

Thoughts on the Future of HI Astronomy at Arecibo

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1 Preamble

The Arecibo telescope has the largest collecting area in world radio astronomy, about 1/10 of the future SKA and comparable with or larger than the SKA precursor telescopes currently under design or construction.

The main disadvantages of Arecibo with respect to those precursor experiments are that it currently has a limited field of view and that it will always have worse angular resolution than a comparable collecting area with a distributed aperture. The paramount advantage is, of course, that Arecibo already exists and is a well understood, efficient photon bucket.

For a telescope such as Arecibo with $T_{sys}/G = 3$ Jy, the minimum integration time per beam in seconds t_s necessary to detect an HI source of HI mass M_{HI} , width W_{kms} , at a distance D_{Mpc} is

$$t_s \simeq 0.25 \left(\frac{M_{HI}}{10^6 M_\odot} \right)^{-2} (D_{Mpc})^4 \left(\frac{W_{kms}}{100} \right)^\gamma, \quad (1)$$

where the exponent $\gamma \simeq 1$ for $W_{kms} < 300$ km s⁻¹ and increases for sources of larger width in a measure which is inversely related to the degree with which standing wave systematics are well understood. This means that the depth of a survey, i.e. the maximum distance at which a given HI mass can be detected, increases only as $t_s^{1/4}$: longer integrations than strictly necessary to achieve scientific goals lead to rapidly diminishing returns. While the emission of an HI mass of 1% that of the Milky Way can be detected at the distance of the Virgo cluster in less than 1 minute, only the most massive HI galaxies can be detected in emission even at moderate redshift. The highest z of any source detected emission in emission is 0.28 (Catinella *et al.* 2007). Detection of the brightest galaxies at such redshift requires integration times of several hours at Arecibo.

The density of galaxies per unit solid angle increases obviously with z . At $z \sim 0.1$, confusion within the 3.5' HPFW of the Arecibo beam cannot often be resolved, unless high quality optical redshifts are available for the sources within the beam, so that confusion can be broken kinematically. This further limits, in addition to the sensitivity issue, the pursuit of blind HI surveys with the Arecibo telescope at high z . A practical rule of thumb indicates that the median centroiding accuracy of a source smaller than the telescope beam, detected at signal-to-noise StN with a beam of HPFW β , is approximately β/StN . A source detected at a marginal $Stn \simeq 6$ will, at 21 cm wavelength, have an associated positional error somewhat larger than 0.5'.

Sensitivity and confusion issues limit the scope of blind HI surveys with the Arecibo telescope beyond the local Universe. However, a number of targeted surveys can overcome that limitation.

2 Local Universe, Mop-up Science

The success of the ALFA surveys recommends that a number of “extension” projects, designed along the lines of the currently ongoing or planned surveys, be considered. I will refer to them collectively as “mop-up science”. Here is a list of possible future projects:

- **ALFALFA++:** The ALFALFA survey, currently under way, will cover 7000 square degrees of sky, a bit more than half the sky accessible with the Arecibo telescope. It will require some 4000 hrs of telescope time to complete. ALFALFA++ would completely map, in the ALFALFA mode (40 sec effective integration per beam area), the full solid angle accessible with the 305m telescope. With ALFA, it will require 3000 hours of telescope time. With a 40-beam focal plane phased array, the project could be completed in 500 hours.
- **AGES++:** The AGES survey, currently under way, aims to map several small patches of sky, centered on interesting objects, covering a total of 200 sq. deg. of sky with an effective integration of 300 sec per beam, which makes it 2.5 times more sensitive than ALFALFA. The AGES++ program would be extended to a more extensive set of targets, including clusters and groups of galaxies with $cz < 10000 \text{ km s}^{-1}$. AGES++ would aim to cover a total of 3000 square degrees, which would require some 10,000 hours of telescope time with ALFA and 1500 hours with a 40-beam focal plane phased array.
- **Virgo Deep:** The ALFALFA mapping of the Virgo cluster is providing an extremely rich basket of surprises: numerous sources with no optical counterpart; extended, low surface brightness (some barely detected) streams stretching hundreds of kpc; examples of galaxies suffering from external hydro- and gravity-driven processes. A survey of the cluster with 10 times the sensitivity of ALFALFA would be certain to reveal new marvels and, bringing the HI detection limit to $2 \times 10^6 M_{\odot}$, will provide an unprecedented investigation of the low mass end of the HI mass and luminosity functions. A Virgo Deep survey that would cover 400 sq. deg. with an effective integration of 4000 sec per beam would require 23,000 hours of telescope time with ALFA. However, a 40-beam focal plane phased array could complete such a survey in 4000 hours. It may be unfair to include Virgo Deep under “mop-up science”: this would deliver genuinely new stuff and provide a fundamental scientific reference.

