MIGHTEE: The MeerKAT International GHz Tiered Extragalactic Exploration

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Abstract. The MeerKAT telescope is the precursor of the Square Kilometre Array mid-frequency dish array to be deployed later this decade on the African continent. MIGHTEE is one of the MeerKAT large survey projects designed to pathfind SKA key science in cosmology and galaxy evolution. Through a tiered radio continuum deep imaging project including several fields totaling 20 square degrees to microJy sensitivities and an ultra-deep image of a single 1 square degree field of view, MIGHTEE will explore dark matter and large scale structure, the evolution of galaxies, including AGN activity and star formation as a function of cosmic time and environment, the emergence and evolution of magnetic fields in galaxies, and the magnetic counterpart to large scale structure of the universe.

1. Introduction
The MeerKAT radio telescope is nearing completion on the Karoo desert in South Africa. MeerKAT is a precursor of the Square Kilometre Array mid-frequency dish array (SKA1-mid), and following several years of operation as a South African telescope, it will be incorporated into the SKA phase 1 facility. The first 32 elements of MeerKAT will be released for shared-risk science programs in 2017, and the full array is expected to be operational by early 2018.

The MeerKAT science program will consist primarily of key science, legacy-style Large Survey Projects (LSPs). The LSPs are direct pathfinders of key science projects and observations being planned for the SKA mid-frequency array. The MeerKAT International GHz Tiered Extragalactic Exploration project (MIGHTEE) is one of the approved MeerKAT LSPs, with the aim to explore the high-redshift radio universe with very deep, broad-band, wide-field, radio continuum and spectral line imaging. This paper briefly describes the MIGHTEE observing plan and science goals.

2. Observing Plan
2.1. MeerKAT
MeerKAT is 64-element array of 13.5-m parabolic antennas laid out in a centrally concentrated configuration with a maximum baseline of about 8 km. Forty-eight of the antennas are situated in a central 1-km diameter core. The antennas have offset Gregorian optics, providing an
Table 1. MeerKAT Imaging Specifications

| Frequency Band | Resolution (arcseconds) | Field of View (degrees) | RMS noise in one hour (microJy) |
|----------------|-------------------------|-------------------------|--------------------------------|
| 1.75 – 2.50 GHz| 4                       | 0.65                    | ~5                              |
| 0.90 - 1.67 GHz| 6                       | 1.1                     | 4.7                             |
| 0.58 - 1.01 GHz| 10                      | 1.75                    | 9.0                             |

unobstructed radiation path to the primary reflector and very high forward gain, low-sidelobe levels and excellent aperture efficiency.

The relatively small diameter of the MeerKAT antennas coupled with the large number of antennas and large total collecting makes it a powerful wide-field imaging instrument, with a combination of large field-of-view, wide-bandwidth, high sensitivity and outstanding sampling of the Fourier transform of the sky with 2016 instantaneous baseline samples. Imaging specifications of MeerKAT for the frequency ranges that will be used for the MIGHTEE project are listed in Table 1. At the lowest frequency band the bandwidth is limited by the available RF to 440 MHz. At the mid- and high-frequency bands the digitizer captures an instantaneous bandwidth of 770 MHz. The correlator provides four correlation products, allowing imaging in all polarization products.

2.2. Observations

MIGHTEE will use the imaging capabilities of MeerKAT to carry out a tiered exploration of the extragalactic sky via a tier-1 medium deep survey to an rms noise level of about 1 microJy over 20 deg², and a tier-2 ultra-deep survey to about 200 nanoJy over 1 deg². With up to 32,768 channels, each 3.27 kHz wide, MIGHTEE data cubes will image both the broad-band spectro-polarimetric properties of continuum emission from galaxies and the narrow-band emission from the spectral line of atomic hydrogen.

The tier-2 survey will be observed commensally with a deep HI spectral line survey (LADUMA). It will comprise a single pointing of the Chandra Deep Field South (CDFS) covering the FoV of the telescope at the two lowest bands. For a planned total of 330 hours of integration at the mid-band (0.9 – 1.67 GHz) MIGHTEE will achieve a theoretical rms noise of 260 nanoJy. At the low band (0.58 – 1.0 GHz) 3090 hours of integration will provide a full-band image with rms noise of 160 nanoJy.

The 20 deg² medium deep tier-1 survey has a planned total observing time of 1920 hours distributed over four fields: the XMM-LSS (6.7 deg²), E-CDFS (8.3 deg²), ELAIS-S1 (1.6 deg²) and the COSMOS field (1 deg²). XMM-LSS, E-CDFS and ELAIS-S1 will be covered by mosaicking of multiple pointings as illustrated in Fig 1. XMM-LSS will be observed at the mid-frequency band only. We will cover 4 deg² of E-CDFS and the COSMOS field with both the mid- and high- bands, providing increased sensitivity and resolution and total bandwidth of 0.9 – 2.5 GHz.

