HI Cosmology at $z = 0$: a Brief Review

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Abstract. Extragalactic HI astronomy is half century old. Its maturity dramatically increased in the 1970s, with the commissioning of new powerful facilities. Its contributions to Cosmology are important, from the observation of galaxy rotation curves that showed the presence of dark matter in galaxies, to the measurement of cosmological parameters and the mapping of the large scale structure of the Universe. The Arecibo telescope has played a key role in these developments. It is also currently engaged in a number of experiments that utilize its L-band feed array to map thousands of square degrees of the sky and obtain the most sensitive large–scale view of the low $z$ HI Universe.

Keywords: 21 cm line, Arecibo

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INTRODUCTION

I have been asked by the organizers of this workshop to devote opening remarks to a brief review of achievements in extragalactic HI astronomy and how these set the stage for current efforts in the field, particularly the ALFALFA survey. Because of the judgement passed not long ago by a national review committee, a dark shadow has been cast on the future — and very existence in the next decade — of the most beautiful of radio observatories, which hosts this workshop today. Finding myself in disagreement with some of the conclusions of said review, I make no apology for the fact that my report will lean towards the body of discovery Arecibo has contributed in extragalactic spectroscopy, while in the last session of this workshop, I chance some predictions on the possible large–scale projects Arecibo may be able to attack in the next decade.

Baryons make up about 4.5% of the mass/energy budget of the Universe, and only 1/6 of its matter density. At $z = 0$ the vast majority of baryons are thought to exist in the form of coronal and intergalactic gas, at temperatures $> 10^5$ K; $\Omega_{stars}$ is a tiny 0.0027 and $\Omega_{cold\ gas}$ an even smaller 0.0008, of which a bit over half is neutral Hydrogen [1], the target of this workshop’s observational concerns. This unimpressive budgetary datum could well prompt the question: why do we care about extragalactic radio spectroscopy? First, HI is easy to detect at 21 cm wavelength, most of the emission originates in optically thin regions and cold gas masses are reliably measured; the abundance of cold gas is a reliable indicator of star forming potential for an extragalactic system. Second, the distribution of HI, which can be found at larger galactocentric distances than other easily detectable components in a galaxy, makes it an excellent tracer of the large–scale dynamics of its host. Third, scaling relations of disks, such as that between luminosity and rotational width, make HI measurements good cosmological tools: for example in the measurement of $H_0$, peculiar velocities, the convergence depth of the Universe
and the local matter density field. Fourth, because of its presence at relatively large galactocentric distances, HI is more vulnerable than the stellar component to external influences and thus constitutes a good tracer of tidal interactions, mergers and other environmental effects. Fifth, it can be the dominant baryonic component in low mass galaxies and thus provide a reliable census of low mass systems in the galactic hierarchy.

The 21 cm line of neutral Hydrogen was first detected in 1951 from Milky Way clouds and in 1953 from the Magellanic Clouds. It took nearly two decades of pioneering work, largely by M.S. Roberts, to bring the number of galaxies detected in HI to exceed one hundred [2]. During this period, the near totality of extragalactic HI observations were made with single dishes, at Green Bank, Nançay, Effelsberg and Owens Valley. In the 1970s, mature, new aperture synthesis telescopes at Westerbork and the VLA were commissioned, followed two decades later by the GMRT, the largest synthesis telescope currently operating at 21cm. In the early 1970s, the primary reflecting surface of the Arecibo telescope was upgraded, making operation at L–band possible. At the same time, lower $T_{\text{sys}}$ receivers and broad band spectrometers also became available. The sensitivity of the 305m telescope provided the complementary counterpart to the high angular resolution capabilities of the synthesis instruments. Sensitivity was unfortunately not matched initially at Arecibo by breadth of field of view. With a field of view of a single–beam of $\sim 3.3'$, unbiased, sensitive, blind, large–scale surveys remained impractical. This situation changed with the implementation of focal plane arrays in large single dishes. The first effective use of that technology for HI spectroscopy took place in the 1990s at Parkes and it yielded the important HIPASS catalog [19] of about 5000 HI sources. ALFA, a seven–feed focal plane array, was commissioned at Arecibo in 2004, making possible full–fledged, wide solid angle survey operations, which started in early 2005.

**DISCOVERY HIGHLIGHTS**

In 1973, in reporting the observations of apparently flat rotation curves of three nearby galaxies, Roberts & Rots[3] wrote: “The shapes of the rotation curves at large radii indicate a significant amount of matter at these large distances and imply that spiral galaxies are larger than found from [optical] photometric measurements”. Through HI observations they had discovered dark matter in galaxies. Since then, thanks to the fact that HI is detectable to larger galactocentric distances than other baryonic forms, HI measurements have been the technique of choice for tracing the mass distribution at large galactocentric radii. This field found fertile grounds at the WSRT, Arecibo and the VLA. The first “outing” in high $z$ territory of the HI line was its detection in absorption in 3C286 at $z = 0.692$ by Brown & Roberts[4].

