

Chapter 8 Our Cosmic History: Atomic Hydrogen (and other Spectral Lines)

Summary: Cosmic History: Atomic Hydrogen

Authors: S. E. Clark (on behalf of the SAC) DSA-2000 will use the 21-cm emission line of atomic hydrogen (HI) to study the detailed distribution of gas in the Milky Way, the reservoirs of gas in nearby galaxies, and the early epochs of structure formation in the universe. There are additional opportunities for DSA-2000 to map other spectral lines, in particular OH and radio recombination lines (RRLs). Storing full-Stokes information for spectral line observations would enable measurements of the line-of-sight magnetic field strength via the Zeeman effect in HI and potentially in OH.

The current baseline design of DSA-2000 is well-suited for studying the evolution of HI in galaxies over cosmic time. DSA-2000 will detect HI in millions of galaxies out to $z \sim 1$, and will resolve many of these systems out to $z \sim 0.2$. These observations will result in a measurement of the HI mass function as a function of redshift (Section 7.1), and will aid the search for electromagnetic counterparts to gravitational waves (Section 7.12). Additionally, the large population of resolved galaxies will enable statistical studies of the kinematics and morphology of gas-rich galaxies (Section 7.2). In the nearby ($D < 100$ Mpc) universe, measurements of rotation curves for resolved galaxies would provide an unbiased census of dark matter density profiles, and thus an important constraint on galaxy evolution theory (Section 7.7). Science with the resolved galaxy population depends on the column density sensitivity of DSA-2000, so augmenting the column density sensitivity via a short baseline array would enhance this science. Additional channels in Zoom Band A could push the completeness of the resolved galaxy population out to 200 or 300 Mpc.

Closer to home, DSA-2000 is capable of making ultra-deep observations of nearby, low-surface-brightness galaxies. Such measurements are important for studying gas cold accretion and galaxy assembly over the full galaxy mass range (Section 7.6). There are two strategies that DSA-2000 could pursue in order to become competitive with MeerKAT for this science: one is to add a compact core, and another is to make deep (50 hour) observations of selected ~ 300 deg² fields. DSA-2000 can also contribute to a large survey of hydrogen radio recombination lines (RRLs), toward ~ 1000 times more sources than are accessible with other upcoming HI surveys (Section 7.9). This science case would strongly benefit from increased spectral resolution in the low-resolution HI channels, as well as increased frequency coverage.

DSA-2000 will make several major contributions to the study of our own Galaxy. High surface brightness sensitivity is critical for the study of diffuse Galactic HI emission, and so the planned DSA-2000 all-sky HI emission survey would be dramatically improved by the addition of a compact array. The high spectral resolution of Tuneable Zoom Band B is capable of resolving cold HI structures in the Galaxy, but increasing the bandwidth could be important for detecting high-velocity gas toward regions such as the Galactic center (Section 7.8). DSA-2000 will produce a sensitive survey of HI absorption over a large region of sky, providing important constraints on the thermodynamic state of the ISM (Section 7.4). However, the current baseline design misses the opportunity to store full-Stokes polarization data in the zoom bands, which would enable critical, direct measurements of interstellar magnetic field strengths via Zeeman splitting of the HI line (Section 7.4) and potentially also of OH, with the addition of further zoom bands (Section 7.8). These measurements would provide crucial information on the magnetic field in the diffuse and molecular ISM, respectively.

Finally, DSA-2000 can also be used as a line-intensity mapping experiment, probing late-time cosmology via measurements of the statistical distribution of 21-cm line emission at $z < 1$ (Sections 7.10, 7.11). The current baseline design offers several advantages over competing experiments, including calibration, systematics, and sidelobe properties that will reduce the foreground leakage that plagues most 21-cm power spectrum measurements. However, this science case would be greatly enhanced by the addition of a compact core array, which would be enabling for measurements of baryon acoustic oscillations.

8.1 Resolved multiwavelength and kinematic studies of atomic gas in all the local galaxies

Authors: Adam K. Leroy

Summary

The proposed DSA 2000 would produce high quality measurements of the structure, quantitative morphology, and kinematics of $> 10^4$ K local galaxies out to ~ 100 Mpc. Existing or planned all-sky multiwavelength coverage that will capture the structure of stars, recent star formation, star clusters, and more for the same samples of galaxies. Combined, this would usher in new era of “big data” for resolved, panchromatic studies of galaxy evolution. The resulting measurements would have the promise to revolutionize our view of (1) how accretion, gas flows, and feedback shape galaxies, (2) how environmental regulates the efficiency of the matter cycle in galaxies, and (3) the link between dark matter and baryons in galaxies. Further, the massive multiplexing power of the DSA 2000 opens the window to truly revolutionary statistical measurements of the extended atomic gas reservoirs and both Galactic and extragalactic 21-cm absorption.

State of the Field

Most of the gas in the disks of galaxies at $z = 0$ is atomic hydrogen (H I) (e.g., Saintonge and Catinella 2022a), and this is likely true across almost all redshifts (e.g., Tacconi, Genzel, and Sternberg 2020). Though stars form directly from molecular gas, observations of the atomic gas capture the ultimate reservoir of material for star formation. Comparing the atomic gas to the distribution of recent star formation over a part of a galaxy represents an important probe of the overall efficiency of the gas-stars-feedback “matter cycle” that governs the buildup of galaxies. Meanwhile, the extended structure of the gas (e.g., Wang et al. 2016b) means that the H I kinematics represent one of our most powerful ways to trace the dark matter in galaxies (e.g., Bullock and Boylan-Kolchin 2017). All of this makes resolves 21-cm mapping of galaxies, which traces the mass and kinematics of the H I, critical to probe a tackle a series of big, open astronomical questions.

Although 21-cm observations represent one of our oldest methods of tracing the interstellar medium in galaxies (Kerr, Hindman, and Robinson 1954), the faintness and low frequency of the line have made it challenging to obtain large samples of high quality, high resolution 21-cm maps of galaxies. At present, a few hundred to $\lesssim 1,000$ 21-cm maps of good quality (resolution $\lesssim 20''$ and sensitivity to $N(H) \sim 10^{20} \text{ cm}^{-2}$) exist from the combined efforts of previous-generation radio telescopes, compared to integrated 21-cm measurements for 10,000s of galaxies.

Meanwhile, recent and upcoming facilities are mapping the whole sky at these $\lesssim 10''$ resolution across the electromagnetic spectrum, providing a resolved view of the recent star formation, stellar content, and more for local universe galaxies. WISE, GALEX, SDSS, and soon Rubin/LSST, SphereX, and perhaps UVEX, and more will cover the sky from infrared to ultraviolet wavelengths at a resolution sufficient to resolve local universe galaxies (out to $\sim 50\text{--}100$ Mpc). The multiwavelength coverage means that we have (or will soon have) a resolved view of the stellar population, star formation rate, and structure of the stellar disk in essentially all local galaxies.

DSA-2000's impact

The DSA-2000 would yield high S/N, resolved 21-cm maps of $\approx 10,000$ local $d \lesssim 100$ Mpc galaxies of all masses. This would represent an order of magnitude increase over current samples of 21-cm mapping, and would combine with this existing or planned panchromatic all-sky coverage to yield a complete, resolved view of baryons in across all types of galaxies. This would yield local measurements of the efficiency with which the “matter cycle” converts gas to stars, measure the morphology of the ISM across the star-forming main sequence, map out the halo mass-stellar mass relation for galaxies, and more. The complete sky coverage would also open the door to incredible stacking experiments, probing the atomic gas out into the CGM and potentially revealing the physical state of the atomic gas in the Milky Way and other galaxies via stacked absorption studies.

These all-sky multiwavelength surveys (and the lack of similar high resolution, high sensitivity 21-cm surveys for the northern sky) represent a huge opportunity for a telescope like the DSA-2000. Using the “zoom bands” and focusing on the 21-cm line, the proposed facility would yield: (1) 21-cm maps that could be compared to measurements of star formation, stellar mass, and more to measure the efficiency of the “matter cycle” and the structure of the neutral gas reservoirs in galaxies, (2) 21-cm kinematics that, together with measurements of the stellar structure probe the structure of dark matter in galaxies, and (3) absorption measurements against background continuum sources that probe the physical state of the atomic gas in our galaxy and others.

Concretely, based on likely sensitivity estimates in March 2023, a DSA-2000 ~ 4 h-per-point all-sky survey would detect the canonical edge of the H I disk of galaxies, typically taken to be $\sim 1 \text{ M}_\odot \text{ pc}^{-2}$, at $S/N \approx 5$ at $\sim 15''$ resolution (the performance could be even better depending on the exact design of the array). Based the H I mass-size relation of Wang et al. 2016b, this would allow the DSA-2000 to resolve (placing ~ 5 resolution elements across) an L_* galaxy like the Milky Way at ~ 100 Mpc, a dwarf spiral like the LMC at ~ 50 Mpc, a dwarf like the SMC at ~ 25 Mpc, and galaxies analogous to the smaller Local Group dwarfs out to ~ 10 Mpc. Based on the HyperLEDA database (Makarov et al. 2014), there are $\sim 10,000$ “Milky Ways” known out to ~ 100 Mpc, $\sim 4,000$ “LMCs” out to ~ 50 Mpc, $\sim 3,000$ “SMCs” out to ~ 25 Mpc, and ~ 400 analogs to Local Group dwarfs out to ~ 10 Mpc. Thus even leaving aside the exciting prospect of discovering many new dwarf galaxies, the DSA-2000 can be expected to provide $\gtrsim 20,000$ resolved maps of the distribution and kinematics of atomic gas in galaxies. This on its will represent an order of magnitude improvement over the results of the previous several decades of 21-cm mapping using the VLA, WSRT, GMRT, and ATCA.

These data have immense scientific potential. We highlight three direct applications of the DSA-2000 survey here. First, the data would allow resolved, quantitative H I morphology measurements for all of these galaxies, which can then be immediately related to the stellar mass and star formation rate of each galaxy to chart out how the distribution of atomic gas within galaxies determines their current properties and future evolution (a topic that has been highly productive in understanding evolution of galaxies in cluster environments, e.g., Cortese, Catinella, and Smith 2021). Second resolve kinematic measurements paired with stellar structure, environmental metrics, and stellar mass mass estimates promise to populate the stellar mass halo mass relation with tens of thousands of diverse, well-understood galaxies, which should yield critical insight into both galaxy assembly (e.g., Wechsler and Tinker 2018) and the nature of dark matter (especially from well resolved, low mass, low baryon fraction galaxies, e.g., Bullock and Boylan-Kolchin 2017). Third, for each galaxy, the combination of the DSA-2000 and panchromatic data will measure the local balance of neutral gas to current star formation activity. This will chart how effective each part of each local galaxy is at concentrating the gas into cold, dense, star-forming objects. This efficiency is well-known to vary within galaxies, e.g., as a function

of local stellar surface density, interstellar pressure, or metallicity (e.g., Leroy et al. 2008), but to date we lack the “big data” needed to complete a general, tested theory that covers the full matter cycle in galaxies.

The potential of the DSA-2000 is even higher when one considers the combination of multiwavelength all sky surveys with this new 21-cm mapping. From the multiwavelength data we will have an excellent prior idea of the mass, orientation, location, and other properties of each galaxy. The all-sky DSA-2000 coverage should, in principle, be well-suited to coherently average the emission from hundreds, or even thousands of similar galaxies. This allows the prospect of statistical “ultradeep” experiments probing low column density H I via stacking or cross-correlation or more advanced techniques. In the simplest term, simply averaging 4 h DSA-2000 observations of 10,000 Milky Way mass galaxies would yield the equivalent (in some ways) of a 40,000 h stare towards the galaxies with a current generation interferometer. Though there are caveats this $10\text{--}100\times$ increase in surface brightness sensitivity may represent the critical leap to reach the column densities expected for the neutral CGM and so offer a powerful probe the most mysterious (but critical) portion of a galaxy’s gas reservoir (e.g., Tumlinson, Peebles, and Werk 2017).

The directions above describe possibilities for emission based studies, but 21-cm absorption also has large scientific potential. Atomic gas in galaxies spans $T \sim 50\text{--}5,000$ K and $n \sim 0.1\text{--}100\text{ cm}^{-3}$, and while 21-cm emission is equally sensitive to all gas, the optical depth accessed by absorption is sensitive to temperature and is key to diagnose the physical state of the gas (e.g., Murray et al. 2018a). To date, 21-cm absorption studies have been mainly restricted to the Milky Way and focused on dedicated observations of bright quasars. Using the high resolution zoom mode, the DSA-2000 would cover every continuum source in the northern sky with similar measurements. This is on its own a potentially powerful data set (discussed elsewhere in this book). The truly transformative (though admittedly uncertain) potential comes from full-sky, deep high resolution coverage of the full radio continuum point source population. Without requiring any additional pointings, the DSA-2000 can potentially capture absorption from both the Milky Way and external galaxies for every continuum source in the sky. If the likely velocity of absorption can be identified to sufficient precision, the radio point source population may potentially be averaged coherently to make powerful statistical statements about the optical depth and spin temperature of the atomic gas and the abundance of the cold neutral medium across a very wide range of environments. Though some technical development work would be needed, we argue that this prospect is exciting enough to merit special consideration in the survey design.

System requirements / desired additions to baseline design

The critical capabilities for this science are the 21-cm zoom bands, an array configuration that yields good surface brightness sensitivity at $\sim 3\text{--}60''$ scales, and as much collecting area and integration per point as possible. The absorption science and detailed ISM science in nearby well-resolved galaxies benefit from the high resolution zoom, 0.22 km s^{-1} or at least $\lesssim 0.5\text{ km s}^{-1}$ to resolve cold H I line profiles. The 21-cm emission-based science benefits from wide coverage at good velocity resolution, and the proposed tunable zoom band A or something close are critical for this. A plan to test the short and zero spacing recovery and integrate with a single dish facility to ensure complete flux recovery will also be an important technical consideration.

