Looking at the distant universe with the MeerKAT Array (LADUMA)

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Abstract. The MeerKAT (64 x 13.5m dish radio interferometer) is South Africa's precursor instrument for the Square Kilometre Array (SKA), exploring dish design, instrumentation, and the characteristics of a Karoo desert site and is projected to be on sky in 2016. One of two top-priority, Key Projects is a single deep field, integrating for 5000 hours total with the aim to detect neutral atomic hydrogen through its 21 cm line emission out to redshift unity and beyond. This first truly deep HI survey will help constrain fueling models for galaxy assembly and evolution. It will measure the evolution of the cosmic neutral gas density and its distribution over galaxies over cosmic time, explore evolution of the gas in galaxies, measure the Tully-Fisher relation, measure OH maser counts, and address many more topics. Here we present the observing strategy and envisaged science case for this unique deep field, which encompasses the Chandra Deep Field-South (and the footprints of GOODS, GEMS and several other surveys) to produce a singular legacy multi-wavelength data-set.

Keywords. surveys, galaxies: evolution galaxies: high-redshift galaxies: ISM galaxies: luminosity function, mass function galaxies: statistics cosmology: observations radio lines: galaxies

1. Introduction

Over the past 8 Gyr, galaxies have evolved dramatically, with the number density of luminous, blue, star-forming galaxies dropping by an order of magnitude (e.g., Bell *et al.* 2005) and the number of luminous red galaxies increasing by a similar amount (Driver *et al.* 1998; Bell *et al.* 2005). Similarly since $z \sim 1$, the star formation rate density in the Universe has plummeted by an order of magnitude (e.g., Madau *et al.* 1998; Hopkins *et al.* 2008), yet the density of neutral hydrogen (HI), the fuel reservoir for star-formation, may have remained constant (Fig. 1). Given that, locally, the overall HI mass and star-formation rate appear to be linked for galaxies (Kennicutt 1998), this points to significant redistribution of the gas reservoir over this epoch.

To complement our view of high redshift galaxy populations (the stellar, ionised, and molecular gas), a key science goal of the Square Kilometre Array (SKA Carilli & Rawlings 2004) is to explore the atomic hydrogen (HI) out to $z \sim 1$ and to explore how galaxies form and evolve. While SKA will study HI in large numbers of galaxies at $z \sim 1$, MeerKAT (Booth *et al.* 2009; de Blok *et al.* 2009), with its high sensitivity and wide instantaneous bandwidth, is the choice pathfinder instrument with which to begin the study of HI in galaxies out to redshift unity. We therefore are undertaking the LADUMA† (Looking At the Distant Universe with the MeerKAT Array) survey for a 5000 hour observation of a single field (Holwerda & Blyth 2010a,b; Holwerda *et al.* 2011a). This survey in combination with existing and planned complementary multi-wavelength

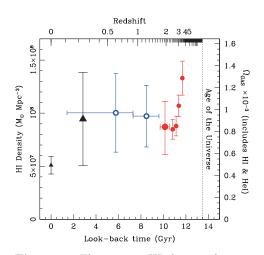† Literally, It thunders. in the Zulu language: `http://www.ast.uct.ac.za/laduma/Home.html`

Figure 1. The cosmic HI density from a variety of methods; direct HI line detections (black tringles Zwaan *et al.* 2005; Lah *et al.* 2007), and Ly-α absorption estimates (open and filled circles Rao *et al.* 2006; Prochaska *et al.* 2005; Noterdaeme *et al.* 2009, respectively).
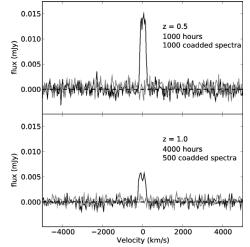

Figure 2. Simulated stacking results (black lines) for z = 0.5 (top panel) and z = 1.0 (bottom panel), ($\Delta z = 0.1$). Galaxies were simulated according to the Oxford S^3 database (Obreschkow *et al.* 2009).

observations will provide the first complete picture of galaxy evolution from $0 < z \lesssim 1.4$ and serve as a key benchmark for future studies with the SKA.

2. Observing Strategy

Target Field The Extended Chandra Deep Field-South was chosen for its wealth of multi-wavelength data and existing spectroscopy (e.g., Cardamone *et al.* 2010; Balestra *et al.* 2010) as well as continuous visibility from the MeerKAT site.

Data The final 5000 hour integration results in a trumpet-shaped data-cube†, as the primary beam widens with redshift, covering an ever larger volume with redshift.

Direct Detections & Line Stacking Given the shape of the survey volume and the gradually decreasing sensitivity with distance, our science will be done with a mix of direct detections (for low redshifts and/or high HI masses) and the stacking of multiple objects with low signal-to-noise (see also Meyer *et al. this volume*). Fig. 2 illustrates the line stacking technique. Using the known positions and redshifts of a sample of sources, their radio spectra are aligned to a common (rest) frequency frame and combined. One can determine the mean HI mass and possibly the HI profile of a sub-class of galaxies. This technique will require an order of magnitude more spectroscopic redshifts than currently available (Cardamone *et al.* 2010; Balestra *et al.* 2010).

3. LADUMA Science

The LADUMA data will address a multitude of science questions;

Cosmic Hydrogen Density (Ω_{HI}) Summing over all objects, one obtains an estimate of the *total* atomic hydrogen volume density of the Universe at a given epoch. Given that the

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† The vuvuzela is a uniquely South African trumpet primarily used for encouragement during soccer matches, as most of the world knows after the 2010 World Cup.

star-formation rate density decreases by a factor ten (Hopkins *et al.* 2008, *this volume)* and specific star-formation rate by a factor three (Noeske *et al.* 2007), over the redshift range $0 < z \lesssim 1.4$, one can expect the star-formation fuel to be depleted, but at what rate? Our direct HI observations will be compared to those Lyα and Mg II absorbers (Ménard & Chelouche 2009; Kanekar *et al.* 2009).

HI Mass Function (HIMF) is the number density of galaxies as a function of their neutral gas content (Zwaan *et al.* 2005). An accurate measurement of this quantity is an important parameter in models of galaxy evolution where processes like gas inflow and star formation are sought to be understood. Evolution in the breakpoint, slope, and normalization of the HIMF can be used to test hierarchical galaxy formation and cold flow models (van der Heyden *et al.* 2009). And finally, we can also explore environmental effects on the HIMF (Bouchard *et al.* 2009).

Galaxy Evolution The HI content of different populations as a function of redshift will place a useful constraint on our understanding of their evolution. We will address questions such as how cold gas mass depends on halo mass? what is the relation between stellar and gas mass over time(e.g., Kannappan 2004), and what is the relation between the cold gas mass and specific star-formation rate?

The Tully-Fisher Relation; Rotationally supported disks lie on the Tully-Fisher relation (Tully & Fisher 1977). For small high-redshift samples, the stellar T-F relation has been determined (e.g. Kassin *et al.* 2007; Puech *et al.* 2010), but the LADUMA data will provide HI data for the first time at higher redshift with the advantage of probing the whole disk (and consequently halo), and with sufficient statistics to determine the normalization and slope of the T-F relation at different redshifts.

Bonus Science includes the number densities and strengths of OH masers over cosmic time (see Briggs 1998), the merger rate from close companions (e.g., Holwerda *et al.* 2011b), and the possible detection of faint 21 cm absorption (e.g., the "Cosmic Web").

Concluding Remarks: The LADUMA survey promises to facilitate a range of exciting science and provide the deepest HI observations available until the SKA is commissioned.

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