



Neutral Atomic Hydrogen surveys: past, present and future

F. M. Maccagni^{*(1)}, W. J. G. de Blok⁽²⁾⁽³⁾⁽⁴⁾

(1) INAF – Osservatorio Astronomico di Cagliari, via della Scienza 5, 09047, Selargius (CA), Italy

(2) ASTRON – Netherlands Institute for Radio Astronomy, Oude Hoogeveensedijk 4, 7991 PD, Dwingeloo, The Netherlands

(3) Dept. of Astronomy, Univ. of Cape Town, Private Bag X3, Rondebosch 7701, South Africa

(4) Kapteyn Astronomical Institute, University of Groningen, PO Box 800, 9700 AV Groningen, The Netherlands

Abstract

Neutral atomic hydrogen (H I) observations are fundamental to understand the dynamics of galaxies, their assembly, the fuelling of their star formation and environmental interactions. H I studies have so far been limited by the capabilities of single-dish radio telescopes or synthesis arrays to either small samples or low resolution and sensitivities. Now, the Square Kilometer Array precursors and pathfinders are providing a novel view of the H I in and around galaxies allowing wide field high resolution deep surveys in nearby galaxies. We give an overview of past, current and future H I surveys consistently comparing their surface brightness sensitivities and spatial resolutions highlighting their main scientific key goals and results.

1 Neutral hydrogen gas in galaxies

Over billions of years, young, star-forming, gas-rich galaxies in the early universe evolved into the massive, red, gas-poor and “dead” giant galaxies that we can observe today. Star formation (SF) drives this dramatic transformation by creating new stars, while simultaneously consuming the cold gas fuel reservoir. The availability of the latter is determined by the delicate balance between the amount of material accreted from the inter-galactic medium (IGM) and the amount of gas expelled from the galaxy. In spiral galaxies as our own, to sustain SF over billions of years the gas reservoirs must be replenished from the inter-galactic medium through cosmic time. In elliptical galaxies SF has been rapidly quenched and the gas reservoirs have been depleted and kept so for billions of years. Several phenomena determine the fate of a galaxy. In the environment, merger-driven tidal motions between galaxies or hydrodynamic interactions can drive gas into galaxies or strip it from them. Cold gas infall from the inter-galactic medium and collapse into dense clouds triggers star formation, whose supernovae and stellar winds may heat and expel the gas (i.e. ‘baryon-cycle’). Cold gas may be funnelled down to the central regions triggering nuclear activity, whose energetic feedback can also eject gas from the galaxy and contribute to the quenching of its star formation. Neutral atomic hydrogen (H I) is the most abundant element in the Universe and ultimately is the gas fuel reservoir of which galaxies

are replenished. A complete knowledge of the H I content in galaxies (e.g. the H I mass function between $\sim 10^6$ and $\sim 10^{12} M_\odot$) and how this correlates with their other gas and stellar properties is crucial to understand how galaxies sustain their star formation. H I gas typically extends beyond the stellar disk, this has allowed to probe the rotation curves of galaxies are flat which implies a divergence between the dynamics expected by the visible matter and the total matter distribution (1). H I is thus an exquisite tracer to study the Dark Matter content in galaxies and identify ‘exotic’ sources which may deviate from the typical assembly expected by the Λ CDM cosmological model (e.g. 2).

H I emits through its hyper-fine transition at 21-cm wavelengths and is observable in the nearby Universe by radio telescopes in the L-band. For the reasons described above, H I surveys have always been key science projects of both single dish and radio synthesis telescopes. The development of new facilities and sensitive receivers has pushed the investigation of cold gas in galaxies to previously unexplored low column density sensitivities ($N_{\text{HI}} \lesssim 10^{19} \text{ cm}^{-2}$), high angular resolutions (10-30”) and over wide areas of the sky ($\gtrsim 20 \text{ deg}^2$), thus allowing us to obtain a detailed view of galaxy dynamics and assembly over large statistical samples of galaxies. In the following sections, we compare the different areas, sensitivities and resolutions achieved by past and on-going H I surveys and will show the potentials of the upcoming Square Kilometer Array (SKA 3) and Deep Synoptic Array (DSA2000 4) telescopes.

