PROCEEDINGS OF SCIENCE

LADUMA: Looking At the Distant Universe with the MeerKAT Array

Sarah-Louise Blyth[*,1], **Andrew J. Baker**[*,2], **Benne W. Holwerda**[3,4]

E-mail: sarblyth@ast.uct.ac.za

Bruce A. Bassett[5,6,1], **Matthew A. Bershady**[7], **Antoine Bouchard**[8], **Frank H. Briggs**[9], **Barbara Catinella**[10], **Laurent Chemin**[11], **Steven M. Crawford**[6], **Catherine M. Cress**[12], **Daniel Cunnama**[6], **Jeremy K. Darling**[13], **Romeel Davé**[14,6,5], **Roger P. Deane**[15], **W. J. G. de Blok**[16,17,1], **Ed C. Elson**[1], **Andreas Faltenbacher**[18], **Sean February**[12], **Ximena Fernández**[2], **Bradley S. Frank**[1], **Eric Gawiser**[2], **Patricia A. Henning**[19], **Kelley M. Hess**[17,16], **Ian Heywood**[20], **John P. Hughes**[2], **Matt J. Jarvis**[21,14], **Sheila J. Kannappan**[22], **Neal S. Katz**[23], **Dušan Kereš**[24], **Hans-Rainer Klöckner**[25], **Renée C. Kraan-Korteweg**[1], **Philip Lah**[9], **Matthew D. Lehnert**[26], **Adam K. Leroy**[27], **Michelle Lochner**[5], **Natasha Maddox**[16], **Sphesihle Makhathini**[15], **Gerhardt R. Meurer**[10], **Martin J. Meyer**[10], **Kavilan Moodley**[28], **Raffaella Morganti**[16,17], **Danail Obreschkow**[10], **Se-Heon Oh**[10], **Tom A. Oosterloo**[16,17], **D.J. Pisano**[29], **Attila Popping**[10], **Gergö Popping**[30], **Swara Ravindranath**[31], **Eva Schinnerer**[32], **Anja C. Schröder**[6], **Kartik Sheth**[33], **Rosalind Skelton**[6], **Oleg M. Smirnov**[15], **Mathew Smith**[34], **Rachel S. Somerville**[2], **Raghunathan Srianand**[35], **Lister Staveley-Smith**[10], **Ian M. Stewart**[3], **Mattia Vaccari**[14], **Petri Väisänen**[6], **Kurt J. van der Heyden**[1], **Wim van Driel**[36], **Marc A. W. Verheijen**[17], **Fabian Walter**[32], **Eric M. Wilcots**[7], **Theodore B. Williams**[6], **Patrick A. Woudt**[1], **John F. Wu**[2], **Martin A. Zwaan**[30], **Jonathan T. L. Zwart**[14,1], **Steve Rawlings**[37]

PoS(MeerKAT2016)004

[1] *University of Cape Town*
[2] *Rutgers, The State University of New Jersey*
[3] *Leiden University*
[4] *University of Louisville*
[5] *African Institute for Mathematical Sciences*
[6] *South African Astronomical Observatory*
[7] *University of Wisconsin*
[8] *McGill University*
[9] *Australian National University*
[10] *International Centre for Radio Astronomy Research, University of Western Australia*
[11] *Instituto Nacional de Pesquisas Espaciais*
[12] *Centre for High Performance Computing*
[13] *University of Colorado*
[14] *University of the Western Cape*
[15] *Rhodes University*
[16] *ASTRON Netherlands Institute for Radio Astronomy*
[17] *Kapteyn Institute, University of Groningen*
[18] *University of the Witwatersrand*
[19] *University of New Mexico*
[20] *Commonwealth Scientific and Industrial Research Organisation*
[21] *University of Oxford*
[22] *University of North Carolina*
[23] *University of Massachusetts*
[24] *University of California at San Diego*
[25] *Max-Planck-Institut für Radioastronomie*
[26] *Institut d'Astrophysique de Paris*
[27] *Ohio State University*
[28] *University of KwaZulu-Natal*
[29] *West Virginia University*
[30] *European Southern Observatory*
[31] *Space Telescope Science Institute*
[32] *Max-Planck-Institut für Astronomie*
[33] *National Aeronautics and Space Administration*
[34] *University of Southampton*
[35] *Inter-University Centre for Astronomy and Astrophysics*
[36] *Observatoire de Paris*
[37] *(in memoriam)*