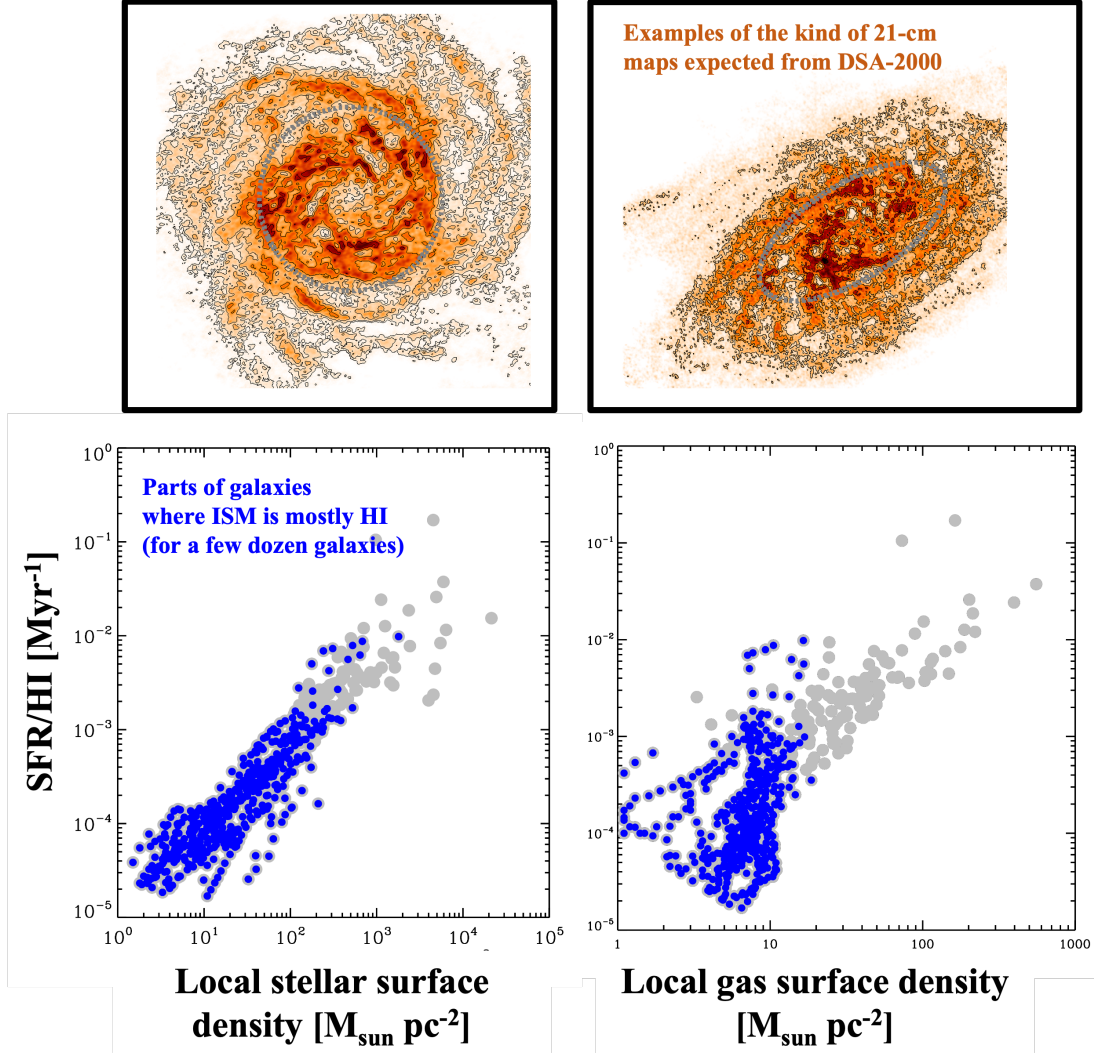


Figure 8.1: Examples from Walter et al. 2008 of the kind of maps (here from THINGS) that the DSA-2000 will produce for all local galaxies. Previously these have required dedicated, expensive array observations, and therefore even after decades, the current sample of such maps cover $< 1,000$ galaxies. The bottom row shows how the combination of 21-cm and multiwavelength data tracing stellar mass and recent star formation capture systematic variations in the efficiency of the ability of the ISM to form stars. Here the plots show a few dozen galaxies from Leroy et al. 2008, but with the DSA-2000 and new all-sky multiwavelength surveys, such coverage would extend to 10,000 or more galaxies, giving a definitive statistical, resolved view of the efficiency of the matter cycle in galaxies.

8.2 Galaxies in the Local Universe

Authors: David Cook, Joseph Mazzarella, George Helou

Summary

Galaxies in the local Universe play vital roles in many astrophysical research domains from galaxy evolution and star formation to finding the hosts to and understanding the environments of exotic transient events (sGRBs, FRBs, kilonovae, etc.). Consequently, understanding the completeness of known galaxies in the local Universe has become an important topic. The NASA/IPAC Extragalactic Database (NED) has recently developed a local volume sample (NED-LVS) which shows that the percentage of cataloged galaxies compared to expectations is 70% by NIR luminosity out to 300 Mpc but significantly decreases at further distances. The number of HI detected galaxies with accompanying redshifts from DSA-2000 will significantly increase the completeness of local galaxies and provide key HI gas mass measurements that are key ingredients for star formation.

State of the Field

One of the main science drivers for increasing the completeness of galaxies in the local Universe is the search for electromagnetic counterparts to gravitational wave (GW) events. The detection of GWs (Abbott et al. 2016) by the LIGO-Virgo collaboration (and later by the LIGO-Virgo-KAGRA collaboration; hereafter LVK) has opened a new window onto the Universe, but many of the most exciting discoveries from GWs are only possible when the electromagnetic (EM) counterpart is detected and studied concurrently. The EM counterpart to only one such event has been found to date (GW170817), yet has yielded remarkable results: constraints on the speed of GWs (Abbott et al. 2019), the origin of most metals heavier than iron (Kasliwal et al. 2017b), and an independent measure of the Hubble constant (Abbott et al. 2017d). Now the race is on to find a population of these events. However, due to the poor sky localizations of GW events, these searches will be difficult for the next several years where they will be limited by the availability and quality of galaxy catalogs.

the NASA/IPAC Extragalactic Database-Local Volume Sample (NED-LVS) is composed of nearly 1.9 million extragalactic objects with distances less than 1 Gpc (Cook et al. 2023; submitted). NED-LVS contains photometry from all-sky surveys (GALEX, 2MASS, and AllWISE) that are used to derive physical properties (M_* and SFR) via integrated-light scaling relationships from WISE luminosities, where 88% of objects have estimated values. The completeness of NED-LVS relative to the GALEX NUV and 2MASS K_s -bands are $\sim 100\%$ out to ~ 30 Mpc. Past this distance, the completeness relative to NIR luminosities (which trace a galaxy's stellar mass) remains moderate (70%) out to 300 Mpc (Fig 8.2). In addition, when considering only galaxies with luminosities brighter than L_* , NED-LVS is $\sim 100\%$ complete out to 450 Mpc. A comparison to other local Universe samples shows that NED-LVS is more complete by number than both GLADE (Dályá et al. 2018) and HECATE (Kovlakas et al. 2021) by 10% and 30%, respectively, in the appropriate limiting distances. Measuring completeness by luminosity, NED-LVS is more complete than both GLADE and HECATE by $\sim 10\text{-}20\%$ at distances beyond ~ 80 Mpc.

Neutral hydrogen gas (HI) is a key component of the ISM of galaxies and makes up the majority of the total baryonic mass in star-forming galaxies (e.g., Catinella et al. 2018). However, given the relatively weak tracer of HI gas, the 21 cm line at 1420 MHz, studies of this key component are difficult even at intermediate redshifts ($z \sim 0.2$; Cortese, Catinella, and Janowiecki 2017). Efforts of blind HI surveys in past decades have made significant progress in mapping the HI content of galaxies (HIPASS, ALFALFA, etc.; Barnes et al. 2001a;

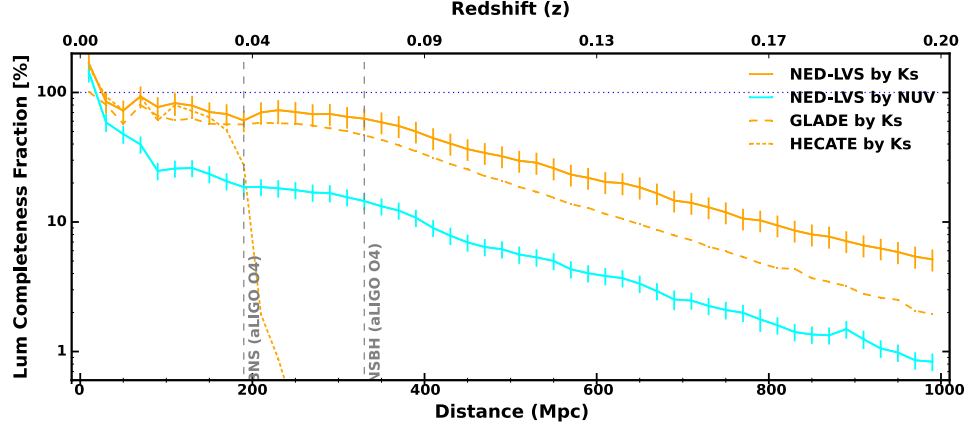


Figure 8.2: The completeness of the NED-LVS catalog as defined by the fraction of luminosity in available bands from 2MASS- K_s (orange) and GALEX- NUV (cyan) to the total luminosity derived from published luminosity functions. We find that NED-LVS in the NIR is highly complete at distances less than 30 Mpc and remains moderately (70%) complete out to 300 Mpc.

Giovanelli et al. 2005a), but are largely limited to more massive galaxies ($M_\star > 10^9 M_\odot$ at 100 Mpc; Haynes et al. 2011)). More recent HI surveys such as WALLABY (Koribalski et al. 2020a) will find an estimated 500,000 galaxies out to a redshift of 0.26, but will still be limited to more massive galaxies due to moderate sensitivities (1.6 mJy per beam; Duffy et al. 2012).

DSA-2000's impact

The DSA-2000 survey will provide the most complete census of HI galaxies in the local Universe given the 500 nJy per beam sensitivities across 3π sky. Based on the semi-analytical models of Obreschkow et al. 2009, it is estimated that the full DSA-2000 survey data will detect approximately 2 million star-forming galaxies out to intermediate redshifts ($z < 0.2$). To put this into context, there are ~ 2 million known galaxies in NED-LVS, where roughly half are star-forming in nature (using UV and MIR colors). Thus, DSA-2000 will provide or discover an additional 50% of known galaxies. These galaxies, their distances and HI masses, will significantly increase the search efficiency for exotic transients and provide needed data for studying the gas reservoirs out to cosmic noon.

System requirements / desired additions to baseline design

N/A

8.3 DSA-2000 Extragalactic HI Surveys

Authors: Marcel Neeleman, Ryan Keenan, Fabian Walter, Leindert Boogaard

Summary

The DSA-2000 will provide an unprecedented improvement in our ability to detect HI-21 cm emission from galaxies out to $z \sim 1$. The all sky survey will detect millions of galaxies in HI emission, while deeper survey tiers will produce the first large samples of $z > 0.1$ HI detections. This will provide a leap forward in our understanding of the role HI plays in the formation and evolution of galaxies.

State of the Field

Spectral line emission from HI plays a vital role in our understanding of galaxy evolution Saintonge and Catinella 2022b. Over the past 25 years projects at a wide range of telescopes carried out surveys of HI emission in the nearby universe (Barnes et al. 2001b; Giovanelli et al. 2005b; Fernández et al. 2016a; Xi et al. 2021), resulting in detections of tens of thousands of galaxies. A new generation of radio telescopes, including the SKA pathfinders and large single dishes, are now pushing these surveys to greater depths and higher redshifts (Koribalski et al. 2020b; Adams et al. 2022a; Glowacki et al. 2022; Rhee et al. 2023a; Zhang et al. 2023).

Figure 8.3 shows the landscape of these surveys in terms of sensitivity, sky coverage, and redshift range. Current blind HI surveys must make a tradeoff between survey area and survey depth. Future facilities, lead by the DSA-2000, will carry out much deeper large area surveys, measuring the gas properties of millions of galaxies.

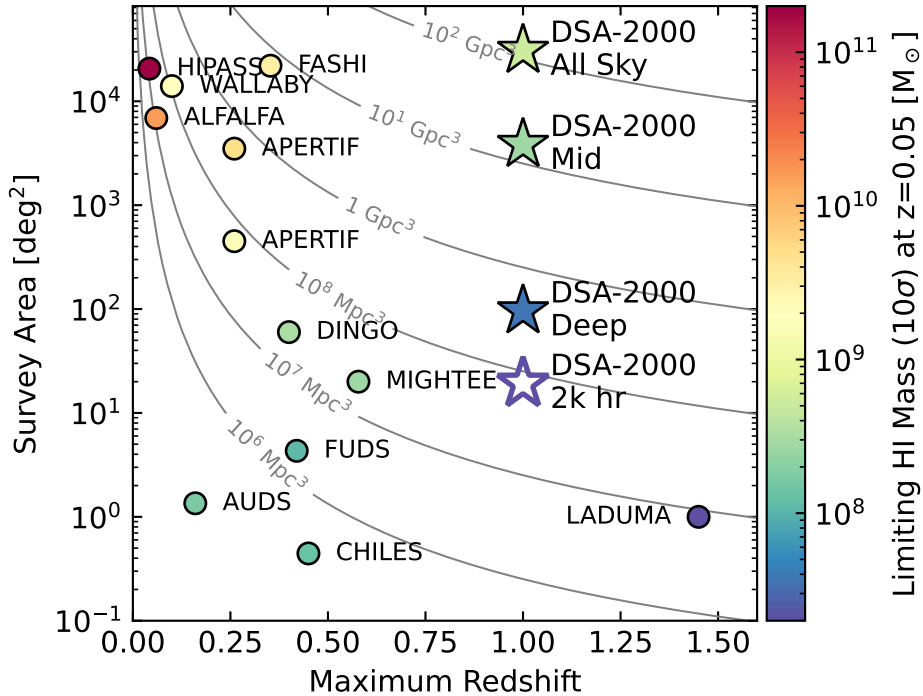


Figure 8.3: Comparison of the survey area, maximum redshift, and HI mass sensitivity of the planned DSA-2000 HI surveys (filled stars), a hypothetical DSA-2000 ultra-deep field (open star), and a selection of completed and ongoing extragalactic HI surveys (circles). Curved gray lines indicate constant total survey volume. Points are color coded according to the limiting HI mass that they can detect at $z = 0.05$.

