# **Extragalactic HI Surveys at Arecibo: the Future**

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**Abstract.** Starting in the 1970s, the Arecibo 305m telescope has made seminal contributions in the field of extragalactic spectroscopy. With the Gregorian upgrade completed in the late 1990s, the telescope acquired a field of view. Population of that field of view with a seven–feed array at L–band (ALFA) increased by nearly one order of magnitude its survey speed. As a result, much of the extragalactic astronomy time of the telescope is now allocated to survey projects, which are briefly discussed. The next technical development stage for the 305m telescope is foreseen as that of a 40 beam system that would take advantage of phased array technology: **AO40**. This would further speed up the survey performance of the telescope. It is shown how the figure of merit for survey speed of AO40 would be comparable with that of SKA–precursor facilities, planned for operation in the next decade. A number of scientifically desirable new surveys that would become possible with AO40 are briefly discussed.

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# EXTRAGALACTIC SPECTROSCOPY AT ARECIBO: A TIMELINE.

The 21 cm line of neutral Hydrogen was first detected in 1953 in a galaxy other than our own. The Arecibo Observatory entered operations a decade later, but it took another decade and the replacement of the 305m telescope primary mirror with a finer surface, for the field of extragalactic spectroscopy to become established at that facility. In the following years, the Arecibo telecope became a protagonist in the field of extragalactic spectroscopy, with fundamental contributions to the understanding of galactic structure, the predominance of dark matter in galaxies and the case of nature vs. nurture in their evolution; the large scale structure of the Universe, its basic parameters and peculiar velocity field. In the 1990s, a second upgrade of the 305m telescope corrected for the spherical aberration of its primary, delivering an extended field of view at its focus. The exploitation of that field of view by populating it with multifeed arrays opened a new era at Arecibo: that of surveys which would cover large fractions of the 13,000 square degrees of the accessible sky. Currently about to start or already underway, extragalactic spectroscopy surveys that use the ALFA feed array will deliver results of unprecedented scope and impact in the field. A progressively larger fraction of telescope time is allocated to survey work.

#### CURRENTLY ONGOING HI SURVEYS

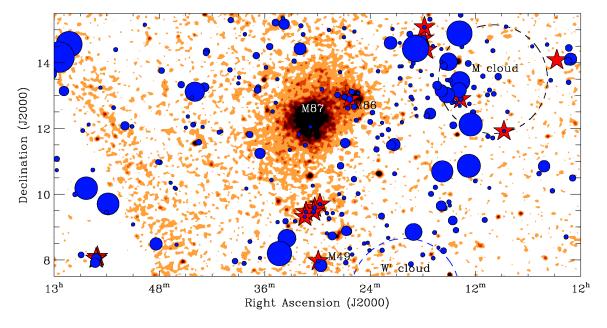
ALFA is a seven-feed focal plane array; surveys enabled by this device started taking data in 2005. Among them: AGES (the *Arecibo Galactic Environment Survey*) aims at the investigation of the HI contents in the periphery of nearby galaxies, groups and clusters; ZOA (the *Zone of Avoidance* survey) will identify galaxies near the Galactic plane, helping overcome the limitations imposed by dust extinction; AUDS (the *Arecibo Ultra Deep Survey*) will carry out a high sensitivity pencil beam exploration to  $z \sim 0.25$ . The most ambitious among the HI extragalactic surveys is ALFALFA (the *Arecibo Legacy Fast ALFA* survey)[1], which in blind mode will cover 7000 square degrees of sky and will detect more than 25,000 HI sources. While ZOA and AUDS will initiate in 2008, ALFALFA and AGES are well under way.

The median cz of the ALFALFA survey is near 8000 km s<sup>-1</sup>, 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 cz is less than 3000 km s<sup>-1</sup>). Moreover, a large fraction of HIPASS sources suffer from confusion, 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.

The collective science goals of extragalactic HI surveys at Arecibo is described in the introductory paper by Giovanelli, of these proceedings, and several initial findings of those surveys have been presented. Here, it is worth refreshing our memory on one of such findings, briefly discussed in the presentation b Brian Kent[2]. ALFALFA reports the discovery of huge gas streams in the outer regions of the Virgo cluster, extending hundreds of kpc and witnessing to dramatic events in therevolution of galaxies in those environments. The northern part of the cluster, now fully mapped by ALFALFA to a detection limit of  $2 \times 10^7 M_{\odot}$ , is shown in Figure 1. The orange shading shows the extent of the X–ray emission centered on M87, by hot intracluster gas (ICM); the blue dots are HI detections, their areas proportional to their HI masses. The picture clearly illustrates the impact of the ICM on gas content of galaxies. The red stars show the location of HI streams, some of which can be tracked over degrees ( $1^{\circ} \simeq 300$  kpc at the cluster distance. These features are detected near the column density limit of ALFALFA ( $\sim 5 \times 10^{18}$  cm<sup>-2</sup>), suggesting that ALFALFA — while allowing us to seeing these structures for the first time — may be seeing just "the tip of the iceberg".