PoS(MeerKAT2016)004

The cosmic evolution of galaxies' neutral atomic gas content is a major science driver for the Square Kilometre Array (SKA), as well as for its South African (MeerKAT) and Australian (ASKAP) precursors. Among the H I large survey programs (LSPs) planned for ASKAP and MeerKAT, the deepest and narrowest tier of the "wedding cake" will be defined by the combined L-band+UHF-band Looking At the Distant Universe with the MeerKAT Array (LADUMA) survey, which will probe H I in emission within a single "cosmic vuvuzela" that extends to $z = 1.4$, when the universe was only a third of its present age. Through a combination of individual and stacked detections (the latter relying on extensive multi-wavelength studies of the survey's target field), LADUMA will study the redshift evolution of the baryonic Tully–Fisher relation and the cosmic H I density, the variation of the H I mass function with redshift and environment, and the connection between H I content and galaxies' stellar properties (mass, age, etc.). The survey will also build a sample of OH megamaser detections that can be used to trace the cosmic merger history. This proceedings contribution provides a brief introduction to the survey, its scientific aims, and its technical implementation, deferring a more complete discussion for a future article after the implications of a recent review of MeerKAT LSP project plans are fully worked out.

MeerKAT Science: On the Pathway to the SKA,
25-27 May, 2016,
Stellenbosch, South Africa

*Speaker.

1. Introduction

Understanding the formation and evolution of galaxies is a central goal of modern astrophysics, and a major driver for the construction of the Square Kilometre Array (SKA). An important step towards this goal is understanding the evolving gas content of galaxies — especially the neutral atomic hydrogen (H I) that comprises the bulk of normal systems' interstellar gas mass in the local universe. The relationships between galaxies' H I properties and their masses, their environments, and the cosmic epochs at which they are observed encode key information about the physical processes that drive their evolution. Frustratingly, the extreme faintness of the $\lambda_{\rm rest} = 21\,{\rm cm}$ H I emission line, compounded by the effects of radio frequency interference (RFI) over many redshift ranges, has left most "high-redshift" studies limited to $z_{\rm HI} \simeq 0.2$ [15, 48, 27], with the first substantial samples of gas-rich galaxies at these redshifts featuring 42 H I detections in two $z \sim 0.2$ galaxy clusters [64] and 39 H I detections at $0.17 \leq z \leq 0.25$ in the Arecibo HIGHz survey [13]. Redshifts as high as $z \simeq 0.4$ have until recently been practically accessible only via stacking techniques (e.g., [44]), although the expanded capabilities of the Karl G. Jansky Very Large Array (VLA) and the brand-new Australian SKA Pathfinder (ASKAP) have now enabled untargeted detections of H I in emission at $z = 0.38$ [26] and absorption at $z = 0.44$ [1]. Going forward, ASKAP will produce two tiers of a new "H I wedding cake" by executing the wide-area WALLABY survey [23] and the narrower but more sensitive Deep Investigation of Neutral Gas Origins (DINGO; [23]) survey. The COSMOS H I Large Extragalactic Survey (CHILES; [26]) already being conducted with 1002 hours of VLA time defines a deeper and narrower tier to $z = 0.45$ with $\sim 5''$ resolution, although the VLA's field of view and frequency coverage are smaller than those of MeerKAT, South Africa's SKA precursor.

