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Looking at the Distant Universe with MeerKAT and SALT

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With the upcoming LADUMA (Looking At the Distant Universe with MeerKAT Array) survey we are aiming to probe the neutral atomic hydrogen (HI) content of galaxies over two-thirds of the age of the universe with the aim to investigate the role of cold gas in the evolution of galaxies over cosmic time. We will use the MeerKAT radio telescope to make these observations which will be the deepest measurements of HI in emission in galaxies prior to the SKA coming online. Here we present an overview of the scientific motivation for the survey and some of the science questions we hope to address. With many of our investigations relying on a combination of the radio observations with other multi-wavelength data, we envision that SALT, due to its location and suite of capabilities, will be instrumental in helping us to achieve our goals.

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1. Introduction

Galaxy formation and evolution are currently areas of intense study, both observationally and theoretically, in astrophysics. There are still many open questions around how galaxies form, grow and evolve over cosmic time, although various observations have shown that their evolution is related to their masses and the environments in which they are located; blue star-forming galaxies are more common in the field whereas the denser environments of groups and clusters harbour more red and 'dead' galaxies. Since $z \sim 2$ when the universe was approximately a quarter of its present age, the star-formation-rate density has dropped by more than an order of magnitude [1]. Over that same time period, observations [2, 3, 4, 5, 6] indicate that the cosmic neutral gas density has shown very little evolution.

To understand how galaxies evolve, it is vital to understand the role of the gas which forms the stars. Key to star formation processes is the reservoir of cold hydrogen gas available to form stars in galaxies. Since it is not possible to directly observe the cold molecular hydrogen from which stars form, astronomers typically look for the presence of other molecules (e.g. CO) as a proxy to indicate the presence of molecular gas or they observe the neutral atomic hydrogen from which the molecular phase should form. Neutral atomic hydrogen emits radiation with a wavelength of 21 cm arising from the spin-flip transition of the electron. Radio observations of galaxies in The HI Nearby Galaxy Survey (THINGS) [7] indicate that the star-formation rate surface density of galaxies seems to scale more directly with the H_2 content than the HI content of galaxies in their sample. However, observations of gas-rich galaxies in the Arecibo Legacy Fast ALFA (ALFALFA) survey [8] seem to indicate a correlation between star-formation rate and HI mass in this regime. In recent work by Kannappan et al. [9], the authors find a relation between the so-called long term fractional stellar mass growth rate (FSMGR_{LT}), which is a means to quantify the star formation rate over the past gigayear compared to the pre-existing mass of the galaxy, and the gas-to-stellar mass ratio. Galaxies with higher stellar masses have higher FSMGRs. Attempts to model their data using closed box τ-models are unsuccessful, seeming to imply that galaxies must be undergoing gas refuelling on a timescale of gigayears. Recent theoretical and simulation work also indicates that both gas inflows and outflows are important in maintaining smooth galaxy growth (see for e.g.[10]).

Until recently it has been very difficult to make observations of HI in external galaxies at redshifts beyond our local universe due to the faintness of the HI emission requiring observing times of order thousands of hours. Recent upgrades to radio telescopes, including the Westerbork Synthesis Radio Telescope (WSRT) in the Netherlands and the Jansky Very Large Array (JVLA) in the USA, have enabled more distant observations of HI in galaxies.

The Blind Ultra-Deep HI Environmental (BUDHIES) Survey [11] on WSRT observed two clusters of galaxies in HI at intermediate redshift ($z \sim 0.2$) with the aim to study the effect of environment on the HI content of galaxies. These observations required $\sim$2000 hours of observing on WSRT with its upgraded correlator and they observed 150 galaxies in HI. The COSMOS HI Large Extragalactic (CHILES) Survey [12] will observe a single pointing on the COSMOS field for 1000 hours using the JVLA. The instantaneous bandwidth of the upgraded JVLA enables measurements of redshifted HI over the redshift range $0 < z < 0.45$ making the CHILES survey the deepest HI observations to date. So far, the CHILES pilot survey consisting of 60h of observations has found

33 direct detections of HI in galaxies, the most distant of which is at a redshift of $z \sim 0.18$.

2. The LADUMA survey

The upcoming Square Kilometre Array (SKA) pathfinder instruments including the JVLA, APERTIF (the WSRT with phased array feeds), ASKAP[1] and MeerKAT will revolutionise our ability to observe HI in galaxies at cosmological redshifts and enable studies of the evolution of gas in galaxies over cosmic time. APERTIF, ASKAP and MeerKAT are currently under construction and are due to start making science observations in the next year or so.

The LADUMA (Looking At the Distant Universe with the MeerKAT Array) survey (PIs: Blyth, Baker, Holwerda) [13] is one of the two top priority large surveys to be completed with the MeerKAT radio telescope. The international team includes both observers and theorists and many of our members are based at SALT-partner institutions. It is also commensal with 2 other MeerKAT large surveys. The MIGHTEE [14] survey is a tiered continuum survey which, for its deepest tier, will piggy-back on the LADUMA observations. ThunderKAT [15] is a transient imaging survey which will observe simultaneously with LADUMA.