2 Past H I surveys

In the past, neutral hydrogen studies were limited by the capabilities of the available radio telescopes. Single-dish telescopes (i.e. Parkes, Arecibo, Green Bank Telescope) guarantee a wide field of view and high surface brightness sensitivity but have arcminute scale angular resolution, while radio synthesis telescopes (i.e. ATCA, VLA, WSRT) enable arcsecond scale resolution observations over smaller fields of view ($\lesssim 1 \text{ deg}^2$). The incomplete coverage of the uv -plane due to the limited number of antennas limits the surface brightness sensitivity to the faint extended emission of H I in the outskirts of galaxies and in the inter-galactic medium. In Figure 1 we compare the column density sen-

sitivity and physical scale resolution of several surveys carried on with single dish or interferometers. All sensitivities are homogenised to a 3σ limit over a velocity range of 16 km s^{-1} . This velocity is representative for the H I line given that the velocity dispersions commonly observed in galactic disks are $\sim 7 \text{ km s}^{-1}$. We convert the angular resolution of each survey based on the distance of the targets. The Figure shows that so far H I studies have focused on two separate parameter spaces. Single-dish telescopes have focused on sensitive ($\sim 10^{18} \text{ cm}^{-2}$) observations over large portions of the sky, but mostly rely on unresolved detections (resolution $\gtrsim 10 \text{ kpc}$). Interferometers, instead, have focused on highly resolved (resolution $\lesssim 1 \text{ kpc}$) observations of a limited number of galaxies in the Local Universe, providing the most detailed studies of dynamics in galaxies from dwarfs to spirals. The surveys shown are WHISP (5), LVHIS (6), THINGS (7), LITTLE THINGS (8) HALOGAS (9) and VIVA (10). For single dish studies we show the full samples of HIPASS (11) and ALFALFA (ALFALFA, 12). The markers show the median redshift investigated by the surveys (respectively). These surveys have enabled to obtain a complete census of the overall H I density in the nearby Universe, of the H I mass function and to determine various scaling relations between the neutral atomic phase and the gas and stellar content in galaxies. The high sensitivity of single dish telescopes has also enabled targeted deep observations in search for the diffuse cold clouds and filaments that may accrete onto galaxies (AGES (13) and the observations of NGC 2903 and M31 (14; 15) and GBT and Parkes observations of nearby galaxies (16; 17; 18)). When diffuse gas has been detected, if it was accreting onto the galaxy or if it was a remnant of an interaction has remained an unanswered question.

The Figure also highlights that interferometers provide a continuous investigation of the angular-resolution column-density sensitivity parameter space. By changing the weights of the short or long baselines (i.e. robustness) one can trade angular resolution for sensitivity thus enabling the detection of diffuse and extended H I features in the outskirts and environment of galaxies. Nevertheless, reaching the column densities probed by single-dish observations for a representative number of sources is almost impossible using realistic observing times.

3 Current H I surveys

In the last decade, the SKA L-band precursors and pathfinders (MeerKAT, ASKAP and Apertif) have opened a new parameter space for H I interferometric observations. For the very first time, MeerKAT can provide wide-field of view ($\sim 1 \text{ deg}^2$ and/or high surface brightness sensitivity ($N_{\text{HI}} \gtrsim 10^{18} \text{ cm}^{-2}$), with $10''$ resolution out to 20 Mpc, with a few tens of hours of integration time. The new phased array feed receivers of WSRT (19, Apertif) and ASKAP (20) have increased the field of view of interferometers by an order of magnitude, thus enabling blind