The Looking At the Distant Universe with the MeerKAT Array (LADUMA) survey will define the deepest, narrowest tier of the new "H I wedding cake." By exploiting the outstanding sensitivity, frequency coverage, and radio-quiet site of MeerKAT, LADUMA will fill the still-significant gaps in our knowledge of the cosmic evolution of H I in galaxies over the last 9 Gyr — more than two thirds of the age of the universe. In 2010, the science potential of MeerKAT in this area was already so clear and compelling that it attracted *two* Large Survey Project (LSP) proposals. The two proposals focused on observing H I in emission over limited areas, shared multiple high-level science goals, and resembled each other in key practical respects: both targeted sky positions with extensive multi-wavelength data, allowed for commensal continuum studies, and envisaged two-stage efforts in which shorter observations with MeerKAT's "Phase 1" (0.9–1.75 GHz) receivers would be followed by longer observations in an expanded "Phase 4" (0.58–2.5 GHz) band (see [6]). The 2010 Time Assignment Committee (TAC) placed a single deep H I survey in "priority group 1" and recommended "that the two deep H I teams be requested to undertake this project jointly," with this allocation accompanied by a further "recommendation to focus on a single field" and guidance that the project "will naturally yield a continuum field, which should be incorporated in [the MeerKAT International GigaHertz Tiered Extragalactic Exploration (MIGHTEE)] project."

2. Field Selection

Both of LADUMA's parent proposals identified a region encompassing the Chandra Deep

Field South (CDFS) as a preferred target field. Much multi-wavelength data already exists for this field in the form of many overlapping surveys, and the LADUMA team has now settled on a pointing at 03:32:30.4 −28:07:57 (J2000), maximising overlap with the footprints of the $3.6/4.5\,\mu$m *Spitzer* Extragalactic Representative Volume Survey (SERVS; [49]), the $ZYJHK_s$ VISTA Deep Extragalactic Observations (VIDEO; [37]) survey, and the *ugri* VST Optical Imaging of the CDFS and ES1 (VOICE; [62]) survey, among others. This choice is motivated chiefly by the CDFS's more southern declination relative to possible alternatives (e.g., the COSMOS and XMM-LSS fields). The resulting longer tracks mean that polarisation calibrators can be observed over wider ranges in parallactic angle — a desirable goal for commensal studies by MIGHTEE (§5) — and that LADUMA can be completed in fewer years — a desirable goal given uncertainty about when SKA1-Mid will absorb MeerKAT. A higher typical observing elevation should also reduce the effects of terrestrial RFI.

The CDFS region will continue to be aggressively targeted by facilities operating at all wavelengths, e.g., the 4-metre Multi-Object Spectroscopic Telescope (4MOST; [21]) in the context of the Wide Area VISTA Extragalactic Survey (WAVES; [22]), the Multi-Object Optical and Near-infrared Spectrograph (MOONS; [17]) on the Very Large Telescope (VLT), and the Large Synoptic Survey Telescope (LSST), for which it has been designated a "deep drilling field." The LADUMA team has been adding to the existing optical spectroscopy (e.g., [2]) in the field since 2013, already securing over 5000 new redshifts over a $2\,\mathrm{deg}^2$ area (i.e., the MeerKAT field of view at $z \approx 0.58$) using the AAOmega spectrograph on the Anglo-Australian Telescope (AAT). To probe fainter and more distant populations going forward, we are taking advantage of Southern African Large Telescope (SALT) time that is being ring-fenced for the support of LSP science, and plan to establish partnerships with groups having privileged access to spectroscopic instruments on other telescopes. The thousands of optical redshifts we expect to secure out to $z = 1.4$ via this effort (provided they are sufficiently accurate; see [45]) will support stacking experiments that bin samples according to redshift *and* detailed source properties.

3. Scientific Motivation

The overarching goal of LADUMA is to use H I observations to study galaxy evolution over two thirds of the age of the universe. Current sensitivity forecasts and the model predictions of [53] imply we will achieve $\geq 5\sigma$ detections of comparably large numbers of sources in the redshift ranges $0 \leq z_{\mathrm{HI}} \leq 0.42$ (observed by the L-band receivers only), $0.42 \leq z_{\mathrm{HI}} \leq 0.58$ (where the L-band and UHF-band receivers overlap), and $0.56 \leq z_{\mathrm{HI}} \leq 1.45$ (observed by the UHF-band receivers only). While RFI in the 1164–1300 MHz GNSS band will compromise about half of the $z_{\mathrm{HI}} \leq 0.42$ sources, our source totals will still exceed those of previous surveys (§2.1) and — in combination with the thousands of optically-selected galaxies on which we will ultimately be able to stack (§2.2) — are clearly sufficient for us to address the following four "headline" science questions:

