe. It may for example be the source of the HI seen around galaxies which takes part in the so-called cold accretion process. A recent observation by Braun (2004) suggests that some very low column density HI detected which connects M31 and M33 may in fact be the "Local Cosmic Web" (see also Braun & Thilker 1994). The material has column densities around 10^{17-18} cm^{-2} and shows what kind of detection levels any survey of the Cosmic Web should be aiming for.

Most of the Local Volume science can be addressed by obtaining deep integrations of a number of nearby galaxies. The detection of low column densities will be the factor that sets the integration time. Assuming a 25 km s^{-1} channel spacing (which is the typically expected linewidth of an HI line), one would need to integrate ~ 200 hours for a 5σ detection of a $10^{17.5}$ cm^{-2} signal at a resolution of $\sim 80''$. Assuming only night-time observing, this means that a direct detection of the low-column density gas at the level of the cosmic web detection by Braun (2004) can be done for a different galaxy every two weeks, thus rapidly enabling comparisons of morphology and properties of the low column density gas for a wide range in Hubble type. For a $10''$ beam this will result in a limit of $\sim 5 \cdot 10^{19}$ cm^{-2}, enabling full and detailed mapping at sub-kpc resolution for any galaxy within 20 Mpc with the same observations.

Depending on the flexibility of the correlator and the presence of background sources these observations could also be used to probe the low column density universe at high redshifts using HI absorption.

3. Groups and Clusters of Galaxies

Much of galaxy evolution is driven by environment. With other telescopes (such as ASKAP) providing the large-scale maps of the general HI distribution in groups, the column density sensitivity of MeerKAT will enable studying some of these environmental processes in great detail, as well as increase the chances of detecting the signatures of the predicted CDM satellites through e.g., HI streams or direct detection.

Many candidate groups and clusters lend themselves to such a study. As evolutionary processes probably depend on the density of the local environment, it will be necessary to study multiple groups or clusters. Obvious candidates are the southern extension of the Virgo cluster, the extension of Canes Venatici, the Sculptor Group or the Centaurus group, with many others possible. Scientific arguments should define the optimum choice of number of groups as well as the survey area per group. Below we present an example using the Scl group, but as stated, many alternatives are possible (and desired)

3.1. Sculptor: a case study

Because the Scl galaxy distribution is rather sparse, these galaxies have had very little interaction with each other. We therefore also expect to find very extended HI envelopes around these objects. Proper characterization of the HI at the edges of these galaxies will help us understand the physical processes involved in galaxy evolution, and the role of environment within it, similar to the galaxies in the Local Volume program. Scl is also known to contain a large number of HI-rich dwarf galaxies, even in the early-type category. A blind survey increases our chance to find new Low Surface Brightness (LSB) dwarf galaxies. This would be crucial to constrain the faint end of the HI mass function in the Local Universe, where there are large discrepancies (an order of magnitude) between theoretical predictions and observations. Currently, the observed mass function has a cutoff at $\sim 10^7\ M_\odot$.

An example of the kind of group studies possible with MeerKAT would be a blind HI survey of a strip through the Sculptor group in search of its neutral intergalactic medium. Taking a 6 $\times$ 24 degrees region (9 $\times$ 36 pointings, to ensure Nyquist sampling), the survey region would start from NGC 300 and follow a strip of sky in the presumed direction of the Local Cosmic Web (Figure 3). Assuming an antenna efficiency of 0.7 and a correlator efficiency of 1.0, an 8 hour integration with MeerKAT gives a 3σ detection of a $10^5\ M_\odot$ for galaxies at $\sim$ 5 Mpc with a linewidth of 20 km s^{-1}. The full 6 $\times$ 24 degrees mosaic would therefore take approximately 2600 hours of observation time.

A much shallower but wider mosaic (720 pointings with 4 hours per pointing) of the Sculptor Group with the KAT-7 array would take 2880 hours (120 days). This mosaic would be a first look survey, later to be expanded and refined with MeerKAT's improved sensitivity and resolution. Alternatively, depending on timelines, the wide-field capabilities of the Australian ASKAP could be used to identify interesting survey areas.