Forecasts for the DSA-2000

We take two approaches to modeling the population of HI emitting galaxies that will be observed by the DSA-2000. In the first, we assume the local HI mass function (Jones et al. 2018), HI mass-size relation (Rajohnson et al. 2022; Wang et al. 2016c), and baryonic Tully-Fischer relation (Ponomareva et al. 2021) are unchanging over $0 < z < 1$ and use these relations to predict the number counts of galaxies that will be seen by the DSA-2000 surveys. We refer to these predictions as the “local relations forecast”. In the second, we use output from the SHARK semi-analytic model (SAM; Lagos et al. 2018) which tracks the growth and evolution of atomic and molecular gas reservoirs in dark matter halos from the Millennium simulation. Galaxies from the SAM are used to create a mock catalog for the DSA-2000 all sky survey including information about the HI mass, line-width, and disk size for each galaxy. We refer to this set of predictions as the “SAM forecast”. Figure 8.4 shows a slice of the sky based on both of these forecasts. The two approaches are selected to be representative of a range of possible scenarios that the DSA-2000 might observe (and differentiate). In particular the SAM approach produces cool gas masses broadly consistent with current knowledge of the nearby and high redshift universe within a framework that also accounts for evolution of galaxy masses, sizes, and star formation rates. This results in predictions for the evolution of galaxy counts and HI mass functions which the DSA-2000 will be able to test. On the other hand, the local relations model produces forecasts that are maximally consistent with our knowledge of HI in the local universe, and represent a scenario in which the mass function has remained unchanged over time - consistent with current observations that cosmic HI density has been roughly constant since $z \sim 2$.

For both approaches, we calculate the fraction of galaxies the DSA-2000 can detect in HI as a function of HI mass and redshift, accounting for the angular size and line-width of each HI emitter. To consider a DSA-2000 survey capable of studying galaxies of a given M_{HI} and z we require that at least 90% of such galaxies be detected at 10σ or above. This may be overly conservative for the deep field surveys, in which galaxies near the sensitivity threshold will typically be unresolved and may have known optical counterparts to help in their identification.

In Figure 8.5 we show the redshift ranges and effective survey volumes over which the various DSA-2000 surveys can detect galaxies as a function of their HI mass. We consider the three planned DSA-2000 survey tiers – the all-sky survey (3π steradians), the pulsar timing fields (200 pointings observed for approximately 50 hours each), and deep-drilling fields (5 pointings observed for approximately 400 hours each) – as well as a hypothetical ultra-deep field consisting of a single 2,000 hour pointing. For comparison, we also show the results for a mock of the ALFALFA survey using our local relations forecast and a detection requirement of 5σ .

DSA-2000’s impact

The DSA-2000 will provide a two order of magnitude increase in effective survey volume relative to previous wide-field HI surveys for sources at any HI mass. Among the most massive HI reservoirs, which can be detected over the full DSA-2000 all sky survey volume, the gain in volume is a factor of a few thousand. At the same time, deeper survey tiers will detect galaxies at the turnover mass of the HIMF (M_{HI}^*) out to $z \sim 0.5$ and an ultra-deep survey tier could potentially detect these galaxies over the full redshift range ($0 < z < 1$).

Table 8.1 gives the expected number of galaxies the DSA-2000 will detect in HI for both of our models. Figure 8.6 shows the expected distribution of these galaxies in redshift and HI mass. The distributions for the all sky survey and pulsar timing surveys are similar, with peaks around $z \sim 0.1$ and $M_{\text{HI}} \sim 10^{10} M_{\odot}$. The deeper fields provide complimentary coverage of the parameter space, with improved sensitivity to

$M_{\text{HI}} < M_{\text{HI}}^*$ and broader redshift distributions.

For the most massive HI reservoirs, extrapolation of the local HIMF assuming an exponential decline at the high-mass end results in the prediction that no objects with $M_{\text{HI}} > 10^{11.5} M_{\odot}$ exist. On the other hand, the such galaxies are predicted by some galaxy evolution models including the SHARK semi-analytic model. The DSA-2000 all sky survey is the only planned project with any facility that achieves both the sensitivity and survey volume necessary to detect such galaxies. The number of such galaxies detected will be a unique test of galaxy evolution models, and provide new insights into feedback and the baryonic processes affecting the most massive dark matter halos in the universe.

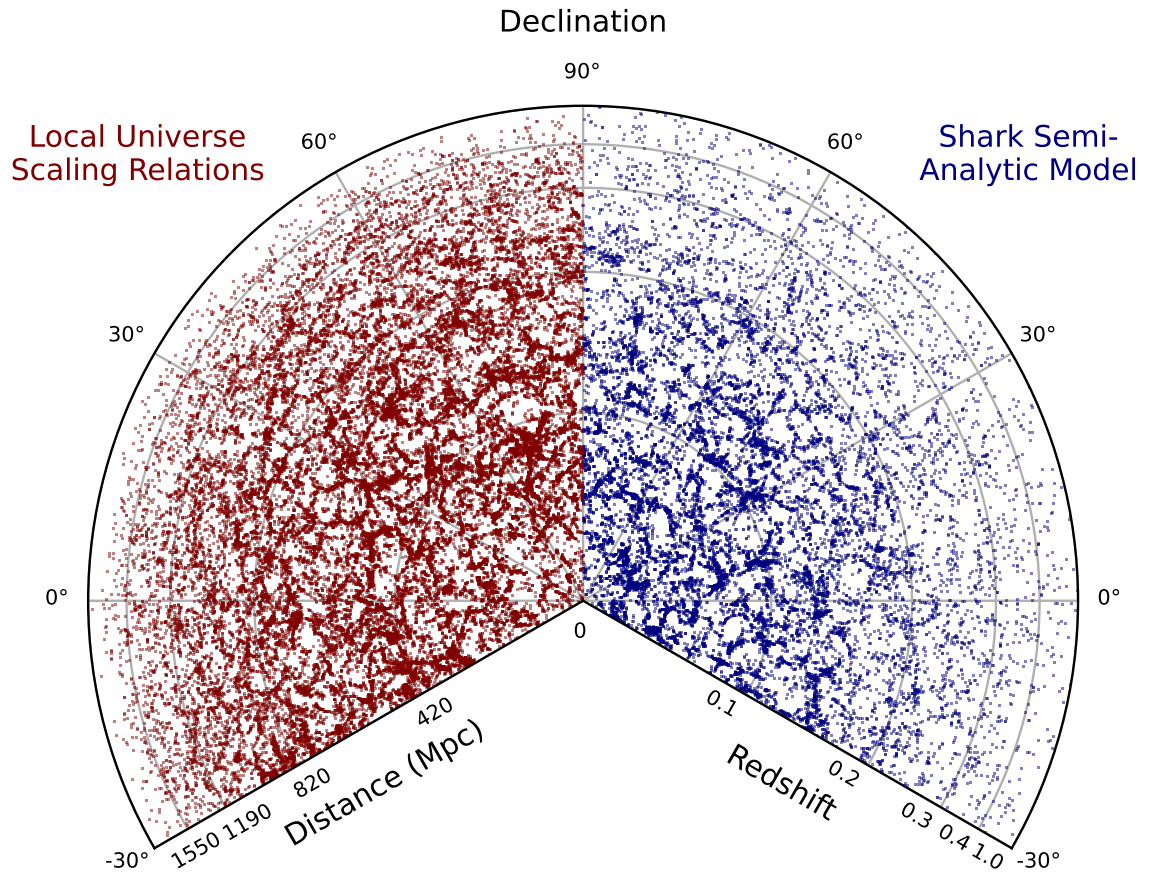


Figure 8.4: Positions of HI sources detected by the DSA-2000 all sky survey in a 1 degree slice in RA. The model derived from local scaling relations is shown on the left and from the SHARK SAM on the right.

Table 8.1: Number of HI detections expected for DSA-2000

Survey	Number (SHARK SAM)	Number (Local Scaling Relations)
DSA-2000 All Sky	1.95 Million	5.96 Million
DSA-2000 Pulsar Fields	170,000	450,000
DSA-2000 Deep Fields	40,000	90,000
DSA-2000 Ultradeep Field	—	60,000
ALFALFA	—	25,437 (Jones et al. 2018)
HIPASS	—	4,315 (Zwaan et al. 2005)

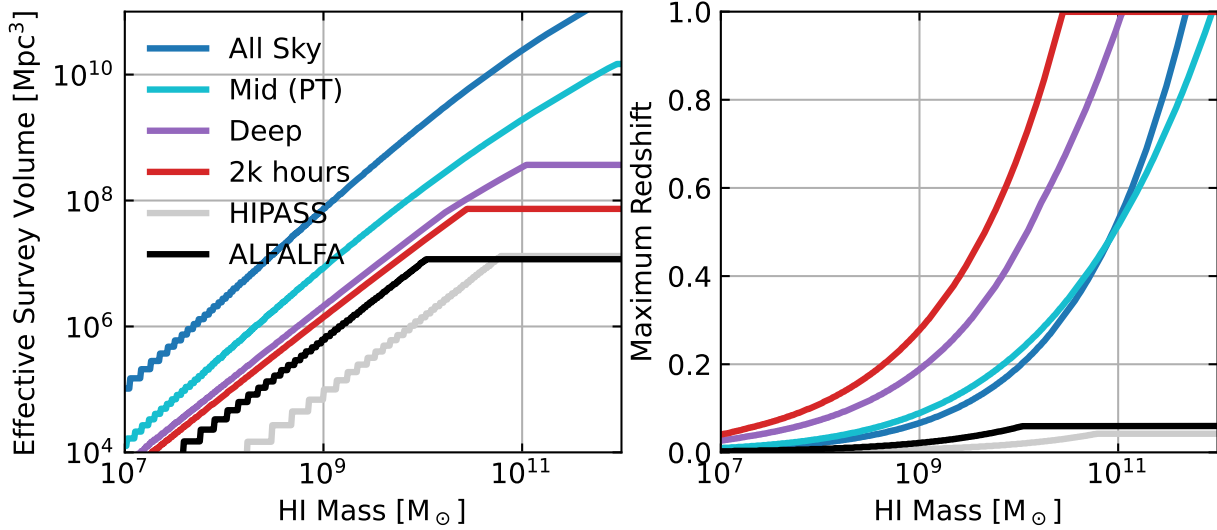


Figure 8.5: The redshift range and survey volume over which DSA-2000 surveys will detect the HI line as a function of HI mass. An estimate for ALFALFA is shown in black for comparison. The all sky survey can detect HI reservoirs of any mass over a volume more than 100 times greater than the previous generation of wide field surveys, and the most massive HI disks over a volume $\sim 3,000$ times greater. This will result in HIMF measurements in a sample essentially immune to cosmic variance. The deep drilling fields will detect M_{HI}^* galaxies up to $z \sim 0.5$, while a hypothetical ultra-deep field could detect these galaxies to $z \sim 0.7$ when the universe was less than half of its present age.

System requirements / desired additions to baseline design

The baseline design is sufficient for most of the science described here. To ensure detections of HI from $z \sim 1$ galaxies, the addition of an ultra-deep survey tier, consisting of 5% of the total observing time ($\sim 2,000$ hours) spent on a single field is necessary.