A. How does the H I mass function depend on environmental density and redshift? Efforts such as the H I Parkes All-Sky Survey (HIPASS) [3] and the Arecibo Legacy Fast ALFA (ALFALFA) [28] survey have measured the H I mass function in the local universe ([68, 48]) and have begun to explore its dependence on environment (e.g., [39]), but we have yet to constrain it for higher redshifts. In partnership with MIGHTEE, whose larger volume will be important for characterizing gas-rich galaxies at $z < 0.2$ ([47]), LADUMA's ability to detect faint individual H I emitters will allow us to investigate whether there is redshift evolution in the low-mass slope, the overall normalization, and/or the characteristic mass $M^*_{\rm HI}$ of the H I mass function, and to compare our results to discrepant theoretical predictions (e.g., [53, 43, 55, 19]). We will also measure the mass function in different (i.e., cluster, group, and isolated) environments, as selected via the extensive multi-wavelength data that exist for our field, thereby shedding light on how the buildup of hot gas in groups and clusters affects the cold gas in their members (e.g., [33, 29, 34, 35, 36]) over cosmic time.

B. How does the cosmic neutral gas density traced by H I emission evolve to high redshift? Current measurements of the cosmic neutral gas density $\Omega_{\rm HI}(z)$ using H I emission (directly detected and stacked) reach out to $z \simeq 0.4$ ([44, 59]), but with large uncertainties. At higher redshifts, with H I emission stacking still yielding only upper limits [40], the cosmic neutral gas density is inferred from magnesium [57] and damped Lyman α [52, 67]) absorbers. By using co-added measurements for sub-samples of galaxies at different redshifts, we aim to bridge the gap between the direct measurements at $z = 0$ and the indirect measurements at higher redshifts. This objective has been identified as a critical priority for MeerKAT by optical astronomers like [60], who write, *"Upcoming surveys with the Square Kilometre Array... and its pathfinders present an exciting prospect for resolving the gas content of galaxies since $z \sim 1.5$."* To this end, we will also stack MeerKAT data cubes at the redshifts of Ca II and (for $z > 0.15$) Mg II absorption lines detected in the stacked spectra of background star-forming galaxies (e.g., [8]), take annular averages, and look for H I in emission. This experiment is inspired by evidence that Mg II absorbers trace the densest parts of starburst-driven outflows at small impact parameters from background sources (e.g., [9]). Understanding the connection between Ca II and Mg II absorption and neutral hydrogen content is critical for efforts to constrain $\Omega_{\rm HI}(z)$ at $0.5 \leq z_{\rm HI} \leq 1.2$ using absorber incidence statistics.

C. How do galaxies' H I masses depend on their stellar masses, dark matter halo masses, and other properties (e.g., star-formation rates) as functions of redshift and environment? Using direct detections of H I in individual systems as well as averaged H I properties of stacked samples, we will be able to exploit the existing multi-wavelength data in our field to identify dependences and correlations that will shed light on the physics of galaxy transformation (e.g., [11, 46]). Recent ALFALFA results illustrate the potential of both approaches. Direct H I detections have been used in [31] to reveal hints of non-universal star-formation laws: galaxies with high gas fractions have star-formation rates that scale with $M_{\rm HI}$, in contrast to galaxies with low gas fractions, whose star-formation rates scale best with *molecular* hydrogen surface density [4]. Stacked ALFALFA spectra of stellar-mass-selected samples have been used to show that H I content is primarily tied to specific star-formation rate rather than stellar mass [11], and that gas is increasingly depleted in higher density environments, including groups, at fixed specific star formation rate [12], confirming results from deep, targeted observations [14]. This result disfavours a starvation-like process, instead suggesting direct removal of gas from the disk by some mechanism that current models cannot reproduce. Beyond the use of global $M_{\rm HI}$ measurements along these lines, we will also be able to explore what asymmetries or offsets of galaxies' stellar and H I distributions (and their dependence on environment) tell us about the drivers of their evolution (e.g., [30]). A generally appealing prospect is the development of volume-limited samples within our very deep $0.42 \leq z_{\rm HI} \leq 0.58$ redshift shell, whose properties can be compared to those of, e.g., the volume-limited sample studied by the REsolved Spectroscopy Of a Local VolumE (RESOLVE; see below) survey at $z = 0$.