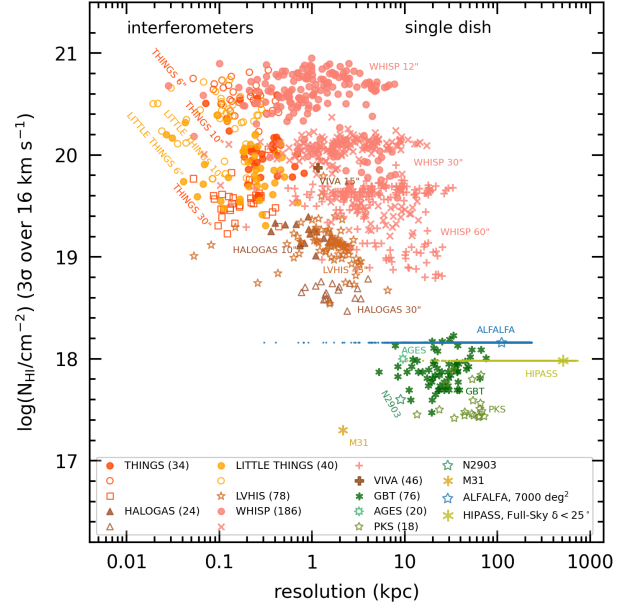


Figure 1. H I column density sensitivity versus spatial resolution of past H I surveys. Symbols show the 3σ column density sensitivity over 16 km s^{-1} , for different interferometric and single dish surveys (see Sect. 2 for further details). The angular resolution of the observations has been converted to spatial resolution according to the distance of the targets (see text for more details). The sample sizes are shown by the numbers within parenthesis in the legend.

interferometric surveys over several thousands of square degrees, also increasing the studies of high redshift H I sources ($\gtrsim 100 \text{ Mpc}$). Figure 2 (left) compares the column density sensitivity of SKA precursors and pathfinders H I surveys with the past H I surveys presented in the previous Section. The phased array feed telescope surveys shown are WALLABY (22) and the Apertif-Shallow and Medium-Deep surveys (23). MeerKAT surveys are the MIGHTEE-HI (24), the MeerKAT Fornax Survey (MFS, 25), the MeerKAT H I Observations of Nearby Galactic Objects: Observing Southern Emitters (MHONGOOSE 26) and VICTORIA (27). For wide-field surveys (WALLABY, Apertif and MIGHTEE-HI) the lines show the spatial resolution at the median distance of the expected H I detections. The dark shaded regions show the range of resolutions for 90% of the detections and the light shaded regions the resolutions for the full sample. The Figure shows that WALLABY and Apertif are wide field surveys with sensitivities and resolutions that previously have been limited only to targeted observations in the Local Volume (LVHIS and WHISP). These surveys will provide with resolutions between 5 and 100 kpc the most complete census of H I galaxies at distances ($\gtrsim 70 \text{ Mpc}$), which so far has been studied only with single-dish surveys. Nevertheless, the system temperature of phased array receivers does not allow to easily reach very low H I column which makes difficult to properly detect and characterize, for example, cold gas accretion features and environmental interactions. These studies are best tackled by the MeerKAT large survey pro-