Storage Requirements: *to aid in planning for data storage requirements, we have estimated the space required to save cutout spectral cubes for each galaxy detected in HI and provide these values in Table 8.3. For this calculation we have assumed cutouts will be at least three times the HI diameter of the galaxy, and consist of 1,000 spectral channels for nearby ($D < 100$ Mpc) galaxies and 100 channels for distant ($D > 100$ Mpc) galaxies. We use the higher expected number counts from the local relations forecast, and assume, unlike elsewhere in this chapter, that galaxies can be detected in frequency ranges with significant RFI. We assume all cutouts are saved with $1''$ pixels and that each pixel requires 4 bytes of disk space.*

Table 8.2: Project requirements compared to DSA-2000 baseline reference design

DSA-2000 baseline reference design		match to project
Ultra Deep Field	Not included	$\sim 2,000$ hour integration on a single field

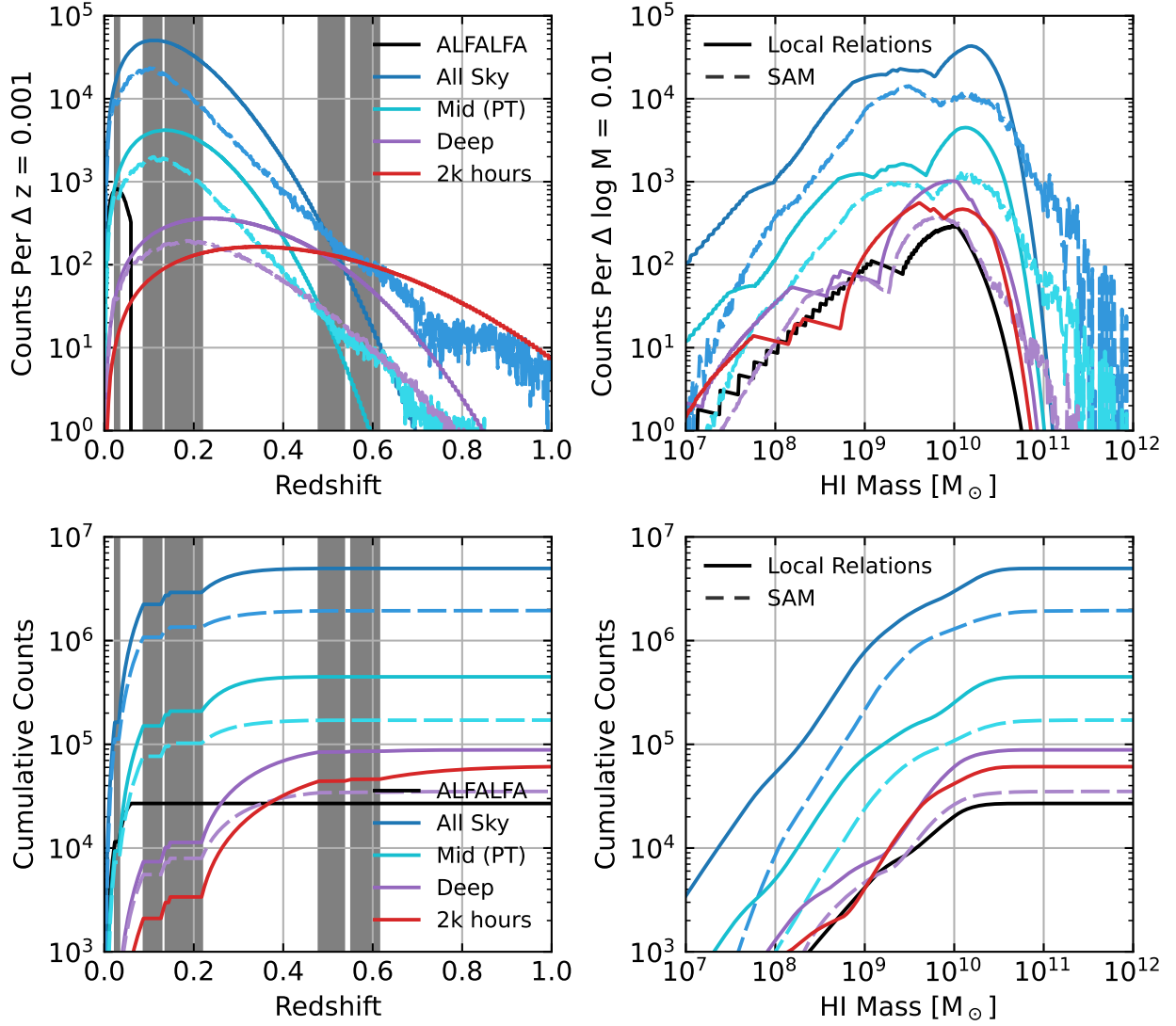


Figure 8.6: Expected HI number counts as a function of redshift (left) and mass (right) for the DSA-2000 (10σ detections) and ALFALFA (5σ detections). Solid lines show predictions from our local relations forecast, while lighter dashed lines show the predictions of the SAM forecast (no SAM predictions are shown for the 2,000 hour field or ALFALFA). Gray bands in the left panel show the locations of a major satellite RFI bands. Galaxies falling in the RFI bands are excluded from the counts in the right hand panel, and the total number counts given in Table 8.1. Number counts are shown in bins of $\Delta z = 0.001$ or $\Delta \log M_{\text{HI}} = 0.01$ in the upper panels, and cumulatively in the lower panels.

Table 8.3: Disk Storage Requirements for HI Cutouts

Cutout Size	Number of Cutouts	Total Size
<i>D</i> < 100 Mpc		
60'' × 60''	7.37e4	1.06 TB
120'' × 120''	5.26e4	3.03 TB
240'' × 240''	3.30e4	7.61 TB
600'' × 600''	1.73e4	24.94 TB
1200'' × 1200''	1.93e3	11.13 TB
3600'' × 3600''	2.63e2	13.69 TB
<i>D</i> > 100 Mpc		
60'' × 60''	6.58e6	9.47 TB
120'' × 120''	3.02e6	17.42 TB
240'' × 240''	2.62e5	6.04 TB
600'' × 600''	1.76e4	2.54 TB
1200'' × 1200''	2.97e1	0.02 TB
Total		96.94 TB

8.4 HI Mass Functions and the Mean Atomic Gas Density of the Universe

Authors: Ryan Keenan, Marcel Neeleman, Fabian Walter, Leindert Boogaard

Summary

The DSA-2000 will detect millions of galaxies in HI with no pre-selection enabling an unbiased determination of the HI mass function and integrated cosmic HI content over three-quarters of the sky and $\sim 60\%$ of cosmic history (up to $z \sim 1$). The planned DSA-2000 all-sky survey can detect the most massive HI reservoirs over a volume $> 10^3$ times larger than previous the previous generation of wide-field surveys (ALFALFA and HIPASS), constraining the HI mass function to number densities a factor of 10^7 below the knee mass (M_{HI}^*) and providing unprecedented constraints on how feedback shapes the neutral gas content of the most massive dark matter halos. At the same time, the DSA-2000 will detect millions of sub- M_{HI}^* galaxies, constraining the low-mass behavior of the mass function over a volume essentially immune to cosmic variance and resolving the the discrepancies in this parameter seen by previous surveys. The pulsar timing and deep-drilling fields will add detections of sub- M_{HI}^* galaxies out to $z \sim 0.5$, providing a direct test for evolution in the shape of the HI mass function over the past 5 billion years.

State of the Field

The mass functions of atomic and molecular gas provide a global picture of the material available to fuel new star formation and galaxy growth. Together with the distributions of star formation and stellar mass, gas mass functions can be used to understand how galaxies process of baryonic matter into stars and collapsed objects over cosmic history (Walter et al. 2020; Péroux and Howk 2020). At the same time, comparison between the gas mass functions and the halo mass function provide insights into the feedback processes that shape the growth of galaxies.

Measurements of the star formation rate and stellar mass distribution functions are now available over a significant fraction of cosmic history (Madau and Dickinson 2014). Pioneering work in the millimeter regime has provided constraints on the molecular gas mass function out to $z \sim 5$ (Decarli et al. 2020; Pavesi et al. 2018; Lenkić et al. 2020; Boogaard et al. 2023). However, owing to the faintness of HI direct measurements of the mass function of atomic gas have thus far been limited to the very nearby universe ($z < 0.1$; Jones et al. 2018; Zwaan et al. 2005). This results in a significant gap in our inventory of the baryon matter in galaxies over the first 12.5 billion years of their assembly. The lack of HI mass function (HIMF) measurements outside the local universe is particularly glaring, as this phase represents the interface between material accreting from the cosmic web and the fuel reservoir available for star formation in galaxies.

At much higher redshifts ($z > 2$), we can use the HI Lyman- α absorption to study the mean HI density (ρ_{HI} ; Noterdaeme et al. 2012; Prochaska and Wolfe 2009), providing an integral constraint the HIMF. These studies find that an evolution in the cosmic HI content from $z \sim 2$ to $z \sim 3.5$, but the value of ρ_{HI} at $z \sim 2$ is consistent with the value found by emission line studies in the local universe. This suggests that the HI content of the universe has been remarkably flat over the past 10 Gyr. Unfortunately directly constraining ρ_{HI} during this period is challenging because Lyman- α emission cannot be observed from the ground at these wavelengths (Neeleman et al. 2016), and current HI-21cm observatories lack the sensitivity to probe HI in large samples outside the local universe.

In the nearby universe the HIMF has been measured to high precision by the ALFALFA and HIPASS projects (Zwaan et al. 2005; Jones et al. 2018). However, these surveys are fundamentally limited by cosmic

variance due to the finite volume of the nearby universe. ALFALFA found the low mass slope of the HIMF differed by more than three times the statistical uncertainty when comparing their observations of the Fall and Spring skies. Advances in this regard will require surveys of larger volumes, which can be achieved only through an all sky survey, the inclusion of a larger redshift range, or both.

DSA-2000's impact

The DSA-2000's all sky survey will expand the volume over which HI reservoirs at a given mass can be detected by at least two orders of magnitude compared to the previous generation of wide-field HI surveys (e.g. ALFALFA and HIPASS). This will result in measurements of the HIMF over volumes essentially immune to cosmic variance. The large volumes will also enable robust measurements of environmental variations in the shape of the HIMF.

Figure 8.7 shows the expected constraints on the $z < 0.1$ HIMF, along with the measurement from ALFALFA (Jones et al. 2018). The DSA-2000 will constrain the mass function with high precision, and can easily differentiate different models in mass ranges where they differ. At the low mass end current surveys are limited by cosmic variance, as can be seen by the significant discrepancy between the ALFALFA measurements of the spring and fall skies. Compared to ALFALFA, the DSA-2000 all sky survey yields a two order of magnitude increase in the volume over which HI reservoirs of any given mass can be detected.

Figure 8.8 shows the HIMF measurements and uncertainties for select redshift bins. We consider the the DSA-2000 all sky survey alone or in combination with either the planned deep fields. In the deep-drilling fields, the DSA-2000 will detect galaxies at the knee of the HIMF out to $z \sim 0.5$, allowing for direct measurements of the HIMF over the past 5 billion years of cosmic history. This will constrain if, and how, HI reservoirs of “typical” galaxies have changed over a period during which the cosmic star formation rate density and molecular gas density have fallen by $\sim 75\%$. We also consider the HIMF constraints possible with an ultra-deep field, consisting of 2,000 hours spent on a single pointing. The inclusion of an ultra-deep (2000 hour) field would extend the redshift range to $z \sim 0.8$ or above, covering more than half of cosmic history and probing the HIMF at the end of cosmic noon.

Figure 8.9 shows the expected constraints on the cosmic HI density (ρ_{HI}) in comparison to a compilation of literature measurements from Walter et al. 2020. For lookback times of 0 to 4 Gyr the all sky survey can constrain ρ_{HI} in bins of 0.5 Gyr with essentially negligible error bars. At earlier times, the inclusion of deep or ultra-deep fields will provide competitive measurements out to $z \sim 1.0$. The DSA-2000 will map out the atomic gas history over more than half of cosmic history, providing accurate measurements of $\Omega(\text{HI})$ over a range in cosmic time currently not well-constrained.

System requirements / desired additions to baseline design

The baseline design is sufficient for most of the science described here. However, to measure the HIMF at the highest redshifts accessible to the DSA-2000, the addition of an ultra-deep survey tier, consisting of 5% of the total observing time ($\sim 2,000$ hours) spent on a single field is necessary.

Table 8.4: Project requirements compared to DSA-2000 baseline reference design

DSA-2000 baseline reference design		match to project
Ultra Deep Field	Not included	$\sim 2,000$ hour integration on a single field

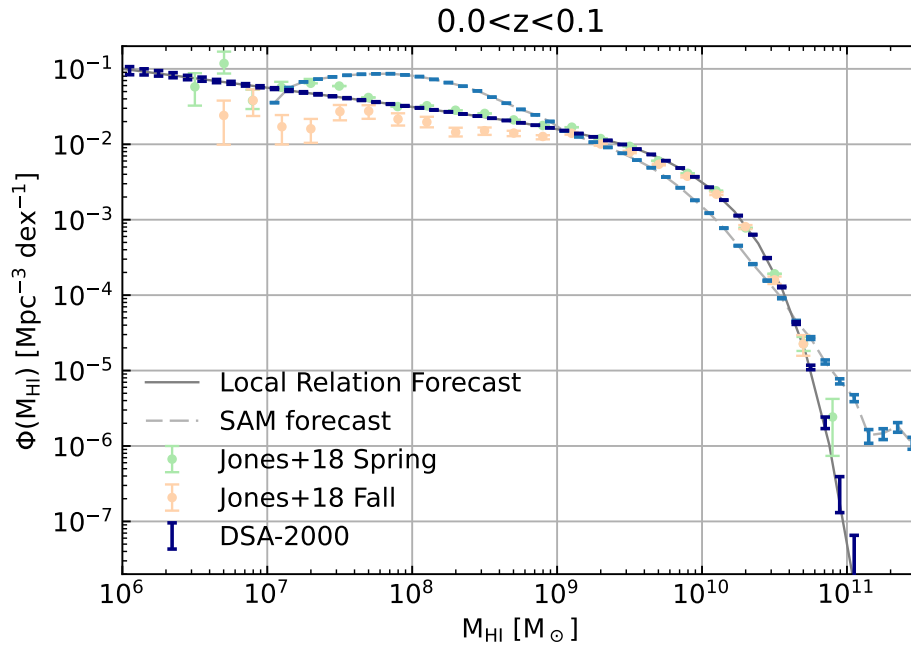


Figure 8.7: Lines show the $z \sim 0$ HIMFs from the “local relations” (black solid) and “SAM” (gray dashed) forecasts from Chapter 8.3, while blue error bars show the expected DSA-2000 measurement in HI mass bins of 0.1 dex for either model. Measurements from ALFALFA in their spring and fall fields are shown by light green and orange points.