Multi-wavelength information is crucial to the science goals of MIGHTEE. Each of the chosen fields has extensive ancillary information from optical and infrared imaging surveys. The layout of the radio coverage of each field was chosen to maximize overlap with such surveys. Rectangular and circular regions in Fig. 1 indicate coverage by the VEILS (pink), VIDEO (blue) and DES (white) image sets.
Figure 1. Pointing strategies for the three mosaic imaged MIGHTEE fields. Left: XMM-LSS (20 pointings, 6.7 deg$^2$). Middle: E-CDFS (24 pointings, 8.3 deg$^2$). Right: ELAIS-S1 (7 pointings, 1.6 deg$^2$). The yellow shaded circles indicate the pointing locations and primary beam areas of the MeerKAT observations. Figure compliments of Ian Heywood.

3. MIGHTEE Science
In concert with multi-wavelength data the MIGHTEE radio spectro-polarimetric continuum and spectral-line image cubes are designed to provide a unique and powerful data set to address scientific questions in large-scale structure and cosmology, galaxy evolution, and cosmic magnetism.

3.1. Large-Scale Structure and Cosmology
The depth and breadth of the MIGHTEE and will also allow us to measure the cosmological bias, e.g. how radio sources of different types (e.g. star forming galaxies, radio galaxies, AGN) trace the underlying dark matter distribution. It is crucial to do this in fields with the best multi-wavelength data as it allows us to accurately disentangle the different types of sources, whilst obtaining the required number density (at least of all types of source apart from FRIs, which are intrinsically rare).

MIGHTEE will yield a grid of Rotation Measures (RM) toward background sources with sufficient area density and precision to detect and measure the properties of magnetic fields embedded in the large-scale structure - the magnetic cosmic web. Simulations predict that the IGMF in filaments would induce excess Faraday Rotation Measures with a flat second-order structure function (SF) of $\sim$100 rad$^2$ m$^{-4}$ for angular separation of $r > 0.1$ deg. The power from this contribution to the RM structure function will be distinguishable from the foreground of the Milky Way galaxy on angular scales smaller than a few degrees [1]. MIGHTEE will probe this structure function with the required number density and precision, and over angular scales of a few arcminutes to several degrees, offering our best opportunity before the SKA to use this technique to detect the magnetic cosmic web.

The coherent distortion of distant galaxy shapes due to the gravitational effect of dark matter (weak lensing) is one of the most powerful probes of dark matter and dark energy. Radio polarization position angle provide unique information on the intrinsic (unlensed) shape of background galaxies that is unaffected by lensing. This effect can be used to mitigate the primary error in weak lensing experiments.
3.2. Galaxy Evolution
While the stellar properties of galaxies spanning the full range of masses over a large range of redshifts have been well studied, our knowledge of the neutral gas (HI) content of these same galaxies is restricted to the local universe. If we hope to understand the build-up of stellar mass, we must observe the neutral gas reservoir of fuel from which the molecular gas forms, eventually turning into stars, along with the interface between this gas and the galaxies and environment in which it is located. MeerKAT will open up new parameter space in the study of the neutral gas component of galaxies.

Galaxies follow known scaling relations, such as the so-called star-formation main sequence [2; 3] relating star formation with stellar mass. Underlying these relations is a complex cycle of acquisition, storage, consumption, expulsion and re-acquisition of gas, acting to regulate a galaxy’s ability to form stars [e.g. 4]. With MIGHTEE we will not only trace the origins of the gas that eventually turns into stars, but with the extreme sensitivity to radio-continuum emission, we will also measure the end-point, namely the star-formation rate. MIGHTEE has the sensitivity and frequency coverage to detect a statistically significant number of galaxies in atomic hydrogen out to $z > 0.2$, and to measure star formation rates from continuum emission to $z > 3$. Together with optical and near-IR data we will trace the star formation history and the evolution of the ISM in galaxies over a significant fraction of cosmic time and diverse environments.

MIGHTEE will detect virtually every active radio galaxy to the edge of the universe in each field. The broad-band polarization data will allow new approaches to measuring the intrinsic properties of AGN core and jet environments.

3.3. Magnetic field in Galaxies and Clusters
Through its ability to detect polarization of sources at high redshift, MIGHTEE will be a cornerstone for investigation of the evolution of cosmic magnetic fields. For disk galaxies, this range is $z < 2.5$, and for AGN and starbursts it reaches out to $z = 7$, into the epoch of reionization. From the integrated polarization properties of galaxies we will trace the emergence and growth of coherent magnetic field in galaxies and in AGN and its relation to star formation.

It is now well established that the intracluster medium (ICM) of galaxy clusters, which is composed mainly of thermal gas emitting in the X-ray energy band, is permeated by magnetic fields over the entire cluster volume [see 5, for a review]. The MIGHTEE RM grid will enable us to probe the spatial structure function of magnetic fields within galaxy clusters, offering the best opportunity before the SKA to constrain the redshift evolution of cluster magnetic fields and providing the first opportunity to test early seed field models for the origin of cosmic magnetic fields.

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