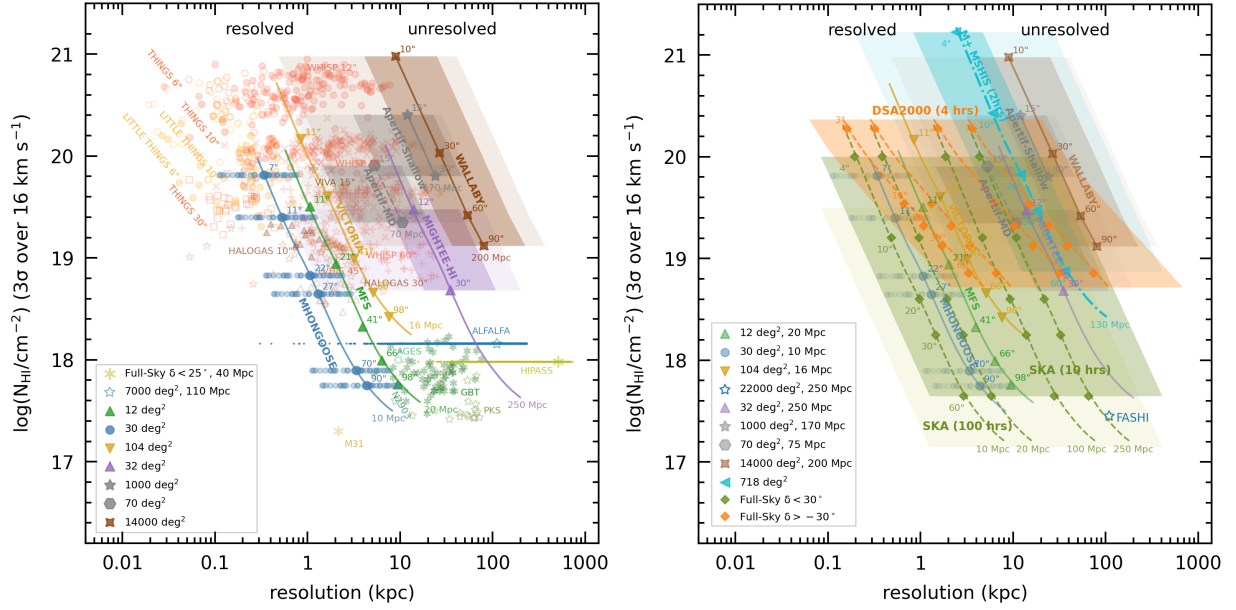


Figure 2. *Left:* Sensitivity versus resolution of past and on-going H I surveys. For wide field surveys, the lines show the median distance of the expected H I detections of the surveys, the dark shaded areas the resolutions reached for 90% of the detections, and the light shaded areas the resolutions for the full sample. *Right:* Sensitivity versus resolution of on-going and future surveys. Lines and shadings are as in the left panel.

grams which, for the very first time, are reaching single-dish column density sensitivity with ten times higher angular resolution. MeerKAT Fornax Survey is observing the nearby Fornax cluster and infalling group of Fornax A (25). MHONGOOSE is targeting 30 nearby galaxies from dwarfs to star forming spirals to detect and characterise the diffuse H I that is potentially accreting onto galaxies and understand its connection to SF. VICTORIA is observing the entire Virgo cluster that was previously only observed with targeted observations of 46 galaxies with VIVA. MIGHTEE-HI is blindly targeting four fields to provide a sensitive unbiased characterisation of the H I population at 250 Mpc.

The Figure shows that even if investigating a new parameter space in sensitivity, resolution and area, the current interferometric H I surveys are still limited by the different optimizations of their telescopes. Phased array feed telescopes and MeerKAT provide similar 10 – 90 arcsecond angular resolutions, but while the first are best suited for wide field surveys, while compromising in sensitivity, MeerKAT enables deep studies but over limited fields, samples of galaxies and environments.

4 Future H I surveys

In the next few years, new radio telescopes will keep exploring new regions of the sensitivity versus resolution parameter space allowing deep wide field H I surveys with improved angular resolution. The upgrade from MeerKAT to MeerKAT+ will increase the survey speed of the instrument and provide higher (4'') angular resolution. This motivates the development of a medium-shallow H I survey (M+

MSHIS) which, compared to current MeerKAT H I studies, will investigate over a wide area (718 deg²), reaching with only 2 hours per pointing, H I sensitivities $\lesssim 10^{20}$ cm⁻². The sensitivity versus angular resolution of the M+MSHIS survey is shown in Figure ?? (right) along with the on-going H I surveys. The Figure shows that an unprecedented and complete view of the H I in and around galaxies will only be provided by DSA 2000 and the SKA observations. Thanks to 2000 antennas guaranteeing a dense coverage of baselines within 10 km, DSA 2000 will reach M+ MSHIS sensitivities at 20 arcseconds in half the integration time. Because of the survey strategy of the instrument, DSA 2000 will scan the full northern sky, thus providing the most complete sample of resolved H I sources in the Northern Hemisphere. Besides survey speed, the main innovation of DSA 2000 is the improvement in angular resolution to 3''. Fig. ?? shows that with only 4 hours of integration DSA 2000 will detect the H I in the star-forming disks ($N_{\text{HI}} \gtrsim 10^{20}$ cm⁻²) sensitivities at 100 pc resolution (half of MHONGOOSE's). In all SF galaxies of the nearby universe (20000 sources from dwarfs to starbursts within 100 Mpc), by increasing the sensitivity of one order of magnitude w.r.t. Apertif and WALLABY it will be possible to perform a direct comparison between the H I distribution and kinematics and the other gas phases of the ISM and the stars to probe how the baryon cycle within galaxies fuels star formation (29).