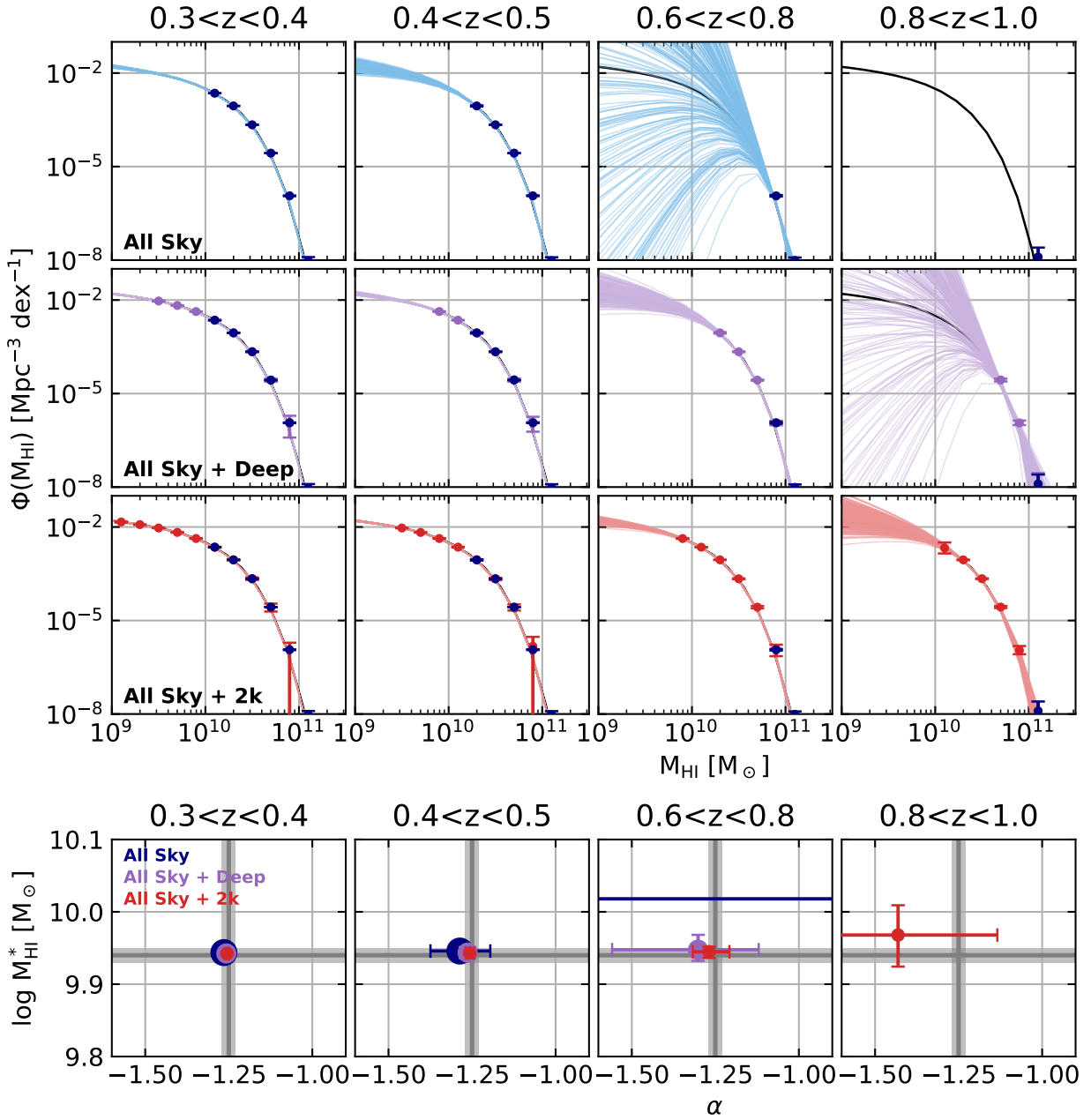


Figure 8.8: Simulated measurements of the HIMF for the DSA-2000 all sky survey alone (blue, top row), or combined with the deep fields (purple, second row) or an ultra-deep field (red, third row). Points and errorbars show the median value and uncertainty for bins of 0.2 dex. In many cases the errorbars are smaller than the markers. Thin colored lines show best fitting Schechter functions for 250 simulated skies generated with the “local relations” forecast from the Chapter 8.3. The black lines show the “true” HIMF underlying our models. The bottom row shows the median and uncertainty in the slope (α) and knee mass (M_{HI}^*) for the Schechter fits. The DSA-2000 all sky plus deep fields can constrain α up to $z \sim 0.5$ and M_{HI}^* up to $z \sim 0.8$ with accuracy comparable to the best current $z \sim 0$ measurements (shown by the gray bands). The inclusion of an ultra-deep tier would extend these constraints to $z \sim 1$

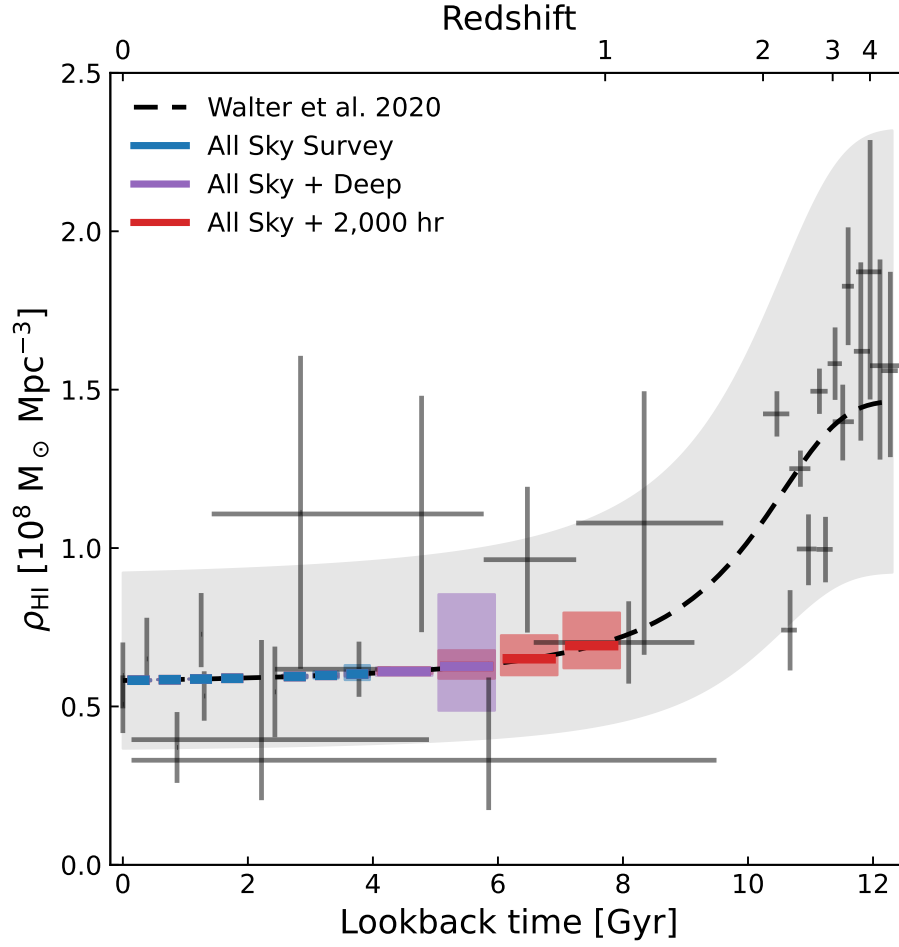


Figure 8.9: Gray points show a compilation of existing measurements and the dashed line and gray band shows an empirical fit (data and fit from Walter et al. 2020). Blue, purple and red bars and filled regions show the cosmic atomic gas density measurements and uncertainties for DSA-2000 all-sky, deep, and ultra-deep HI surveys. The DSA-2000 predictions have been scaled to match the Walter et al. 2020 fit.

8.5 Ultra-deep neutral hydrogen observations of nearby galaxies

Authors: F.M. Maccagni, W.J.G. de Blok

Summary

Ultra-deep studies of neutral hydrogen (HI) enable us to investigate several processes of galaxy formation and evolution in the nearby Universe. Low column density gas ($\lesssim 10^{19} \text{ cm}^{-2}$) is thought to replenish the interstellar medium (ISM) of star forming galaxies from the inter-galactic medium. Moreover, only by reaching low-mass detection limits ($\sim 10^6 M_\odot$) we can characterize the gas content in low-surface brightness galaxies and therefore understand their evolution through cosmic time. Here, we show how these studies are currently done with MeerKAT on a limited field of view and show how DSA-2000 will expand these surveys to a much larger volume, and possibly all-sky.

Current ultra-deep HI studies

Identifying the processes that fuel galaxies has been an active topic of research over the last few decades, both theoretically and observationally. Attempts to directly detect the cold infalling gas have so far not yet resulted in unambiguous detections, and led to many efforts to map the HI around galaxies to increasingly lower column densities. The deepest HI survey of nearby galaxies to date (MHONGOOSE, de Blok et al. 2016) is currently in progress on the 64-dish MeerKAT radio telescope in South Africa. It will characterize a sample of 30 gas-rich spiral and dwarf galaxies down to HI column densities of $\sim 5 \times 10^{17} \text{ cm}^{-2}$, one to two orders of magnitudes deeper than previous observations.

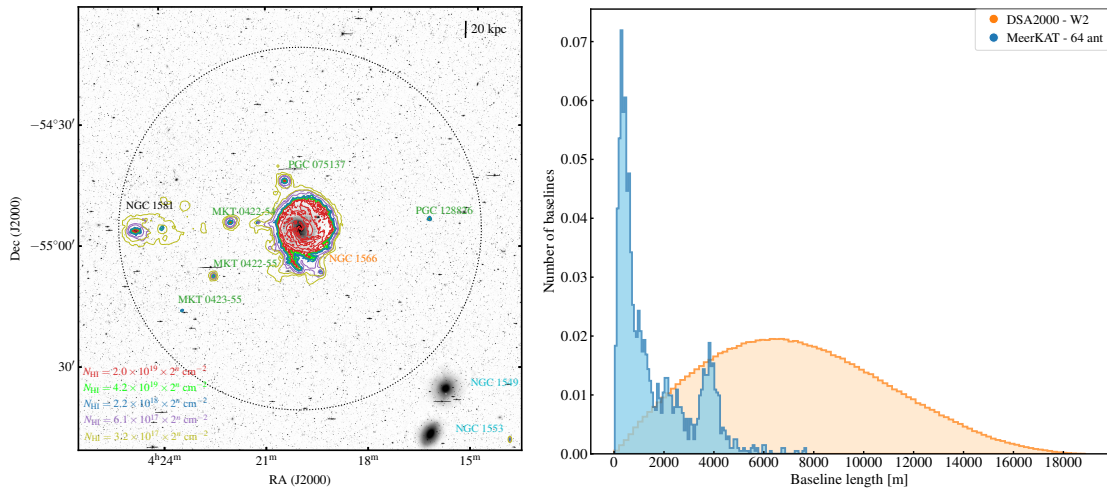


Figure 8.10: *Left:* DESI image of the NGC 1566 group with overlaid the HI detected in MHONGOOSE at $\approx 7.6, 12, 23, 30, 70, 92''$ (the PSFs are shown in the bottom right corner). For each resolution the contours of 2^n times the $S/N = 3$ value sensitivities of the datacubes are shown in the bottom left corner. Distinct low-column density ($\sim 5 \times 10^{18} \text{ cm}^{-2}$) HI asymmetries and clouds are detected in the outskirts of NGC 1566 and between it and NGC 1581, along with several low-mass ($\sim 5 \times 10^6 M_\odot$) newly discovered gas rich dwarfs galaxies (marked in green). The dashed circle marks $1.5 \times 1.5 \text{ deg}^2$ f.o.v imaged with MeerKAT. *Right:* Normalized baseline length distribution of MeerKAT and DSA-2000.

First results show that the outer parts of galaxies are complex environments, with signs of potentially accreting gas, but also with clear signs of minor interactions with low-mass companion galaxies (Fig. 8.10). Moreover, because both low-column density clouds and diffuse streams of HI are found in the inter-galactic medium, disentangling the effects of environment from direct cold gas accretion is an observational challenge.

System requirements / desired additions to baseline design**Table 8.5:** Project requirements compared to DSA-2000 baseline reference design

	DSA-2000 baseline reference design	match to project
low-resolution HI channels need for short-baseline array	5600 channels from 0.7–1.45 GHz, N/A	NO compact core of 10×10 antennas

8.6 Spatially resolved census of HI in the nearby (100 Mpc distance) Universe

Authors: Fabian Walter (MPIA), W.J.G. de Blok (ASTRON), et al.

Summary

The DSA-2000 will obtain an unbiased (sub-)kpc view of the atomic hydrogen of all galaxies out to 100 Mpc (and ideally, 200 or even 300 Mpc). Together with the lower-velocity resolution (but mostly spatially unresolved) HI survey out to $z=1$ (CROSSREF), this survey represents the 'Sloan HI' counterpart in the local universe, enabling a multitude of analysis, including precise measurements of the dark matter content through HI kinematics. This, together with the fact that the DSA-2000 will push down to HI masses that were previously inaccessible for large volumes will provide new and unique constraints for state-of-the art numerical simulations.