In 1972, Gunn & Gott[5] proposed that ram pressure would have an important effect on the evolution og galaxies in clusters. After pioneering work at Jodrell by Davies & Lewis[6], the effect was detected at Nançay[7]. The correlation between truncation of the gas disks with HI deficiency was revealed at Arecibo([8],[9]), and the wealth of Arecibo data lead to a clear match between the distributions of the hot IGM and HI deficiency [11]. On a complementary path, synthesis observations[10] illustrated the details of the galaxy–IGM interaction, more recently surveyed at the VLA by Kenney, van Gorkom
and collaborators (VIVA) and as described by Jacqueline in these proceedings.

In the 1980s, Arecibo became a productive redshift machine. As evidence for structure in the distribution of galaxies on scales well in excess of clusters started to mount in the late 1970s, a program was started to map putative supercluster structures by measuring the redshifts of large, optically selected samples of galaxies. The data gathered by Giovanelli, Haynes and collaborators through that effort, including nearly 10,000 redshifts and HI parameters, are accessible in digital form through an archive maintained at Cornell University\footnote{http://arecibo.tc.cornell.edu/hiarchive/}. These data provided a clear view of the filamentary character of the large-scale structure of the Universe, especially in the characterization of the Pisces–Perseus supercluster.

The relationship between optical luminosity and rotational velocity of spiral disks, first proposed by Tully & Fisher\cite{13} to be usable as a tool to estimate extragalactic distances independent on redshift, became widely used in the 1980s and 1990s, both for the measurement of the Hubble constant and of peculiar velocities. Galaxies' peculiar velocities arise from gravitational perturbations due to inhomogeneities in the density field. The peculiar velocity at a given location in space is the cumulative effect of such perturbations, out to a maximum distance often referred to as the “convergence depth”. Perturbations originating at locations farther than the convergence depth have negligible amplitude, as they collectively balance against each other. The determination of the convergence depth, which can be measured by gauging the reflex motion of the Local Group with respect to galaxies populating spherical shells of progressively increasing radius, is a proxy for that of the scale of a fair sample of the Universe. The largest sample of spiral galaxy peculiar velocities is known as SFI++, consisting of a data base of I-band photometry and 21cm line and H\textalpha{} spectroscopy of approximately 4500 galaxies\cite{14}. About half of the SFI++ sample lies within the Arecibo telescope Declination range. A complementary sample of cluster galaxies allowed the accurate determination of a template Luminosity–linewidth relation\cite{13}, which has been used to map the peculiar velocity field, determine the convergence depth and confirm the Doppler nature of the CMB dipole\cite{17}, measure the Hubble constant\cite{16} and $\Omega_{\text{mass}}$\cite{18}.

In the mid–to–late 1990s, the Arecibo telescope’s astronomical activities were largely suspended as most of its line feeds — early devices for correction of the aberration resulting from its spherical primary —, were replaced with a Gregorian subreflector system. In the period during which partial operation was possible, two pioneering surveys were carried out in the 21 cm line: AHISS by Briggs and co–workers\cite{20} and ADBS\cite{21}. Although they covered relatively small solid angles of sky — respectively 13 and 430 square degrees for AHISS and ADBS, they were the first in surveying unbiasedly the extragalactic HI Universe with interesting sensitivities. They detected respectively 65 and 265 HI sources, or 5 and 0.6 sources per square degree. The two surveys yielded very different HI mass functions, especially at the faint end. These differences arise mainly from the small numbers of sampled objects and the uncertainties in the distances of the faintest objects in each survey: for those, the (unknown) individual peculiar velocities can be comparable with or even larger than the Hubble velocity. HI masses can thus be uncertain by factors of several.
FIGURE 1. R.A. [hours] vs $cz$ [km s$^{-1}$] wedge diagrams of four independent data sets, corresponding to declination ranges, top to bottom: [13°–16°], [10°–13°], [07°–10°], [04°–07°]; the R.A. range is the same in all graphs, between 07:30 and 16:30 hours. ALFALFA detections are plotted. Each diagram includes approx. 2000 objects. The sky region corresponds to approximately 22% of the projected survey solid angle of ALFALFA. Note that due to RFI, ALFALFA is effectively blind in the redshift range between approximately 15000 and 16000 km s$^{-1}$. 
TABLE 1. Comparison of Blind HI Surveys