Prior to the SKA coming online, LADUMA will be the deepest HI survey, probing HI emission from galaxies out to redshifts $z < 1.4$. The observations will consist of a single pointing, encompassing the extended Chandra Deep Field-South (ECDF-S) which is a well-studied field containing a wealth of ancillary multi-wavelength data already. Due to the MeerKAT receiver design, the LADUMA observations will be split over two receiver bands – the L-band receiver (0.9–1.67 GHz) and the UHF receiver (0.58–1.015 GHz) which correspond to the redshift ranges $0 < z < 0.56$ and $0.4 < z < 1.4$, respectively. We do not present the expected sensitivities or source counts here because all the MeerKAT Large Surveys, including LADUMA, will be subject to a time allocation reassessment in May 2016 due to the MeerKAT telescopes performing above the original planned specifications. For more information on this we refer the reader to the upcoming proceedings from that process in 2016.

2.1 LADUMA science

With the LADUMA survey we will investigate the evolution of galaxies over two thirds of the age of the universe. Our headline science goals include investigating:

- the HI mass function of galaxies in different environments out to $z \sim 0.6$. How the characteristic mass, M^*_{HI}, and other Schechter parameters vary with environment and redshift are yet unknown and can help to shed light on galaxy formation and evolution scenarios.
- the evolution of the cosmic neutral gas density, Ω_{HI}, out to $z \sim 1.2$ in emission. This will allow us to to compare to previous measurements of this quantity using absorbers (see [16] and references therein) over a redshift range where current measurements have large uncertainties.
- how galaxies' HI masses depend on their stellar masses and halo masses as a function of redshift. Direct observations over a broad range of stellar masses and redshift will provide

[1] Australian SKA Pathfinder

much-needed input to galaxy formation and evolution models and may help to clarify modes of galaxy gas re-fuelling.

- how the baryonic Tully-Fisher relation evolves over cosmic time. The stellar mass Tully-Fisher relation has been observed to evolve with redshift [17], but it is still not known how the baryonic Tully-Fisher may evolve. Even though most of LADUMA's HI detections will be unresolved spatially, we will observe thousands of HI profiles allowing us to measure rotation velocities of thousands of galaxies over cosmic time.

Other science that can be done with LADUMA is to investigate redshifted OH mega-masers which can be used to trace the galaxy merger rate out to redshifts of $z \sim 1.8$ [18].

Most of our studies will rely not only on the HI radio data, but on a combination of these with ancillary multi-wavelength data in the field. There is already a significant amount of publicly available imaging data across the LADUMA field as well as photometric redshifts. We will also require spectroscopic redshifts to enable many of our analyses including HI stacking and we have an active campaign to acquire these to add to the existing ~ 7000 galaxy redshifts available across the field already.

3. LADUMA and SALT

With SALT and MeerKAT located at such similar latitudes, there is a natural overlap for observing similar targets. SALT's smaller field of view makes it an ideal instrument to do targeted follow-up observations of individual or small sub-samples of objects identified by LADUMA. SALT will not however be the best choice of instrument for gathering thousands of spectroscopic redshifts; for that we require a telescope with a larger field of view and high number multi-object spectroscopy capabilities such as AAΩ on the Anglo-Australian Telescope which we have previously used to observe galaxy redshifts for LADUMA.

We view the RESOLVE (REsolved Spectroscopy Of a Local VolumE) survey [19], which is a volume-limited, very complete census of galaxy properties from dwarfs to cluster scales, and which is led by our co-I S. Kannappan, as an important $z = 0$ reference sample. This survey has made heavy use of SALT including Fabry-Pérot observations and long-slit spectroscopy.

In the future, ideally, we will use SALT as a follow-up instrument for interesting sources detected with MeerKAT. Our ideas around this include:

- Fabry-Pérot observations: With Fabry-Pérot we will be able to compare the HI velocity fields of resolved nearby galaxies in LADUMA with their Hα velocity fields as well as determine velocity fields for more distant galaxies which are unresolved in the radio observations. With these observations we aim to disentangle the gas dispersion from its rotation.

- Long-slit observations of expected/detected HI sources: this will enable us to estimate the metallicity and metallicity-gradients of galaxies to probe the gas reservoir enrichment. This spectroscopy will also allow us to investigate the causes of offsets between the HI and optical redshifts. We will be able to study close pairs identified by their unusual HI profiles where the fainter pair member has been missed by our optical spectroscopy campaign due to magnitude constraints. We will also be able to probe AGN-driven feedback on HI reservoirs in an HI-selected sample.

- Long-slit observations of suspected OH-detections: this can help constrain the location of the mega-maser in a galaxy and if these are found in dusty galaxies, they may not have been observed previously in our spectroscopic campaign.

We are looking forward to 2017 when the LADUMA survey will begin taking data with MeerKAT and we are sure that SALT will play an integral role in following up various populations of galaxies identified by LADUMA using a variety of techniques.

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