4. HI over Cosmic Time

Investigation of galaxy formation and evolution and the formation of large scale structure in the Universe over cosmic time is one of the key sci-

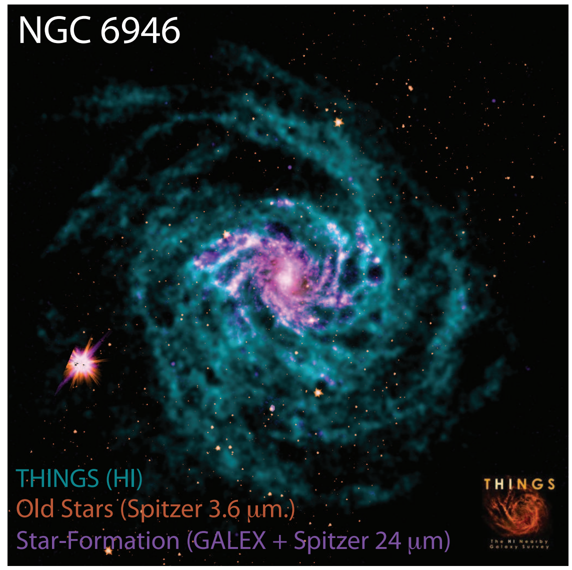

Fig. 1.— The THINGS/SINGS/GALEX color composite of NGC 6946, illustrating the benefits of the multi-wavelength approach to nearby galaxies; the fuel (HI), star-formation (both Spitzer and Galex observations) and the old stellar disk (Spitzer).

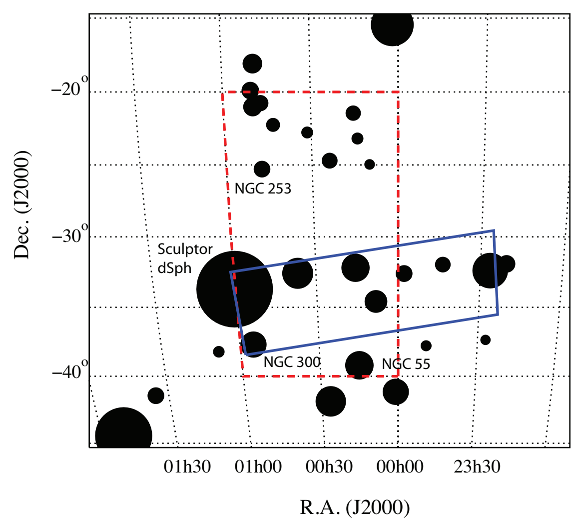

Fig. 2.— A possible survey area of the Sculptor Group. Galaxies are dots scaled inversely proportional to their distance, with the Sculptor Dwarf Spheroidal the closest (80 kpc). The red dashed area is the shallow mosaic considered for KAT-7 and the solid blue area is a possible MeerKAT strip survey.

ence goals of the Square Kilometer Array (SKA) project. HI provides the fuel for galaxy formation and evolution, and it is therefore important to measure how the cosmic neutral gas density and HI content of galaxies vary as a function of lookback time.

The HI mass function in the local Universe ($z < 0.04$) has been well measured down to masses of $\sim 10^7\ M_\odot$ (Zwaan et al. 2005). However, it is yet unknown how this distribution varies with redshift. Hierarchical structure formation models predict an evolution in the shape of the HI mass function with lookback time which would differ from that observed in the local universe and also from that implied by models involving structure formation through accretion along gas filaments. A deep HI survey with MeerKAT will allow probing the HI mass function at higher redshifts and will also allow us to estimate the cosmic neutral gas density which is currently ill-constrained at redshifts between $0.2 < z < 2$. HI has been measured at redshifts $z > 1.5$, using damped Lyman-α absorption observations in QSO spectra (Storrie-Lombardi & Wolfe 2000; Prochaska et al. 2005). However, it is still unclear how HI evolves from these high redshifts to the local Universe.