State of the Field

Obtaining a full account of neutral hydrogen in the Universe using large-area sky surveys has been a key goal in radio astronomy for decades. One of the most comprehensive surveys of this kind is the 'HI Parkes All Sky Survey' (HIPASS, Barnes et al. 2001) which mapped the entire sky south of declinations of +25 degrees over a velocity range from -1300 to +13,000 km s^{-1} . Even though the spectral (18 km s^{-1}) and spatial resolution (15 arcmin) of this single-dish survey were limited, it led to breakthrough science, and to first good constraints on the HI mass function in the local Universe (Zwaan et al. 2003), a key constraint for hydrodynamical galaxy simulations (e.g. Stevens et al. 2019). The extragalactic northern sky was since fully observed with the 'The Effelsberg-Bonn HI Survey' (EBHIS, Flöer et al. 2015, Winkel et al. 2016, Schröder et al. 2019) at comparable spectral and spatial resolution (10 km s^{-1} , 9 arcmin). These single-dish surveys provide a full census of the bright end of the HI luminosity function with typical HI mass limits of about 10^7 - $10^8 M_{\odot}$ at distances of 0-10 Mpc (10^8 - $10^9 M_{\odot}$ at distances of 10-30 Mpc, and 10^9 - $10^{10} M_{\odot}$ at 30-100 Mpc, Zwaan et al. 2003).

The next revolution in constraining the HI content of galaxies (and thus the HI mass function) to significantly lower masses is afforded by the latest generation of sensitive interferometric surveys. For example, the Australian WALLABY survey (Koribalski et al. 2020) is currently being executed at ASKAP, and will provide a HI survey covering the Southern Sky over the next few years at a spatial (spectral) resolution of 30 arcseconds (km s^{-1}). Dedicated MeerKAT surveys, e.g. on the Fornax cluster, target special group and cluster environments at unprecedented depths (Serra et al. 2016, pilot data in Kleiner et al. 2021). Also, the 3400 hour LADUMA survey, a deep drilling in a single MeerKAT pointing, will detect HI emission out to redshift $z=1.4$.

DSA-2000's impact

The sensitivity and resolution of the all-sky DSA-2000 HI survey will take these studies to an entirely new level. It will provide a spatially resolved HI census of all galaxies out to $D=100$ Mpc (ideally: out to 200 Mpc, see below, 3.5'' at 100 Mpc (200, 300) gives a spatial resolution of 1.5 kpc (3, 4.5), galaxies will be resolved over 10+ beams at least out to 200 Mpc). Among many other things, this will enable to derive accurate rotation curves for the galaxies, and thus dark matter density profiles / content. For each HI-detected galaxy, the multi-wavelength properties will put them in context with the general galaxy population. In particular characterizing the properties of the smallest galaxies is crucial for understanding galaxy evolution, as in the hierarchical growth of galaxies it is these smallest galaxies that are the building blocks of more massive galaxies. Optical imaging for most fields will be available

through Pan-STARRS, SDSS, EUCLID, with significant overlap by the Rubin LSST survey. Given the high velocity resolution, the project will thus also push measurements of the HI luminosity function at $z \sim 0$ many orders of magnitudes below single-dish all-sky surveys, providing new constraints for state-of-the art hydrodynamical simulations.

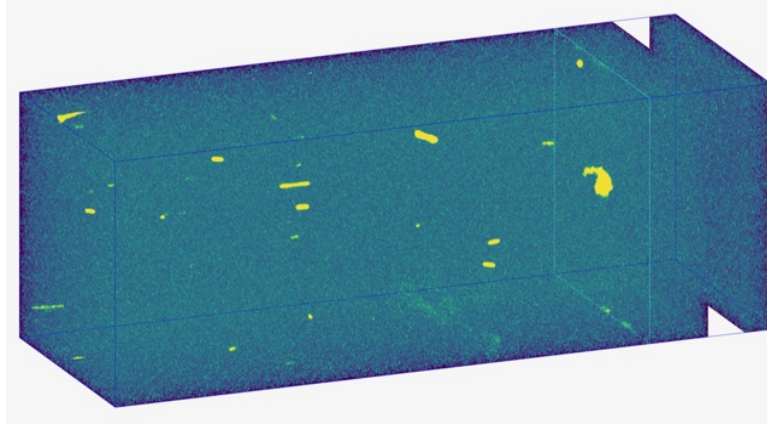


Figure 8.12: The HI universe out to $D=100$ Mpc from one 5-hour pointing of the MeerKAT MHONGOOSE survey (de Blok et al., 2016). After reaching full depth, the DSA-2000 will reach deeper mass limits over an area that is 30,000 times larger (the entire sky).

System requirements / desired changes to baseline design (see table below)

The current baseline design would allow detailed spatial and spectral resolved HI imaging out to 100 Mpc (7000 km s^{-1}). Doubling (or even tripling) that distance would be highly desirable. This would imply additional channels for zoom band A, as the current velocity resolution is needed for the nearby galaxies. An alternative would be to have an additional zoom band with coarser velocity resolution (5 km/s) starting at $D=100 \text{ Mpc}$.

Table 8.6: Project requirements compared to DSA-2000 baseline reference design

	DSA-2000 baseline reference design	match to project
Frequency band	0.7–2.0 GHz	only needs $\Delta\nu < 100 \text{ Mhz}$ around HI
Declinations	$\delta > -31^\circ$	restricted DEC range OK
Spatial resolution	$3.5''$	✓ gives 0.5 kpc res at 30 Mpc – OK
need for short-baseline array	N/A	benefits nearby targets $D < 10 \text{ Mpc}$
need for additional modes	N/A	add'l zoom band $100 \text{ Mpc} < D < 300 \text{ Mpc}$?

ToDo: need to calculate number of galaxies targeted out to $D=100 \text{ Mpc}$, 200 Mpc , 300 Mpc .

8.7 HI galaxy surveys out to $z=1$

Authors: Kristine Spekkens

Summary

The HI content and structure of gas-rich galaxies is an important evolutionary probe; population studies are the current state of the art. Several large HI surveys at new facilities around the world are now underway or set to begin soon. They will deliver the first statistical samples of local HI disks and a first look at HI in individual galaxies out to $z \sim 1$. An all-sky survey with the DSA-2000 will detect millions of galaxies out to $z \sim 1$, resolving many systems out to $z \sim 0.1$: these statistical samples of HI reservoirs and disks will be unparalleled by any survey through the mid-2030s.

State of the Field

The HI content, morphology and kinematics of gas-rich galaxies are important evolutionary probes. For example, the HI disks of Milky Way-like systems extend further into their parent dark matter halos than their stellar counterparts (e.g. Wang et al. 2016d); at lower star-forming galaxy masses, HI is the dominant baryonic component (e.g. Bradford, Geha, and Blanton 2015). The statistics of HI disks at $\log(M_{\text{HI}}/M_{\odot}) \gtrsim 7$ therefore places important constraints on the interplay between baryons and dark matter during galaxy formation, while widefield HI surveys are the most efficient tracer of the faintest star-forming galactic building blocks. The state of the art for confronting galaxy formation models is transitioning from detailed studies of individual systems (e.g. Katz et al. 2017, Adams and Oosterloo 2018) to population-wide constraints (e.g. Dutton, Obreja, and Macciò 2019). Because of historical limitations in detector bandwidth, sensitivity and field-of-view, the vast majority of HI samples available today are restricted to $z < 0.1$ (e.g. ALFALFA, Haynes et al. 2018), with only a few direct detections beyond this redshift (e.g. Fernández et al. 2016b, Chakraborty and Roy 2023).

A revolution in HI sky surveys is underway now, with several large ($\sim$ thousands of hours) initiatives underway or set to begin soon at new or retrofitted observatories around the world. Figure 8.13 provides a visual summary of these major efforts, grouped by sky coverage and depth. Widefield HI surveys such as WALLABY on ASKAP (Koribalski et al. 2020a), CRAFTS on FAST (Zhang et al. 2021) and CHORD (Vanderlinde et al. 2019) will provide a new $\sim$ full-sky HI view of the Universe, with deeper efforts such as MALS, MIGHTEE-HI, Fornax and MHONGOOSE on MeerKAT (Gupta et al. 2016, Maddox et al. 2021, Serra et al. 2023, de Blok et al. 2020) and Apertif (Adams et al. 2022b) also underway. Pencil beam surveys will push individual HI detections out in redshift for the first time, and include the completed CHILES on the VLA (Dodson et al. 2022), with DINGO on ASKAP (Rhee et al. 2023b) and LADUMA on MeerKAT (Blyth et al. 2016) starting observations now. The upshot of this massive, global investment of telescope time is that by 2030, the first statistical samples of HI disks (e.g. Deg et al. 2022) and the first HI detection statistics beyond $z \sim 0.1$ will have been collected and made publicly available (e.g. Westmeier et al. 2022).

DSA-2000's impact

The DSA-2000 will detect millions of galaxies across 3π sr out to $z = 1$, an order of magnitude more at $z \lesssim 0.1$ than ongoing widefield surveys (Figure 8.14), and several orders of magnitude more at $z \gtrsim 0.1$ than ongoing pencil beam surveys. Galaxies with $\log(M_{\text{HI}}/M_{\odot}) \gtrsim 10$ out to $z \sim 0.1$ will be spatially resolved, which no other ongoing survey will achieve. The DSA-2000 will deliver unparalleled HI detection and HI disk statistics out to $z \sim 1$ until a putative SKA Key Science Project in the mid-2030's.

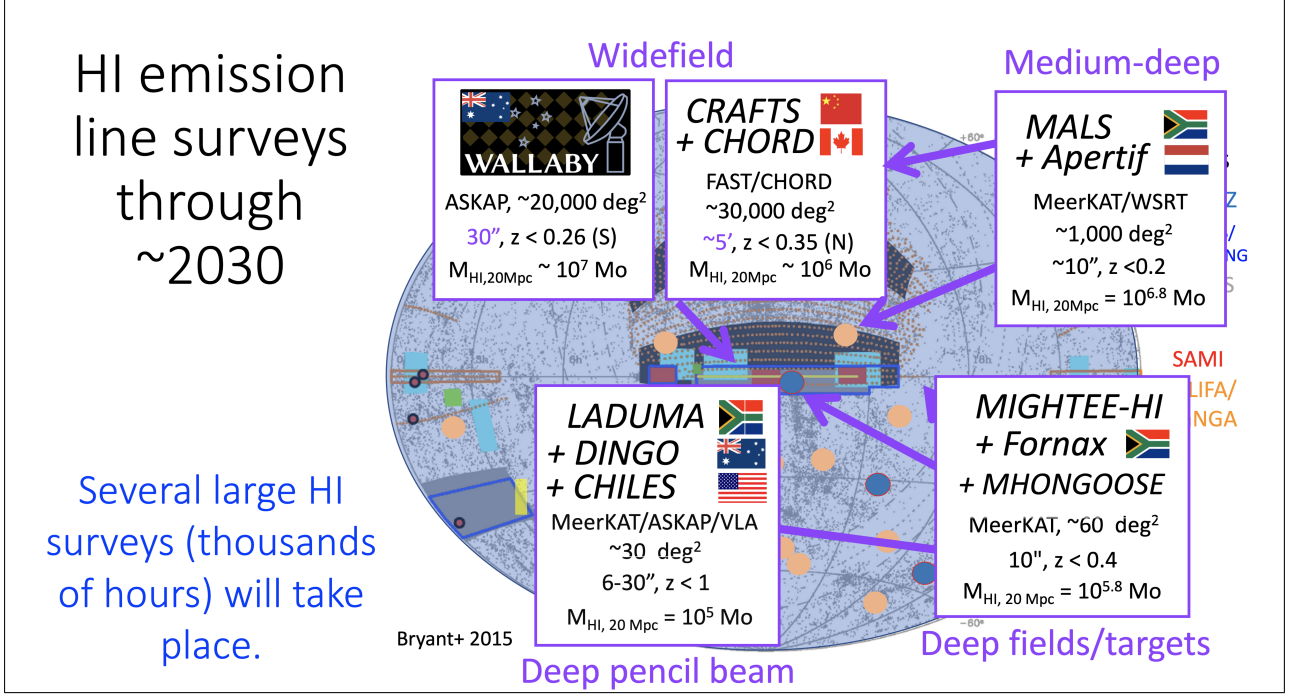


Figure 8.13: Summary of large HI emission line surveys underway or beginning soon, grouped by sky coverage and depth; approximate footprint, angular resolution, redshift range, and sensitivities (expressed in detectable HI mass at $D = 20 \text{ Mpc}$) are given for each group. References in text.

DSA-2000 HI forecasts

Thanks to Marcel Neeleman

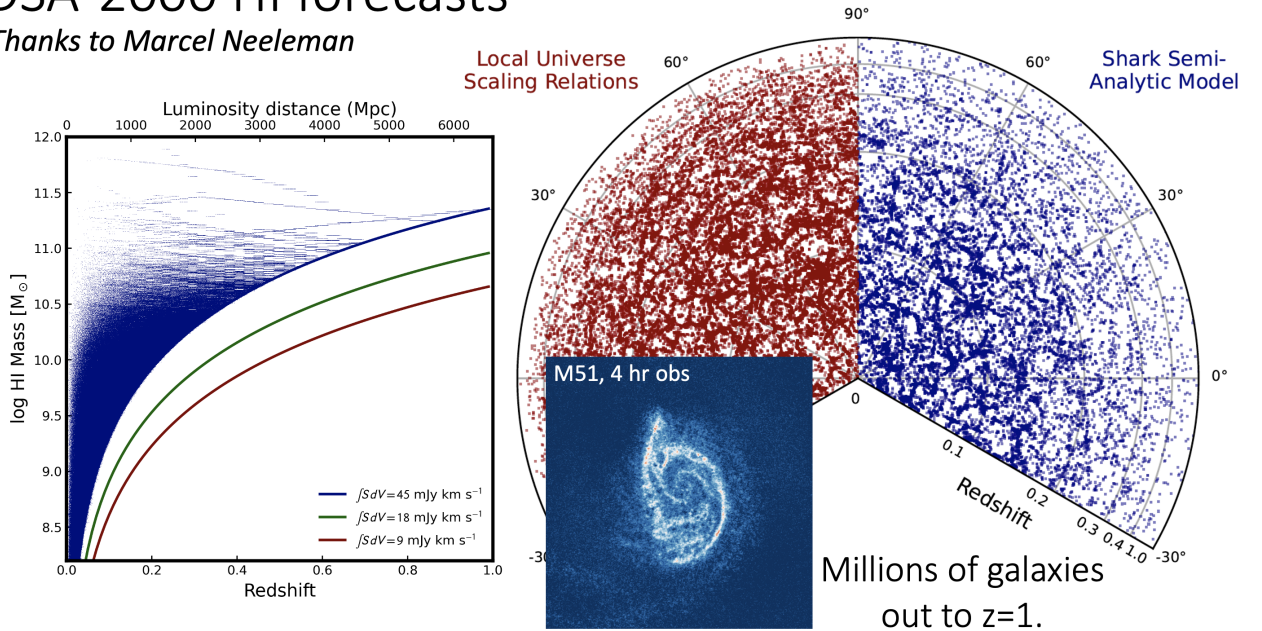


Figure 8.14: HI galaxy forecasts for the DSA-2000 (courtesy Marcel Neeleman and Fabian Walter). The left panel shows all-sky survey HI galaxy masses as a function of redshift predicted by the Obreschkow and Meyer 2014 mock catalog, with the sensitivities for deeper DSA-2000 indicated by green and red lines. The right-hand side shows a simulated sky HI detection distribution spanning $-30^\circ < \delta < 90^\circ$ in declination in a 10° -wide RA slice. A simulated 4-hour observation of the nearby spiral galaxy M51 is inset.