The SKA H I observations will be groundbreaking. They will reach between 10^{19} and 10^{18} cm⁻² at unmatched resolutions (5-50) arcseconds in only 10 hours per pointing. This will allow us to perform MFS and MHONGOOSE surveys not anymore on limited samples and environments but over the entire Southern Hemisphere (i.e. hundreds of

thousands of galaxies). A full-sky SKA survey with 100 hours per pointing (light shaded green area in the figure) will potentially give a definitive answer to cold gas accretion in galaxies and on the existence of cold gas cosmic filaments: either a detection and full characterisation of these systems will be possible either a non-detection will require to improve our understanding of the physical processes that sustain star formation over cosmic time. The Figure also shows the H I survey planned with the single-dish FAST telescope (FASHI 30). This wide-field survey will be complementary to MeerKAT and SKA observations providing high H I sensitivities to even larger angular scales.

The other game-changer of SKA H I surveys is the complete description of the neutral gas phase in galaxies out to redshift ($z \sim 0.5 - 1$). High redshift studies have so far been limited to ‘pencil beam’ surveys in emission (e.g. CHILES and LADUMA), or to targeted H I absorption surveys (FLASH and MALS) or to stacking experiments (e.g. 31). Large volume H I surveys of resolved sources will enable to characterise the H I mass function throughout the last Gyr and the cosmic H I density. This will allow us to understand if and how the strong decrease in star formation rate observed in the last billion years is linked to a variation in their H I gas reservoir.

5 Acknowledgements

This project has received funding from the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation programme (grant agreement no. 679627 and grant agreement no. 882793).

References

- [1] Bosma, A., “The distribution and kinematics of neutral hydrogen in spiral galaxies of various morphological types”, *PhDT*, 1978.
- [2] Mancera Piña, P. E., “Off the Baryonic Tully-Fisher Relation: A Population of Baryon-dominated Ultra-diffuse Galaxies”, *The Astrophysical Journal*, vol. 883, no. 2, 2019. doi:10.3847/2041-8213/ab40c7.
- [3] Blyth, S., “Exploring Neutral Hydrogen and Galaxy Evolution with the SKA”, in *Advancing Astrophysics with the Square Kilometre Array (AASKA14)*, 2015. doi:10.22323/1.215.0128.
- [4] Hallinan, G., “The DSA-2000 — A Radio Survey Camera”, vol. 51, no. 7, 2019. doi:10.48550/arXiv.1907.07648.
- [5] Swaters, R. A., “The Westerbork HI survey of spiral and irregular galaxies. I. H I imaging of late-type dwarf galaxies”, *Astronomy and Astrophysics*, vol. 390, pp. 829–861, 2002. doi:10.1051/0004-6361:20011755.
- [6] Koribalski, B. S., “The Local Volume H I Survey (LVHIS)”, *Monthly Notices of the Royal Astronomical Society*, vol. 478, no. 2, pp. 1611–1648, 2018. doi:10.1093/mnras/sty479.
- [7] Walter, F., “THINGS: The H I Nearby Galaxy Survey”, *The Astronomical Journal*, vol. 136, no. 6, pp. 2563–2647, 2008. doi:10.1088/0004-6256/136/6/2563.
- [8] Hunter, D. A., “Little Things”, *The Astronomical Journal*, vol. 144, no. 5, 2012. doi:10.1088/0004-6256/144/5/134.
- [9] Heald, G., “The Westerbork Hydrogen Accretion in LOcal GALaxieS (HALOGAS) survey. I. Survey description and pilot observations”, *Astronomy and Astrophysics*, vol. 526, 2011. doi:10.1051/0004-6361/201015938.
- [10] Chung, A., “VLA Imaging of Virgo Spirals in Atomic Gas (VIVA). I. The Atlas and the H I Properties”, *The Astronomical Journal*, vol. 138, no. 6, pp. 1741–1816, 2009. doi:10.1088/0004-6256/138/6/1741.
- [11] Meyer, M. J., “The HIPASS catalogue - I. Data presentation”, *Monthly Notices of the Royal Astronomical Society*, vol. 350, no. 4, pp. 1195–1209, 2004. doi:10.1111/j.1365-2966.2004.07710.x.
- [12] Haynes, M. P., “The Arecibo Legacy Fast ALFA Survey: The ALFALFA Extragalactic H I Source Catalog”, *The Astrophysical Journal*, vol. 861, no. 1, 2018. doi:10.3847/1538-4357/aac956.
- [13] Auld, R., “The Arecibo Galaxy Environment Survey: precursor observations of the NGC 628 group”, *Monthly Notices of the Royal Astronomical Society*, vol. 371, no. 4, pp. 1617–1640, 2006. doi:10.1111/j.1365-2966.2006.10761.x.
- [14] Irwin, J. A., “ Λ CDM Satellites and H I Companions—the Arecibo ALFA Survey of NGC 2903”, *The Astrophysical Journal*, vol. 692, no. 2, pp. 1447–1463, 2009. doi:10.1088/0004-637X/692/2/1447.
- [15] Wolfe, S. A., “Sensitive 21cm Observations of Neutral Hydrogen in the Local Group near M31”, *The Astrophysical Journal*, vol. 816, no. 2, 2016. doi:10.3847/0004-637X/816/2/81.
- [16] Sorgho, A., “Early observations of the MHONGOOSE galaxies: getting ready for MeerKAT”, *Monthly Notices of the Royal Astronomical Society*, vol. 482, no. 1, pp. 1248–1269, 2019. doi:10.1093/mnras/sty2785.
- [17] Sardone, A., “A Census of the Extended Neutral Hydrogen around 18 MHONGOOSE Galaxies”, *The Astrophysical Journal*, vol. 910, no. 1, 2021. doi:10.3847/1538-4357/abde45.