A deep HI survey with MeerKAT would probe the HI mass function at intermediate z and simultaneously measure Ω_{HI} at a range of redshifts between $0.2 < z < 1$. To date, the highest redshift galaxies observed in HI emission are at $z = 0.2$ (Verheijen et al. 2007).

With such a survey measurements of the HI Mass Function at higher redshift will be possible. Figure 5 shows the expected HI mass distribution (to a 5σ level) for survey times of 1 year, 6 months and 3 months for the redshift range $0.2 < z < 0.3$. These numbers will be sufficient to make initial estimates of the HI mass function at higher redshifts than has been possible previously. In one year of observing at a single pointing, MeerKAT would retrieve nearly 10^4 galaxies up to a redshift of 0.3.

Statistical measures of the gas density at different redshift can also be determined using the stacking technique. The advantage of this technique is that high signal-to-noise detections of individual galaxies are not necessarily required. See e.g. Chengalur et al. (2001); Verheijen et al. (2007) and Lah et al. (2007). This method involves surveying galaxies in HI whose redshifts have been previously spectroscopically confirmed by other means (e.g., a large optical survey). We can use this information to shift even very low signal-to-noise spectra (which would not on their own constitute a reasonable detection) such that all the spectral lines fall into a common channel and then stack the spectra to produce an average spectrum (Figure 6). Since spectroscopic redshifts are required for this technique, the HI survey will need to overlap with an existing or near-future redshift survey field. A possible candidate is the COSMOS field, focus of the zCOSMOS-bright survey (Lilly et al. 2007) which aims to measure redshifts for $\sim 20\,000$ galaxies with $0.1 < z < 1.2$ in a 1.7 deg^2 area in the equatorial region. This survey would match well with the ~ 1 deg^2 field-of-view of MeerKAT as well as being accessible from the southern hemisphere (See Figure 7). An alternative could be the GEMS survey (Rix et al. 2004) in the Chandra Deep Field South field. The multi-wavelength coverage of this field is substantial (Chandra, Spitzer, Galex and HST) and the COMBO-17 redshift estimates are readily available. The LSST consortium is currently selecting deep fields, with both COSMOS and GEMS positions under consideration.

5. Zone of Avoidance

The observed velocity flow of galaxies in the nearby Universe is dominated by the Great Attractor (Dressler et al. 1987; Lynden-Bell et al. 1988; Tonry et al. 2000) and the ~ 3 times more distant Shapley Supercluster (Hudson et al. 2004). Both are extended overdensities in the large-scale mass distribution of the local Universe and both are thought to contribute significantly to the peculiar motion of the Local Group (Lucey et al. 2005; Kocevski & Ebeling 2006). The relative contribution of the Great Attractor and the Shapley supercluster to the motion of the Local Group, however, remains poorly determined and is still a matter of debate. MeerKAT will be superbly positioned to observe distant galaxies in the Zone of Avoidance, the plane of our Milky Way, to probe the large scale structure beyond. It will be an ideal tool to probe the Great Attractor (GA)/Shapley (SH) controversy; which of these large scale structures is the dominant gravitational attractor in the local Universe?

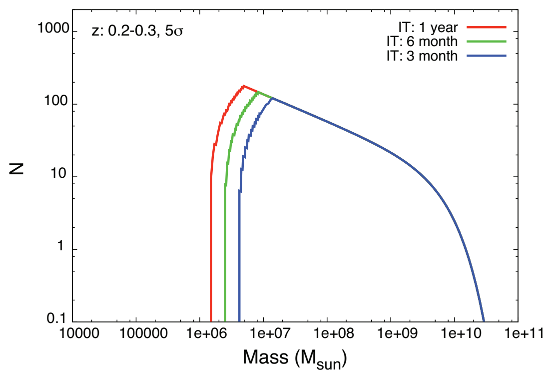

Fig. 3.— Number of galaxies detected to the 5σ level (in redshift range $0.2 < z < 0.3$) vs. observational mass limit for different survey scenarios with MeerKAT. Detection numbers are given in steps of 0.1 in $\log(M_{HI})$.