D. How does the baryonic Tully–Fisher relation evolve over cosmic time? The stellar-mass Tully–Fisher relation, which relates the luminosities and rotational velocities of disk galaxies, shows evolution with redshift in terms of its slope and intercept [65]. 2006). It is as yet unknown how the *baryonic* (i.e., stars plus gas) Tully–Fisher relation [50, 63] evolves with redshift, although simulations suggest that it is sensitive to the details of outflow physics (e.g., [24]), with some indications that individual systems evolve along the relation and thus preserve its overall shape [56]. LADUMA will provide a conclusive probe here (also of the information encoded in the *residuals* relative to the mean relation; [41]) by virtue of its sensitivity, resolution, and redshift range. For the relatively small fraction of systems that LADUMA spatially and/or spectrally resolves, we will fold information about H I kinematics — extracted with the help of VLT/MUSE spatially resolved optical spectroscopy and/or novel stacking techniques [51] — into our dynamical analysis. This technique will also support studies of the baryonic angular momentum in disk galaxies and their cosmic evolution in the mass-angular momentum plane (e.g., [54]).

LADUMA will also pursue a range of "beyond-the-headlines" science that includes searching for gravitationally lensed H I emission, which promises to extend the study of $\Omega_{\rm HI}(z)$ described above (e.g., [20, 32]), and probing the demographics of low column density H I absorbers. The survey will also encompass non-H I science, specifically observations of OH megamasers, which arise in galaxy major mergers associated with extreme star formation, and thus probe mergers across cosmic time as well as the most extreme starbursts [18, 66]. Indeed, the "contamination" fraction of OH in the H I survey may become substantial over the survey's redshift range [10]; however, OH megamasers in merging galaxies that mimic H I lines in disk galaxies can still be disentangled using mid-IR or far-IR continua and photometric redshifts (e.g., [61]).

LADUMA's pursuit of all its scientific objectives will be facilitated by collaborations of two types. First, as the 2010 TAC recommended (§1), LADUMA has now established a tight commensal partnership with MIGHTEE in relation to continuum science, encompassing coordinated acquisition of multi-wavelength data (§2), the development of a unified calibration and imaging pipeline (§4), and joint analysis of continuum and spectral-line data. Second, LADUMA will take advantage of the RESOLVE survey, which is obtaining H I observations *and* high-quality optical imaging and spatially resolved spectroscopy of a volume-limited sample within $5 \times 10^4\,{\rm Mpc}^3$ at $z = 0$ [42]. Together with the *GALEX* Arecibo SDSS Survey (GASS; [16]), RESOLVE will define a key local reference dataset for LADUMA.

4. Data Acquisition and Processing

Scheduling of LADUMA is presently being modeled in the wake of an LSP project plan review. We note, however, that the effects of RFI due to the Sun and (especially) the expected launch of SKA1-Mid construction activity during the day mean that LADUMA observations will benefit to the extent that they are scheduled at night. Similarly, MIGHTEE polarisation science will benefit from repeated visits to a secondary polarisation calibrator, and thus from a sizable fraction of *long*

PoS(MeerKAT2016)004

tracks to ensure that these visits span a wide range in parallactic angle. For calibration of the data, LADUMA will work closely with MIGHTEE to develop a unified pipeline; we plan to explore multiple possibilities for a pipeline software framework, given the diversity of calibration expertise that exists within the team, as well as past history that suggests there may be no single calibration package that addresses all of our needs out of the box. In most respects, LADUMA will follow a standard approach to calibration. Frequency-dependent and time-dependent calibration will be separated, since the spectral response of the array can be assumed to be constant. Bandpass calibration will use observations of an external calibrator; PKS 1934−638 is the southern hemisphere gold standard, but we will also investigate other calibrators appropriate to the RA of the LADUMA field. Given the field of view and the sensitivity of MeerKAT, every calibrator observation will also detect other sources in the field apart from the calibrator itself. Hence, for the bandpass calibration, a model of the entire calibrator field will be used instead of the standard assumption of a point source.