Instrumental and Telescope Time Needs:

- With ALFA, no new hardware necessary; 30,000–35,000 hours of telescope time
- With a 40-beam phased array, new spectrometer with 6 times the spectral capacity of current ones at AO; 6000 hours of telescope time

3 GASS++, a Targeted Survey of Galaxies at Intermediate z

GASS is a planned survey to obtain complete “ID cards” for a sample of galaxies in the local Universe ($z < 0.04$). It uses the SLOAN and GALEX surveys as target finders for objects for which cold gas content and kinematics is to be obtained. The collective information will be used to measure galaxy parameters, such as masses, current and past star formation activity, etc. The survey sample includes some 1000 objects, of which a fraction of order 10% will be provided by ALFALFA.

HI can be currently detected in emission from extragalactic objects out to a $z \sim 1/3$, with integration times of order of 10 ksec at AO. A redshift of one third corresponds to a lookback time of about 4 Gyr, a significant evolutionary step. An important, unexplored science niche untouchable by any telescope other than AO at this time consists in the study of the evolution of the HI mass to optical luminosity ratio, which is linked to the evolution of the cosmic star formation and merger rates. HI sources at distances > 100 Mpc are most unlikely starless, as the masses required for their detection with AO correspond squarely in the category of giant galaxies, for which no theoretical expectation exists of any inhibition to profuse star forming activity. Thus the study of such objects is best done via targeted, rather than blind searches.

The Sloan Digital Sky Survey (SDSS) is delivering optical photometry and spectroscopy for millions of galaxies. The one important datum SDSS is missing is gas content. GASS will help characterize the properties of galaxies at $z \sim 0$. An even more ambitious effort, aimed at characterizing the evolution of galaxies back to 4 Gyr, will likely follow a few years hence. Such an effort will likely require several thousand hours of AO time and be carried out as a legacy survey with broad community participation.

Technical challenge: because it will be a targeted search, multibeam capability will not be necessary to multiplex sky coverage. However, special attention will be required to dealing with rfi. Dual beam option, as well as sophisticated rfi excision and managing techniques will need to be applied. Obviously, minimization of system noise will also be desired.

4 Ω_{HI} as a Function of Look-back Time

From observations of Damped Lyman Alpha systems we know that $\Omega_{HI} \simeq 10^{-3}$ at $z > 2$. Estimated values at $z = 0$ are about a factor of 3 to one order of magnitude lower. Theoretical estimates of the $\Omega_{HI}(z)$ differ substantially (Baugh *et al.* 2004; Cen *et al.* (2003); Nagamine *et al.* 2005; Millenium run). The steeper part of the change in $\Omega_{HI}(z)$ may have taken place between look-back times of 1–5 Gyr. The observational characterization of that function is of paramount importance, especially with respect to plans for the “Billion HI Galaxy” surveys, the measurement of baryon acoustic oscillations and the elucidation of the nature of dark energy.

In spite of its large collecting area, the Arecibo telescope is not well suited to carrying blind surveys of galaxies at intermediate z : its relatively large beam size rapidly leads to confusion. However, an interesting alternative possibility presents itself. The Arecibo beam is well matched to the angular size of intermediate redshift clusters of galaxies. For example, A1835, at $z = 0.25$, has an SZ signature 4' in diameter. Pointed observations would aim at the detection of the integrated HI emission of the whole cluster. An HI mass of $10^{12} M_{\odot}$ spread over a width of 1500 km s^{-1} could in principle be detectable in less than 10 hours with the Arecibo aperture. A number of possible complications could make such an experiment difficult, however: the ability to detect a broad spectral signature against system standing waves, the increase in the continuum noise especially by radio galaxies in the cluster itself, easily come to mind. Yet, the concept offers substantial promise, which may lead to the characterization of $\Omega_{HI}(z)$ through much of the interval of cosmic history to which ground-based DLA work is blind ($z < 1.6$).

This is an experiment that will require much tender loving care in the understanding of telescope systematics. A dual beam option and sophisticated rfi identification/excision techniques would be required.

5 A Focal Plane Phased Array

The technology of focal plane phased arrays (FPPA) is not well developed yet, and it is still uncertain that such devices will be able to deliver the low temperature performances we have become used to. Nonetheless, they dominate the current plans for SKA and SKA-precursor technology. Two important advantages of FPPAs are relevant: (i) they can exploit a larger physical area of the focal plane and (ii) beams can be packed together more closely than in feed arrays, such as ALFA. With ALFA, the focal plane is undersampled by about a factor of 16 (beam centers are separated by approximately 2 beamwidths); a FPPA may be able to reach nearly Nyquist sampling of the FOV. ALFA consists of a central beam and a ring of 6 surrounding it; a FPPA may be able to accommodate an additional outer ring. It is thus possible to consider the possibility of an L-band focal plane array with several tens of beams with nearly complete mapping of the FOV. While the technology of these devices is still at the experimental level, especially in their ability to deliver low T_{sys} , it makes plenty of sense to experiment with them at a telescope of aperture already equal to 1/10 of an SKA.