System requirements / desired additions to baseline design (see table below)

Checkmarks show an element of the baseline design that is both required and sufficient for the science case described above. Baseline design elements that are not relevant for this science case are left blank. The limiting factor in the reference design for this science case is column density sensitivity: an HI column density sensitivity of $\sim 1 \text{ M}_\odot \text{ pc}^{-2} = 1.25 \times 10^{20} \text{ atoms cm}^{-2}$ across a spectral extent of $\sim 15 \text{ km s}^{-1}$ is required to reach the edges of HI disks (e.g. Wang et al. 2016d), which implies a minimum spatial smooth to $\sim 6''$. A short baseline array to enhance column density sensitivity would benefit this science case, though it is not strictly necessary for the science case as described. The tuneable zoom bands will be of limited use for this science case because the DSA's column density sensitivity is low compared to compact array configurations (e.g. CHORD, Vanderlinde et al. 2019).

Table 8.7: Project requirements compared to DSA-2000 baseline reference design

	DSA-2000 baseline reference design	match to project
Spatial resolution	3.5''	smoothing needed
need for short-baseline array	N/A	beneficial

8.8 Galactic neutral hydrogen and magnetic fields with DSA-2000

Authors: Susan E. Clark (Stanford)

Summary

Measurements of neutral hydrogen absorption probe the phase distribution of the interstellar medium. Measurements of Zeeman splitting in the 21-cm line in absorption probe the magnetic field strength in the cold neutral medium.

State of the Field

Understanding star formation and galactic evolution requires a physical model of the flow of matter and energy throughout the interstellar medium (ISM). The ISM is a multi-phase medium, spanning orders of magnitude in temperature and density (e.g., Ferrière 2001; Hacar et al. 2022). A complete physical understanding of the ISM requires measurements that probe this range of phases, as well as physical properties like the interstellar magnetic field.

Interstellar neutral hydrogen (HI) is traced by the 21-cm line in both emission and absorption (Kalberla and Kerp 2009). Recent large-area surveys of the 21-cm line in emission have been enormously productive for understanding properties of the ISM (Kalberla and Haud 2015; Winkel et al. 2016; HI4PI Collaboration et al. 2016a; Peek et al. 2018). The addition of measurements of the 21-cm line in absorption enable estimates of the HI temperature and optical depth, and thus constrain the thermodynamic state of the ISM (Heiles and Troland 2003b; Murray et al. 2018b; Murray et al. 2021; Dickey et al. 2022a). These data are enabling new insights into the phase structure and density distribution of the ISM, as well as how gas transitions between phases in the ISM (Murray et al. 2021; Stanimirović and Zweibel 2018; Lei and Clark 2022).

The role of the magnetic field in interstellar processes remains one of the most elusive parts of the picture. One of the key challenges is a paucity of observational measurements of the magnetic field strength in the neutral and molecular ISM. Measurements of starlight polarization and polarized dust emission probe the magnetic field in these phases, but only trace the plane-of-sky magnetic field orientation. Similarly, cold filamentary structures in diffuse neutral hydrogen trace the magnetic field orientation (Clark, Peek, and Putman 2014; Clark et al. 2015; Kalberla et al. 2016). These data can only be used to indirectly estimate the plane-of-sky magnetic field strength via statistical techniques that come with strong caveats and systematic uncertainties. Measurements of Faraday rotation can be used to estimate the line-of-sight magnetic field strength in molecular clouds, but rely on background subtraction techniques to isolate the contribution to the rotation measure from the molecular cloud, as well as models of the thermal electron density (Tahani et al. 2018; Tahani et al. 2022). Zeeman measurements stand alone as the only tracer that *directly* measures the line-of-sight magnetic field strength in the neutral and molecular ISM (Heiles and Crutcher 2005).

Zeeman measurements of HI in absorption measure the line-of-sight magnetic field strength in the cold neutral medium of the ISM. Because these absorption measurements are made toward background radio galaxies, which are randomly distributed with respect to the Galactic HI, they provide an unbiased view of the magnetic field strength in the neutral medium. The state-of-the-art HI absorption Zeeman survey remains the Millenium Survey with Arecibo (Heiles and Troland 2004; Heiles and Troland 2005). These measurements anchor much of what we know about the magnetic field in the diffuse ISM and the evolution of the magnetic field strength with gas density – a critical discriminant of the role of the magnetic field in star formation (Crutcher et al. 2010; Crutcher 2012; Tritsis et al. 2015; Pattle et al. 2022). However, as crucial and widely-used these data are,

“the number of actual detections is, from a statistical standpoint, pitifully small” (Clark, Heiles, and Robishaw 2019). (See the Decadal 2020 White Paper by Clark, Heiles, and Robishaw 2019 for more on this science case.) More high-sensitivity measurements are desperately needed, and would have an immediate and lasting impact on the field.

DSA-2000’s impact

There is an opportunity for DSA-2000 to conduct a sensitive HI absorption line survey toward all bright background radio sources in the observable region. This would provide an unbiased survey of the phase composition of HI gas over much of the sky. If carefully calibrated measurements of Stokes V were also achieved, DSA-2000 would provide much-needed HI Zeeman measurements in absorption. This would potentially substantially bolster our understanding of the magnetic field strength distribution and evolution with gas density in the Galaxy, a measurement with wide-ranging consequences for ISM physics.

System requirements / desired additions to baseline design (see table below)

The proposed Zeeman splitting measurements would necessitate the addition of Stokes V measurements for the tuneable zoom band B channels. The 0.22 km s^{-1} velocity resolution of tuneable zoom band B is sufficient to resolve CNM linewidths.

Table 8.8: Project requirements compared to DSA-2000 baseline reference design

DSA-2000 baseline reference design	match to project
I only for all other channels	Add V for Zoom band B

8.9 Galactic HI, OH and recombination line surveys – results and perspectives from the THOR survey

Authors: M. R. Rugel, H. Beuther, J. Stil, B. Winkel, E. Koch, J. Urquhart, K. Emig, J. Dawson, and R. Klessen

Summary

The evolution of molecular clouds in the Milky Way is a key missing piece in our understanding of how matter is processed in galaxies, and an essential ingredient of galaxy evolution models. In particular: How do molecular clouds form out of the atomic gas? What is the impact of stellar feedback on the evolution of the interstellar medium (ISM)? To address these questions, DSA-2000 will provide HI observations at high resolution and high sensitivity to study the atomic gas, observations of the OH 18 cm transitions and several radio recombination lines to observe molecular and ionized gas, as well as measurements of the continuum in full polarization to study magnetic fields. This contribution gives a summary of the VLA Galactic plane survey THOR (The HI/OH/Recombination line survey) and the follow-up THOR-GC, as well as delineating perspectives for future surveys with DSA-2000.

State of the Field:

The mechanisms governing the formation of molecular gas out of the diffuse interstellar medium (ISM) occur in multiple gas phases, extend from kpc down to sub-pc scales, and involve a variety of processes, e.g., supernova explosions, stellar feedback and galactic shear motions. Observational data on the formation of molecular clouds, especially investigations of the diffuse molecular and atomic material in our Galaxy, are lacking to constrain galaxy simulations and models of galaxy evolution. Particularly suited to study the atomic gas component are observations of the HI 21 cm line at 1.4 GHz, as well as the OH transitions at 18 cm to probe diffuse molecular gas. The last decades brought about several observational surveys of HI at high resolution and/or high sensitivity, such as the Canadian Galactic Plane Survey (CGPS; Taylor et al. 2003), the Southern Galactic Plane Survey (SGPS; McClure-Griffiths et al. 2005), the VLA Galactic Plane Survey (VGPS; Stil et al. 2006), the HI/OH/Recombination line survey (THOR; Beuther et al. 2016), the GALFA-HI survey (Peek et al. 2011) and the EBHIS/GASS/HI4PI surveys (HI4PI Collaboration et al. 2016b, and references therein). Over a similar period, studies have investigated HI in different phases between the cold and warm ISM with HI emission and absorption observations (e.g., Heiles and Troland 2003a; Lee et al. 2012; Murray et al. 2015), as well as with HI self-absorption, e.g., Li and Goldsmith (2003), which also reported matching detections of the hyperfine splitting transitions of the OH molecule. OH transitions at 1612, 1665, 1667 and 1720 MHz can be sub-thermally excited and provide a probe of molecular gas in a variety of physical conditions. The hyperfine splitting levels of the OH ground state are also subject to inversion, resulting in maser emission in a variety of astronomical environments. First detected in the 1960s (e.g., Weinreb et al. 1963), these transitions gained attention in recent years in multiple surveys, also as potential tracer of molecular gas not traced by CO emission (CO-dark gas; e.g., Allen et al. 2012; Dawson et al. 2014; Allen, Hogg, and Engelke 2015; Xu et al. 2016; Li et al. 2018a; Rugel et al. 2018; Busch et al. 2021; Dawson et al. 2022b). Several larger surveys addressing various aspects of OH and HI have reported initial results or are ongoing, with existing telescopes (e.g., ODIN(plus) or THOR-GC with the VLA), with SKA-pathfinders in the southern hemisphere (e.g., GASKAP-HI, e.g., Dickey et al. 2022b; GASKAP-OH) or also by studying ground state transitions of OH in the far infrared with SOFIA (HyGAL, e.g., Jacob et al. 2022).

THOR: This contribution focusses on the THOR and THOR-GC surveys with the Karl G. Jansky Very Large

Array (VLA), which simultaneously observed the HI, OH, and radio recombination lines (RRLs) lines, as well as the continuum emission in full polarization over a large portion of the first quadrant of the Milky Way (THOR; $67.4^\circ > l > 14.0^\circ$; Beuther et al. 2016), and towards the Galactic Center and surroundings (THOR-GC; Rugel et al., in prep.). Main goal is to study how the evolution of the ISM leads to the formation of molecular clouds and to the formation of new stars. Both surveys provide maps of the atomic gas at a resolution comparable to existing surveys of dust and molecular gas across the Milky Way. The angular resolution of the data products range between $15''$ to $40''$, in particular providing HI emission maps at $40''$ with an rms of 4 K at 1.5 km/s channel width. The THOR survey allows us to constrain the HI content of the cold neutral medium in star-forming regions and spiral arms (Bihl et al. 2015; Bialy et al. 2017; Wang et al. 2020b), and identify cold HI in molecular clouds through HISAs (Wang et al. 2020a; Syed et al. 2020, Syed et al., in prep.). Spatial correlations between HI and CO emission, as well as global orientations of HI filaments have been used to investigate the imprints of feedback processes on the structure of gas in the Milky Way (Soler et al. 2019; Soler et al. 2020), and have led to the detection of a purely atomic filament (“Maggie” Soler et al. 2020; Syed et al. 2022). Additional studies focused on OH absorption in star forming regions and “quiescent” molecular clouds (Rugel et al. 2018), OH masers (Beuther et al. 2019), the detection of new supernova remnant candidates (Anderson et al. 2017), signatures of stellar feedback (Rugel et al. 2019), and the structure of magnetic fields with rotation measure synthesis (Shanahan et al. 2019). THOR is currently extended to other regions of the Galaxy with ODIN(plus), focussing on more nearby molecular clouds, e.g., Orion and Ophiuchus (Soler et al., in prep.), and to the Galactic Center (THOR-GC), which extends THOR to Galactic longitudes $18^\circ > l > -5.9^\circ$ (Rugel et al., in prep.).

DSA-2000’s impact

The high angular resolution is ideally suited for studying HI and OH absorption towards Galactic and extra-galactic background sources and provides a new all-sky survey of HI emission.