Since LADUMA is primarily a spectral-line experiment, the main aim of time-dependent calibration is to enable continuum subtraction (the spectral-line data will require only modest dynamic range). The time-dependent calibration will split the full MeerKAT band into ~ 20 sub-bands, with each sub-band calibrated separately so as to avoid having to take chromatic effects (in particular, those induced by the primary beam) into account for continuum subtraction. Rather than using a secondary calibrator (apart from the first few tracks in a given observing "season"), we will perform time-dependent calibration using the continuum sources in the field mapped at coarse spectral resolution. Given that LADUMA observes the same field repeatedly, most of the calibration can be done using a pre-existing sky model derived from previous observations. After a first iteration using this pre-existing model, successive iterations will use a sky model derived from the observation itself (i.e., self-calibration), so as to take continuum source variability into account. Continuum subtraction will be done by copying the calibration of the continuum data to the spectral-line data, followed by subtraction of the final continuum model from each sub-band. This operation will be done in the visibility domain, due to frequency-dependent flagging of RFI that will result in a variable synthesized beam (incompatible with image-plane subtraction), but also because the stronger continuum sources will be located away from the field centre (ruling out the use of, e.g., the `uvlin` algorithm). Given the large field of view, the low frequency of the (especially UHF-band) observations, and small effects due to sky rotation of the primary beam, we will take direction-dependent effects into account in order to properly subtract the continuum. We will use *a priori* primary beam models together with direction-dependent gain solutions for brighter sources.

Although we expect to devote significant early effort to characterising and removing RFI from our data, our goal is to move in the direction of (a) producing a continuum-subtracted data cube for each observation separately, and (b) combining all available cubes in the image domain by computing their noise-weighted average (on a per-channel basis). This approach is more scalable than combining in the *uv* domain, especially at late stages of the project when data volumes become prohibitively large, and immediately delivers the most sensitive data cube possible at a given juncture: each channel of each observation is weighted by the appropriate noise, and small noise (or noise-like) contributions from residual RFI will be down weighted. We will produce data cubes with multiple weighting schemes and resolutions: natural weighting for stacking, Briggs weighting with robust = 0 for an $8.3\,(1+z_{\rm HI})$ arcsec FWHM synthesized beam (sufficiently compact to mitigate confusion in stacking experiments: [38, 25]), and tapering to build 15 and 30 arcsec resolution versions of cubes — all with the corresponding (and 4× larger) dirty beam cubes.

LADUMA will use the resources of the Centre for High Performance Computing (CHPC) and the newly established Inter-university Institute for Data Intensive Astronomy (IDIA) for (i) storing Tier 1 visibility data from MeerKAT, and (ii) undertaking calibration, flagging, processing, imaging, and analysis of our data. The IDIA Tier 2 facility will also host a radio data pipeline development platform that will respond to the needs of multiple MeerKAT H I surveys. IDIA will also serve as a centre for co-developing improved visualisation applications and data analysis techniques. Involvement of a distributed team in processing, analysing, and archiving LADUMA data will be facilitated by a newly established South African/Dutch SKA data science partnership, which aims to develop federated storage and processing facilities for radio astronomy as a prototype for SKA infrastructure.