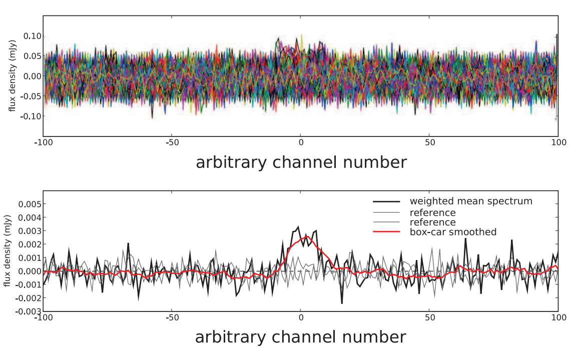

Fig. 4.— Illustration of the stacking method for a 6 month integration at $z = 0.7$. The top panel shows the 1 000 raw spectra shifted so that all the HI lines are centered at channel zero. The bottom panel shows the resulting weighted average spectrum (thick black line) after co-adding. The grey lines are reference spectra computed by randomly shifting the spectra in the top panel and then coadding them. The red line shows the weighted average spectrum after box-car smoothing.

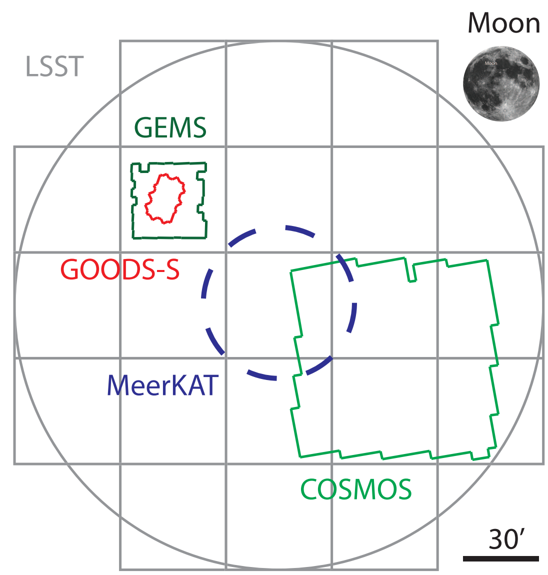

Fig. 5.— The Field-of-View of MeerKAT (1 deg diameter) in comparison with the GEMS/GOODSSouth (green and red) and COSMOS (green) survey fields. The LSST footprint and the Moon are shown for comparison. The GEMS field features multi-wavelength coverage, a field neatly covered by the MeerKAT FoV and a southern lattitude. The COSMOS field would need multiple MeerKAT pointings.

In order to resolve the Great Attractor controversy, the next HI survey will need to be a substantial improvement over existing ones: an improvement of 2 orders of magnitude in sensitivity, better spatial resolution (at least $0.5'$ to $1'$), a wider instantaneous bandwidth with an increased number of channels, and a larger FOV for survey speed. Figure 8 shows the number counts per redshift and the HI mass function for simulated ZOA surveys for two different integration times per pointing (0.5 hr and 2 hr). KAT-7 will not be able to improve significantly over existing results but a 30-dish MeerKAT configuration will already allow for significant initial results with a modest investment of time (2 hour integration per pointing, a survey of 42 days). Such a survey will trace galaxies into the dwarf regime ($M_{HI} = 10^{7.8}\ M_{\odot}$) in the Great Attractor and one order of magnitude below the characteristic HI-mass of $10^{9.8}\ M_{\odot}$ in the Shapley overdensity. The full MeerKAT will complete the same survey in only 10 days (30 min of integration per position).

6. Combining surveys

The characteristics of the MeerKAT correlator (512 MHz bandwidth, upgrade to 1024 MHz, variable resolution in each band) and the relative transparency of the Universe to 21-cm emission, opens the possibility to conduct a survey at different redshifts in the same field. Strategic target selections would result in data sets that contain a nearby galaxy in the foreground, a galaxy group at intermediate redshift, and a cluster at high redshift. This would allow aspects of all projects described above to be addressed with a single observation.