- [18] Pingel, N. M., “A GBT Survey of the HALOGAS Galaxies and Their Environments. I. Revealing the Full Extent of H I around NGC 891, NGC 925, NGC 4414, and NGC 4565”, *The Astrophysical Journal*, vol. 865, no. 1, 2018. doi:10.3847/1538-4357/aad816.
- [19] van Cappellen, W. A., “Apertif: Phased array feeds for the Westerbork Synthesis Radio Telescope. System overview and performance characteristics”, *Astronomy and Astrophysics*, vol. 658, 2022. doi:10.1051/0004-6361/202141739.
- [20] Johnston, S., “Science with ASKAP. The Australian square-kilometre-array pathfinder”, *Experimental Astronomy*, vol. 22, no. 3, pp. 151–273, 2008. doi:10.1007/s10686-008-9124-7.
- [21] Jonas, J. and MeerKAT Team, “The MeerKAT Radio Telescope”, in *MeerKAT Science: On the Pathway to the SKA*, 2016. doi:10.22323/1.277.0001.
- [22] Koribalski, B. S., “WALLABY - an SKA Pathfinder HI survey”, *Astrophysics and Space Science*, vol. 365, no. 7, 2020. doi:10.1007/s10509-020-03831-4.
- [23] Adams, E. A. K., “First release of Apertif imaging survey data”, *Astronomy and Astrophysics*, vol. 667, 2022. doi:10.1051/0004-6361/202244007.
- [24] Maddox, N., “MIGHTEE-HI: The H I emission project of the MeerKAT MIGHTEE survey”, *Astronomy and Astrophysics*, vol. 646, 2021. doi:10.1051/0004-6361/202039655.
- [25] Serra, P., “The MeerKAT Fornax Survey. I. Survey description and first evidence of ram pressure in the Fornax galaxy cluster”, *Astronomy and Astrophysics*, vol. 673, 2023. doi:10.1051/0004-6361/202346071.
- [26] de Blok, W. J. G., “MHONGOOSE – A MeerKAT Nearby Galaxy H I survey”, 2023, submitted to *Astronomy and Astrophysics*.
- [27] Boselli, A., “ViCTORIA project: MeerKAT H I observations of the ram pressure stripped galaxy NGC 4523”, *Astronomy and Astrophysics*, vol. 676, 2023. doi:10.1051/0004-6361/202346812.
- [28] M+ white paper
- [29] DSA2000 Community Science Document
- [30] Zhang, CP., “The FAST all sky H I survey (FASHI): The first release of catalog”, *Sci. China Phys. Mech. Astron.* 67, 219511 (2024). doi:10.1007/s11433-023-2219-7.
- [31] Chowdhury, A., “H I 21-centimetre emission from an ensemble of galaxies at an average redshift of one”, *Nature*, vol. 586, no. 7829, pp. 369–372, 2020. doi:10.1038/s41586-020-2794-7.