5. Public Outreach

Recognizing the SKA project's commitment to human capital development, the LADUMA team has conducted a program of public outreach activities focused on high school visits and online media. We have planned and executed school visit campaigns across the Cape Town area in both 2012 and 2016, in order to publicise radio astronomy, MeerKAT, LADUMA, and opportunities for education and training in scientific and technical fields. In 2012, LADUMA team members visited a total of 20 high schools in the greater Cape Town area spanning a broad socio-economic range — 17 in a single day, reaching over 2100 learners, and three more later in the year (see [5]). In February 2016, we held a similar event in which team members reached six schools and ~ 300 learners in one day, with a seventh school visited in March and more schools requesting visits in the queue for later this year. Our online media campaign began with the 2012 launch of a regularly updated Facebook page. Subsequently, working with South African filmmaker Paul Yule, we produced a set of five short soccer-themed[1] videos to introduce MeerKAT and LADUMA science to the general public (aimed at South Africa, but accessible to anyone).

6. Conclusion

In a broader context, LADUMA survey science is clear SKA-precursor science falling squarely in the SKA Key Science area of "Galaxy Evolution, Cosmology, and Dark Energy" (e.g., [58]). Thanks to the exquisite sensitivity MeerKAT will provide to LADUMA, we will be able to push H I emission studies out to previously inaccessible redshifts on larger scales than have been possible before, breaking new ground in understanding the role of gas in galaxy evolution over cosmic time. Scientific results and technical lessons from LADUMA will strengthen the definition of and planning for future SKA H I surveys. As a case in point, the SKA1-Mid-C survey baselined to cover 20 deg^2 at 0.95–1.75 GHz in an internal project document on SKA1 Generic Surveys will deliver $\sim 40\%$ better sensitivity than LADUMA and will have the advantage of enabling resolved

[1] "LADUMA" ("it thunders" in isiZulu) is the unique South African exclamation celebrating a goal scored in soccer. Appropriately, the trumpet-like volume in which the survey will be sensitive to H I emission (due to its $\lambda/D \propto (1+z_{\rm HI})$ field of view) resembles the vuvuzela horns that define the sound of South African soccer around the world.

galaxy studies due to the more extended SKA1-Mid configuration. It will, however, be limited to $z_{\mathrm{HI}} < 0.5$; thus, until such time as a deep H I survey can be undertaken with SKA1-Mid Band 1 receivers, LADUMA will remain the state-of-the-art high-redshift legacy survey for H I science.

References

[1] Allison, J. R. et al. 2015, MNRAS, 453, 1249

[2] Balestra, I. et al. 2010, A&A, 512, A12

[3] Barnes, D. G. et al. 2001, MNRAS, 322, 486

[4] Bigiel, F. et al. 2008, AJ, 136, 2846

[5] Blyth, S., Baker, A., & Holwerda, B. 2012, SKA South Africa eNews, 17, 11

[6] Booth, R. S. et al. 2009, "An open invitation to the Astronomical Community to propose Key Project Science with the South African Square Kilometre Array Precursor" (arXiv:0910.2935v2)