- *From the “Reference configuration summary (March 2023)”, we estimate a point-source sensitivity of ~ 0.2 mJy/beam or a surface brightness sensitivity of ~ 9 K @ $3.5''$ in a 1 km/s channel for 4 h of observations. Smoothing to $20''$ improves the surface brightness sensitivity to ~ 2 K or better, at a point source sensitivity of ~ 1 mJy/beam. For OH and HI absorption, this would imply a 5σ -sensitivity to optical depths of $\tau \sim 0.01$ across the entire sky for continuum sources > 100 mJy. It is highly complementary to on-going surveys of the southern sky (GASKAP-HI; Dickey et al. 2013).*
- *The survey will provide an all-sky OH maser census at unprecedented sensitivity, tracing a variety of different astronomical sources, e.g., AGB-stars, star-forming regions and supernova remnants. With its cadence of one all-sky coverage every 4 months over 5 years, the DSA-2000 will be ideally suited to identify variable OH masers on time scales of months to years.*
- *The wide bandwidth and high target sensitivity promise a deep view of the polarized continuum sky and a fine grid of rotation measures to constrain the magnetic field in the ISM.*
- *We note the excellent multi-frequency synergies for compact continuum sources at $3.5''$ resolution with Galactic plane surveys such as MMGPS (2.0-2.8 GHz; Padmanabh et al. 2023) and GLOSTAR (4-8 GHz; Brunthaler et al. 2021).*
- *If spectral lines are recorded in full-polarization mode, DSA-2000 will provide direct measurements of the line-of-sight magnetic field in molecular clouds and star-forming regions through Zeeman-splitting of OH.*
- *Its all-sky maps will be an excellent starting point for detailed, multi-frequency follow-ups with*

future radio telescopes such as the SKA or the ngVLA.

System requirements / desired additions to baseline design (see table below)

Comparing the DSA-2000 baseline reference design to VLA studies such as THOR/THOR-GC:

- **High surface brightness sensitivity** is crucial to study Galactic HI emission. Short spacings are necessary, particularly for HI: THOR/VGPS showed the importance of baselines smaller than 1 km ($\sim 40''$ @ 1.4 GHz). Improving the resolution to $\sim 20''$ @ 1.4 GHz will require baselines < 2 km. A separate compact array and/or a change in the current baseline configuration, which add baselines at these lengths, will dramatically improve the response of the DSA-2000 to diffuse Galactic HI emission.
- **“Zoom band B”** (bandwidth: 2.1 MHz or 450 km/s @ 1.4 GHz) may not be sufficiently wide for HI in some Galactic targets, in particular for regions with high velocities such as the Galactic center. Its high spectral resolution is beneficial for distinguishing cold, narrow HI components along the line of sight. Deep integrations of HI (~ 30 h over 5 years) could be obtained with simultaneous HI observations for a subset of the NANOgrav fields. See also other contributions on HI in this series.
- To cover the **four OH hyperfine splitting transitions at 18 cm**, we recommend to evaluate adding extra zoom bands at this or a later stage, potentially at lower spectral resolution (< 0.5 km/s) or restricted to, e.g., the Galactic plane, nearby galaxies, and the Gould Belt. If the setup remains unchanged, we suggest simultaneous OH observations for a subset of the NANOgrav fields, iterating the tuning between the 4 OH transitions. Also, “Zoom band A” could be tuned to the two OH main lines, although we notice the importance of the OH satellite lines to investigate the excitation.
- Linear receivers require full-Stokes observations to measure **Zeeman-splitting of OH**.
- Simultaneous observations of **continuum in full polarization and limited coverage of radio recombination lines** are possible with the current setup and we refer to other contributions in this series for a detailed discussion.

Table 8.9: Project requirements compared to DSA-2000 baseline reference design

	DSA-2000 baseline reference design	match to project
Spatial resolution	3.5"	✓ (short-baselines essential for HI)
low-resolution HI channels	5600 channels from 0.7–1.45 GHz, 134 kHz (28 km s^{-1} at $z=0$, 56 km s^{-1} at $z=1$)	(potentially: RRLs if $dv < 10 \text{ km s}^{-1}$)
tuneable zoom band A	4096 channels, 8 kHz (1.8 km s^{-1})	✓ (potentially: OH main lines)
tuneable zoom band B	2048 channels, 1.05 kHz (0.22 km s^{-1})	✓ (HI, potentially: all 4 OH lines) (full-Stokes for Zeeman-splitting)
need for short-baseline array	N/A	✓
Cadence	1 every 4 months	(potentially: variability of OH masers)
need for additional modes	N/A	4 x “Zoom band B” for OH

ToDo: Test image-plane deconvolution for Galactic HI emission.

8.10 Exploring OH with the DSA-2000

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Summary

The conditions for molecular cloud formation vary with Galactic environment. Studying molecular gas in phases where molecules have just formed can reveal information on the molecular cloud formation process and the overall star formation efficiency in galaxies. Observationally, large fractions of molecular gas have been identified in the Milky Way, which are not detected by standard molecular gas tracers such as CO. Lines from hydrides such as hydroxyl (OH) are better suited for tracing the HI-to-H₂ transition as they easily form once molecular hydrogen is present and since their cm transitions are readily excitable. We predict that simultaneous observations of the OH 1667 MHz lines with the DSA-2000 should be able to reveal OH in gas parcels of molecular gas. Here, we propose to search for weak OH absorption corresponding to the 1667 MHz line towards strong cm continuum sources to detect and map the galaxy-wide distribution of CO-dark gas.

8.10.1 Introduction

CO-dark gas pervades the multiphase interstellar medium (ISM) of the Milky Way, but it is elusive to widely surveyed molecular emission lines of gas in giant molecular clouds such as CO (Grenier, Casandjian, and Terrier 2005; Planck Collaboration et al. 2011; Pineda et al. 2013). As molecular hydrogen forms at lower column densities than typical clouds detected in CO, understanding the properties of CO-dark gas can be highly relevant for constraining not only the phase transition of atomic to molecular gas, but also the onset of self-gravitation of molecular clouds as shielding from increased dust and gas columns enables clouds to cool (Glover and Clark 2012). Moreover, it has been determined from both observations and theoretical predictions that CO-dark gas amounts to significant fractions of the molecular gas (Grenier, Casandjian, and Terrier 2005; Pineda et al. 2013; Busch et al. 2021; Wolfire, Hollenbach, and McKee 2010). Hence, deciphering its origin is critical for our understanding of galaxy formation.

Spectral line surveys including observations of the 18 cm ground state hyperfine structure lines of OH have established its use as a tracer of molecular gas in a variety of environments in our Galaxy and beyond (Goss 1968; Turner 1979; Nguyen et al. 2018; Rugel et al. 2018; Dawson et al. 2022a; Hafner et al. 2023; Gupta et al. 2018; Balashev, Gupta, and Kosenko 2021; Busch 2023). Further, recent studies have found OH both in emission and absorption without CO emission counterparts or in regions of CO-dark gas (Xu et al. 2016; Li et al. 2018a; Allen, Hogg, and Engelke 2015; Busch et al. 2021). OH in CO-dark environments occurs over a range of column densities, roughly between $N_{\text{OH}} = 10^{12} - 10^{14} \text{ cm}^{-2}$ (Li et al. 2018a; Busch et al. 2021), which corresponds to a molecular column density range of $N_{\text{H}_2} = 10^{19} - 10^{21} \text{ cm}^{-2}$ assuming an OH abundance of 10^{-7} (Crutcher 1979; Weselak et al. 2010; Jacob et al. 2022; Rugel et al. 2025).

8.10.2 Revealing CO-dark gas with the DSA-2000

The DSA-2000 offers a unique opportunity to conduct highly sensitive observations of the OH hyperfine splitting transitions of the rotational ground state. We evaluate the benefits of a deep Galactic plane survey of the OH 1667 MHz line which can be conducted simultaneously with the DSA-2000 survey, and will illuminate OH's ability to trace CO-dark gas as detailed below. For economic reasons and for limitations in the overall number of channels that can be correlated, we decided to focus this contribution solely on the OH 1667 MHz line, as it has the highest statistical weights and its absorption should be strongest among the four hyperfine splitting transitions (1612 MHz, 1665 MHz, 1667 MHz, and 1720 MHz).

Figure 8.15 shows the proposed survey area. To keep the overall data volume in reasonable limits we propose to limit the survey area to $255 > l > -10$ degree and $|b| < 10$ degree around the Galactic midplane (5300 square degree, 17% of the DSA-2000 survey area). An inclusion of individual Gould belt clouds will be considered separately.

We use the sensitivity estimates for the DSA-2000, as reported in March 2023, of $0.5 \mu\text{Jy}/\text{beam}$ for the continuum sensitivity over all epochs (80% of time usable) and 1.3 GHz bandwidth (65% of the useable) ¹. The mean full width of half maximum (FWHM) of OH absorption features as found by Hafner et al. (2023) is adopted to be 1.5 km/s. Broad CO-dark OH layers as detected in Busch et al. (2021) are likely even broader. To sample 1.5 km/s by two channels, we can degrade the narrowest currently planned resolution of the DSA-2000 (1.05 kHz) by a factor of four. We calculate the sensitivity for a resolution of 0.76 km/s at 1667 MHz (4.2 kHz), which results in a line sensitivity of $\sigma_{\text{line}} = \sigma_{\text{cont}} * \sqrt{\frac{1.3 \text{ GHz} \times 65\%}{4.2 \text{ kHz}}} = 0.2 \text{ mJy}/\text{beam}$. Towards pulsar timing fields with a continuum sensitivity of 200 nJy/beam, we can reach a line sensitivity $\sigma_{\text{line}} = 0.09 \text{ mJy}/\text{beam}$. For column density, we use

$$\frac{N_{\text{OH}}}{T_{\text{ex}}} = \frac{C_0}{f} \int \tau dv, \quad (8.1)$$

with $C_0 = 2.24 \times 10^{14} \text{ cm}^{-2} \text{ K}^{-1} \text{ km}^{-1} \text{ s}$ for the 1667 MHz transition (e.g., Goss 1968; Turner and Heiles 1971; Stanimirović et al. 2003), and assume $T_{\text{ex}} = 5 \text{ K}$. We estimate that when observing the 1667 MHz line across all epochs of the DSA-2000, we will reach a 5σ RMS of $N_{\text{OH}} \leq 1.2 \times 10^{12} \text{ cm}^{-2}$ in a 0.8 km/s channel for absorption towards sources with a continuum flux of $S_{\text{cont}} > 1 \text{ Jy}$, or $N_{\text{OH}} \leq 1.2 \times 10^{13} \text{ cm}^{-2}$ for sources $S_{\text{cont}} > 100 \text{ mJy}$.

Based on the NVSS survey (Condon et al. 1998), we estimate at least one source per square degree with $S_{\text{cont}} > 100 \text{ mJy}$, which will enable the study of spatial variations of CO-dark gas with OH. At a distance of 1 kpc this corresponds to an average probed spatial scale of $\sim 20 \text{ pc}$, and at the Galactic center (8.13 kpc) to $\sim 150 \text{ pc}$, which should be sufficient to distinguish between arm and inter-arm regions of large-scale spiral wave density perturbations in the Galaxy disk (although 3D dust maps indicate that the distribution of gas in our Galaxy is likely more flocculent than suggested by spiral arm determinations from longitude-velocity diagrams of HI or CO emission alone (Burton 1971; Reid et al. 2016; Peek, Tchernyshyov, and Miville-Deschenes 2022; Edenhofer et al. 2024). The number of strong cm-continuum sources is even higher in the Galactic plane, and could be enhanced by averaging over sources of extended emission. Stacking may further enhance the spatial grid of OH observations of CO-dark gas. Due to their deeper integration times, pulsar timing fields falling into the survey region (~ 20 ; see Fig. 8.15) will result in a factor of two lower in noise, and provide an additional set of deep probes of OH 1667 MHz absorption towards extragalactic continuum background sources. All in

¹<https://static1.squarespace.com/static/614f008bdbba3159ac98c058/t/65c382c3a8bc6f6fc9228730/1707311819097/Cheatsheet.pdf>

Figure 8.15: CO(1-0) emission, integrated over velocities (Dame et al., 2001). The sky visible from the DSA-2000 above elevation $> 10\text{deg}$ ($\delta > -40\text{deg}$) lays outside of the white shaded area outlined by red markers. The proposed OH 1667 MHz survey regions is outlined by blue lines. Green circles indicate Pulsar timing fields.

To search for CO-dark gas, we propose to exclusively dedicate a subset of channels for a high-sensitivity search of OH absorption in the 1667 MHz transition. To maximize integration time, these channels should be allocated via an additional sub-band, separate from other high-resolution bands. Most adequately suited would be a copy of the (HI) zoomband B, a 1024 channel band with 1.05 kHz resolution, resulting in 0.2 km/s @1667 MHz, and providing an overall bandwidth of 205 km/s. While this spectral resolution is adequate for typically narrow molecular line widths, the main science goal can also be reached by slightly undersampling the OH transitions at 0.8 km/s, reducing the number of channels to 256.

We note that OH has a total of four transitions within the coverage of the DSA-2000, at 1612 MHz, 1665 MHz, and 1720 MHz transitions. These lines are also prominent maser transitions which trace a variety of Galactic environments (Beuther et al. 2019). We do not include them in this proposal due to the limited number of channels of the radio camera backend. They may be covered with short observations by retuning the high-resolution HI zoom band in individual epochs of the all-sky DSA-2000 surveys to provide a unique census of interstellar masers.

DSA-2000's impact

The DSA-2000 offers a unique opportunity for deep observations of the OH hyperfine splitting transitions of the rotational ground state. The proposed deep OH absorption observations have the potential to detect CO dark gas in different Galactic environments. The new contribution of the DSA-2000 to the discovery of CO-dark gas is the impressive sensitivity of the all-sky survey over its entire lifetime after combining 16 epochs. With the simultaneous OH 1667 MHz observations and the novel mix of survey speed and sensitivity, the DSA-2000 will provide a new view on the diffuse ISM in the Milky Way.

System requirements / desired additions to baseline design (see table below)

For the search of CO-dark gas, we propose a separate zoom band for the OH 1667 MHz line, which is always recording data when observing the Galactic plane, ideally using 1024 channels at 1.05 kHz resolution, with a minimum of 4.4 kHz (0.8 km/s) resolution and 256 channels to cover a bandwidth of 200 km/s.