| Survey    | Beam(*) | Solid angle (deg^2) | res(km s^{-1}) | \( V_{med}(\text{km s}^{-1}) \) | \( N_{det} \) | Ref |
|-----------|---------|---------------------|----------------|-------------------------------|---------------|-----|
| AHISS     | 3.3     | 13                  | 16             | 0.7                           | 4800          | 65  | [20] |
| ADBS      | 3.3     | 430                 | 34             | 3.3                           | 3300          | 265 | [21] |
| WSRT      | 49.     | 1800                | 17             | 18                            | 4000          | 155 | [22] |
| HIPASS    | 15.     | 30000               | 18             | 13                            | 2800          | 5000| [19] |
| HI-ZOA    | 15.     | 1840                | 18             | 13                            | 2800          | 110 | [23] |
| HIDEEP    | 15.     | 32                  | 18             | 3.2                           | 5000          | 129 | [24] |
| HIJASS    | 12.     | 1115                | 18             | 13                            | \( \dagger \)  | 222 | [25] |
| J-Virgo   | 12.     | 32                  | 18             | 4                             | 1900          | 31  | [26] |
| AGES      | 3.5     | 200                 | 11             | 0.7                           | 12000         |     | [27] |
| ALFALFA   | 3.5     | 7074                | 11**           | 1.7                           | 7800          | \( >25000 \) | [28] |

\( ^* \) rms in mJy per beam uniformly referred at 18 km s^{-1} resolution

\( ^\dagger \) HIJASS has a gap in velocity coverage between 4500-7500 km s^{-1}, caused by RFI

\( ^{**} \) raw data at 5.5 km s^{-1}

While Arecibo was being upgraded, a feed array was being commissioned at Parkes, which eventually delivered the widest extragalactic HI survey to date, HIPASS\[19\]. Now complete, HIPASS has surveyed 30,000 square degrees of sky, including the full southern hemisphere. With an average sensitivity of 13 mJy per beam at 18 km s^{-1} spectral resolution, it produced a catalog of approximately 5000 HI sources, a sky density of 0.17 sources per square degree. Table\[1\] shows a comparison of various blind HI surveys, past and current.

ALFALFA

The most ambitious among currently ongoing, blind HI extragalactic surveys is ALFALFA (the Arecibo Legacy Fast ALFA survey)\[28\], which will cover 7000 square degrees of sky and is on course to detect more than 25,000 HI sources, over a 100 MHz bandwidth with 25 kHz (\( \sim 5.5 \) km s^{-1}) spectral resolution.

Figure\[1\] shows the redshift distribution of a 22% section of the ALFALFA survey. The median \( c_z \) is near 8000 km s^{-1}, the typical scalelength of baryonic acoustic oscillations. ALFALFA is the only large-scale HI survey that samples a fair volume of the Universe (HIPASS’ median \( c_z \) is less than 3000 km s^{-1}). A comparison of ALFALFA and HIPASS is clear from inspection of Figure\[2\] of the \( \sim 8000 \) ALFALFA sources displayed, HIPASS would detect fewer than a few dozens to its completeness level, and a few percent to its overall detection limit. Moreover, a large fraction of HIPASS sources suffer from confusion because of the large Parkes telescope beam, making the identification of optical counterparts difficult and often impossible without follow-up, higher resolution HI observations. The smaller Arecibo beam largely obviates the problem: more than 95% of ALFALFA sources can be unambiguously associated with the correct optical counterpart. HIPASS detected fewer than two dozen sources with HI mass \( < 10^{7.3} \) solar; ALFALFA is on track to detecting a few hundred.
FIGURE 2. Spähnauer plot of 7938 HI sources in the region R.A.=[7.5\,h–16.5\,h], Dec=[4°–16°]. Nearby objects of uncertain distance, possibly galactic HVCs, “pollute” the plot at $M_{\text{HI}} < 10^{6.5}$. The two smooth lines identify the completeness limit for sources of 200 km s$^{-1}$ linewidth (dotted) and the overall detection limit (dashed) for the HIPASS survey. Note that due to RFI, ALFALFA is effectively blind in the redshift range between approximately 15000 and 16000 km s$^{-1}$.

ALFALFA will allow an accurate determination of the HI mass function to unprecedented low levels; elucidating the large–scale structure characteristics of HI sources, their impact on the “void problem”; mapping the local mass density field; providing a catalog of HI tidal remnants; directly determining the HI diameter function; including ~2000 continuum sources with fluxes sufficiently large to make useful measurements of HI optical depth, it will provide a low z link with DLA absorbers; dramatically expand the targets for the study of environmental effects on the evolution of galaxies, through the use of diagnostic tools such as gas deficiency; significantly expand the redshift database for the dynamical study of nearby groups and clusters; bringing to unprecedented flux limits the census of High Velocity Clouds and possibly clarifying their relationship to Local Group and other nearby galaxies.

As of early 2008, ALFALFA observations have been completed for approximately 40% of the survey goal of 7000 square degrees. Data processing to "level I" (see [28]) is complete for those data, data cubes and source extraction is complete for approximately 25% of the survey. Public access to cataloged sources in digital form is available through robust software tools. Several preliminary results of ALFALFA are presented in these proceedings, with particular emphasis on discoveries in the Virgo cluster region, which was given priority in coverage in the early phases of the survey.

2 http://arecibo.tc.cornell.edu/hiarchive/alfalfa
Possible developments with next generation HI surveys at Arecibo, as an SKA precursor, are discussed in the last session of these proceedings.

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