[7] Booth, R. S. & Jonas, J. L. 2012, African Skies, 16, 101

[8] Bordoloi, R. et al. 2014, ApJ, 784, 108

[9] Bouché, N. et al. 2007, ApJ, 669, L5

[10] Briggs, F. H. 1998, A&A, 336, 815

[11] Brown, T. et al. 2015, MNRAS, 452, 2479

[12] Brown, T. et al. 2017, MNRAS, 466, 1275

[13] Catinella, B. & Cortese, L. 2015, MNRAS, 446, 3526

[14] Catinella, B. et al. 2013, MNRAS, 436, 34

[15] Catinella, B. et al. 2008, ApJ, 685, L13

[16] Catinella, B. et al. 2010, MNRAS, 403, 683

[17] Cirasuolo, M. et al. 2014, Proc. SPIE, 9147, 91470N

[18] Darling, J. 2007, ApJ, 669, L9

[19] Davé, R., Thompson, R. J., & Hopkins, P. F. 2016, MNRAS, 462, 3265

[20] Deane, R. P., Obreschkow, D., & Heywood, I. 2015, MNRAS, 452, L49

[21] de Jong, R. S. et al. 2014, Proc. SPIE, 9147, 91470M

[22] Driver, S P. et al. 2016, ASSP, 42, 205

[23] Duffy, A. R. et al. 2012, MNRAS, 426, 3385

[24] Dutton, A. A. 2012, MNRAS, 424, 3123

[25] Elson, E. C., Blyth, S. L., & Baker, A. J. 2016, MNRAS, 460, 4366

[26] Fernández, X. et al. 2016, ApJ, 824, L1

[27] Fernández, X. et al. 2013, ApJ, 770, L29

[28] Giovanelli, R. et al. 2005, AJ, 130, 2598

[29] Hess, K. M. & Wilcots, E. M. 2013, AJ, 146, 124

[30] Holwerda, B. W. et al. 2011, MNRAS, 416, 2426

[31] Huang, S. et al. 2012, ApJ, 756, 113

[32] Hunt, L. R., Pisano, D. J., & Edel, S. 2016, AJ, 152, 30

[33] Jaffé, Y. L. et al. 2012, ApJ, 756, L28

[34] Jaffé, Y. L. et al. 2013, MNRAS, 431, 2111

[35] Jaffé, Y. L. et al. 2015, MNRAS, 448, 1715

[36] Jaffé, Y. L. et al. 2016, MNRAS, 461, 1202

[37] Jarvis, M. J. et al. 2013, MNRAS, 428, 1281

[38] Jones, M. G. et al. 2016a, MNRAS, 455, 1574

[39] Jones, M. G. et al. 2016b, MNRAS, 457, 4393

[40] Kanekar, N., Sethi, S., & Dwarakanath, K. S. 2016, ApJ, 818, L28

[41] Kannappan, S. J., Fabricant, D. G., & Franx, M. 2002, AJ, 123, 2358

[42] Kannappan, S. et al. 2016, BAAS, 227, 311.01

[43] Lagos, C. D. P. et al. 2014, MNRAS, 440, 920

[44] Lah, P. et al. 2007, MNRAS, 376, 1357

[45] Maddox, N. et al. 2013, MNRAS, 433, 2613

[46] Maddox, N. et al. 2015, MNRAS, 447, 1610

[47] Maddox, N., Jarvis, M. J., & Oosterloo, T. 2016, MNRAS, 460, 3419

[48] Martin, A. M. et al. 2010, ApJ, 723, 1359

[49] Mauduit, J.-C. et al. 2012, PASP, 124, 714

[50] McGaugh, S. S. et al. 2000, ApJ, 533, L99

[51] Meyer, S. A. et al. 2016, MNRAS, 455, 3136

[52] Noterdaeme, P. et al. 2012, A&A, 547, L1

[53] Obreschkow, D. et al. 2009, ApJ, 703, 1890

[54] Obreschkow, D. et al. 2015, Proceedings of Advancing Astrophysics with the Square Kilometre Array (AASKA14), id.138

[55] Popping, G., Somerville, R. S., & Trager, S. C. 2014, MNRAS, 442, 2398

[56] Portinari, L. & Sommer-Larsen, J. 2007, MNRAS, 375, 913

[57] Rao, S. M., Turnshek, D. A., & Nestor, D. B. 2006, ApJ, 636, 610

[58] Rawlings, S. et al. 2004, New Astronomy Reviews, 48, 1013

[59] Rhee, J. et al. 2016, MNRAS, 460, 2675

[60] Sánchez-Ramírez, R., et al. 2016, MNRAS, 456, 4488

[61] Suess, K. A. et al. 2016, MNRAS, 459, 220

[62] Vaccari, M. et al. 2012, in Science from the Next Generation Imaging and Spectroscopic Surveys, id.49

[63] Verheijen, M. A. W. 2001, ApJ, 563, 694

[64] Verheijen, M. A. W. et al. 2007, ApJ, 668, L9

[65] Weiner, B. J. et al. 2006, ApJ, 653, 1049

[66] Willett, K. W. et al. 2011, ApJS, 193, 18

[67] Zafar, T. et al. 2013, A&A, 556, A141

[68] Zwaan, M. A. et al. 2005, MNRAS, 359, L30