7. Summary

The HI science goals discussed above could thus be pursued with the following projects.

- Mosaic of (part of) a nearby group or cluster; a survey of the local cosmic web and a laboratory for the group environment for galaxy evolution/properties.
- The MeerKAT Deep field(s); deep pointings to characterize the HI mass function at intermediate redshift and the HI content of the

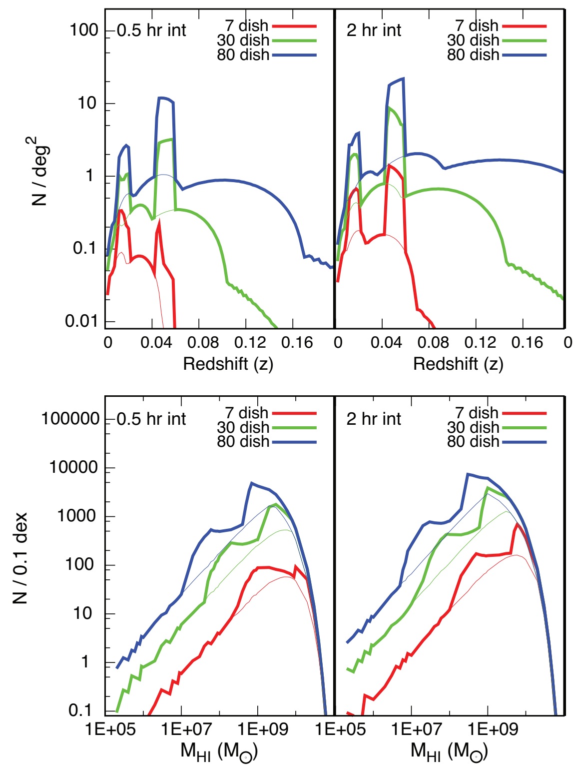

Fig. 6.— Top: projected galaxy sky density versus redshift. The double bumps are the Great Attractor and Shapley Cluster respectively. Bottom: the HI mass function. Left panels are for 0.5 hour integration per pointing and the right panels for 2 hours integration. MeerKAT stages are the initial seven dishes KAT-7 (red), halfway through construction (30 dishes, green) and the complete instrument (80 dishes, blue).

Universe at high-redshift, stacking galaxies with spectroscopic redshifts.

- Galaxy portraits: deep observations of selected galaxies to detect the cosmic web column densities. Tuning the data to higher resolutions will result in high-resolution Hi maps of these galaxies with sub-kpc resolution out to 20 Mpc.

- A mosaic of large scale structure in the Zone of Avoidance; an unequivocal identification of the identity of the great attractor.

References:

Braun, R. 2004, New Astronomy Review, 48, 1271
Chengalur, J. N. et al. 2001, A&A, 372, 768
Dressler, A. et al. 1987, ApJ, 313, L37
Hudson, M. J. et al. 2004, MNRAS, 352, 61
Kocevski, D. D., & Ebeling, H. 2006, ApJ, 645, 1043
Lah, P. et al. 2007, MNRAS, 376, 1357
Lilly, S. J. et al. 2007, ApJ Suppl., 172, 70
Lucey, J. et al. 2005, in Astronomical Society of the Pacific Conference Series, Vol. 329, Nearby Large-Scale Structures and the Zone of Avoidance, ed. A. P. Fairall & P. A. Woudt, 21-+
Lynden-Bell, D. et al. 1988, ApJ, 326, 19
Prochaska, J. X. et al. 2005, ApJ, 635, 123
Rix, H.-W. et al. 2004, ApJS, 152, 163
Sancisi, R. et al. 2008, A&A Rev., 15, 189
Storrie-Lombardi, L. J., & Wolfe, A. M. 2000, ApJ, 543, 552
Tonry, J. L. et al. 2000, ApJ, 530, 625
Verheijen, M. et al. 2007, ApJ, 668, L9
Walter, F. et al. 2008, AJ, 136, 2563
Zwaan, M. A. et al. 2005, MNRAS, 359, L30