#### AO40

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. ALFA has provided a nearly one order of magnitude survey speed, with respect to single beam operation. However, the focal plane of the telescope is undersampled by about a factor of 16 by ALFA (beam centers are separated by approximately 2 beamwidths). An improvement on this state of affairs can be achieved with the development of focal plane phased arrays (FPPA). Two im-



Source: Brian Kent

**FIGURE 1.** Composite of the Virgo cluster: X ray emission (orange), HI sources (blue circles) and HI streams (red stars). See text for details.

	D(m)	Beam(')	$N_{tel}  imes N_{beam}$	FoV	$T_{sys}(K)$	BW(MHz)	FoM
AO1	225	3.5	$1 \times 1$	1	25	100	1
ALFA	225	3.5	$1 \times 7$	7	30	300	14
AO40	225	3.5	$1 \times 40$	40	50	300	30
APERTIF	25	30	$14 \times 25$	1800	50	300	33
ASKAP	12	60	$30 \times 30$	8800	50	300	37

**TABLE 1.** Parameters for the Computation of Survey Speed

portant 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. A FPPA approaching Nyquist sampling of the FOV may allow for 40 instantaneous beams at L-band. We shall refer to such an implementation on the Arecibo telescope as "AO40". FPPA technology is not well developed yet, and it is still uncertain that such devices will be able to deliver the low temperaure and broad bandwidth performances we have become used to. We underscore that most SKA precursor future telescopes, such as ASKAP and APERTIF, are betting on the success in implementing such technology.

Using a standard expression for the survey speed figure of merit, *FoM*, of a telescope of effective aperture  $A_{eff}$ , system temperature  $T_{sys}$ , total instantaneous solid angle of the survey  $\Omega_{fov}$  and bandwidth *BW*:

$$FoM \propto (A_{eff}/T_{sys})^2 \Omega_{fov} BW, \tag{1}$$

and using the same expectation values for  $T_{sys} = 50$  K and BW = 300 MHz for FPPAs at AO40, ASKAP and APERTIF, the relative *FoM* for those 3 systems with respect to the single beam Arecibo are respectively 30, 33 and 37, as shown in Table 1. The *FoM* for ALFALFA is 5. With the implementation of FPPA technology on which future facilities rely on, Arecibo (AO40) can be as fast a survey machine as any currently planned. 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.

Is there a niche for Arecibo as a competitive HI survey machine? The density of galaxies per unit solid angle increases obviously with z. At  $z \sim 0.1$ , confusion within the  $\sim 4'$  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 overcome kinematically. This limits 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 StNwith a beam of HPFW  $\beta$ , is approximately  $\beta/StN$ . A source detected at a marginal  $Stn \simeq 6$  will, at 21 cm wavelength, have an associated positional error somewhat larger than 0.5'. Identification of the optical counterpart of an HI source without the benefit of an accurate optical redshift at even modest  $z \sim 0.1$  thus becomes doubtful. The maximum distance at which a given HI mass can be detected increases only as  $t_s^{1/4}$ , where  $t_s$  is the dwell time per beam. The highest *z* of any source detected in HI emission is 0.28, achieved by Catinella and collaborators at Arecibo[3]. Detection of even the brightest galaxies at such redshift requires dwell times of several hours at Arecibo, and much longer at any other telescope. The survey niche for AO40 is thus that of  $z \sim 0$ , deep surveys. A number of those have especially strong astrophysical appeal.

### FUTURE EXTRAGALACTIC BLIND HI SURVEYS.

A necesary observational activity that will require significant telescope time after completion of currently ongoing surveys consists in the follow–up corroboration of interesting but weak sources and deeper mapping of a subset of such objects. Statistical exercises (e.g. [1]) indicate that ~20% of the total survey time will be required for those functions after survey completion. At the current rate of telescope time allocation, AL-FALFA will require 7 calendar years to complete. The next stage of exploitation of the capabilities of an AO40 facility may be the extension of such surveys as ALFALFA and AGES to fuller sky coverage. The extension of <u>ALFALFA++</u> to cover the 13000 square degrees of sky accessible with the telescope would require approximately 500 hours of AO40 time. An extension of <u>AGES++</u> to a more extensive set of targets, including clusters and groups of galaxies with  $cz < 10000 \text{ km s}^{-1}$ , to cover 3000 square degrees with 300 seconds of dwell time per beam, would require 1500 hours with AO40. These would constitute a veritable legacy of complete extension.

More interesting, however, would be deeper surveys that would reach significantly

fainter levels of the HI mass function. As mentioned before, a significant new discovery of ALFALFA consists in the detection of numerous sources with no optical counterpart and giant streams of HI, very near the detection limits of the survey. 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 down to  $2 \times 10^6$  M<sub>☉</sub>, would provide an unprecedented investigation of the low mass end of the HI mass and luminosity functions. A Virgo Deep survey that would cover 200 sq. deg. with an effective dwell time of 4000 sec per beam would require 2000 hours with AO40. Such Virgo Deep survey would deliver genuinely new science and provide a fundamental scientific reference.

The  $\lambda$ CDM paradigm of galaxy formation predicts the presence of low mass systems in mini-filaments within cosmic voids. Such structures have never been detected. The nearest large-scale void in the local universe lies in the foreground of the Pisces-Perseus supercluster. With a diameter of order of 60 Mpc, its center is near  $cz \simeq 2500$  km s<sup>-1</sup>. A Deep Void survey that would cover 400 square degrees of the void solid angle with 10 times the sensitivity of ALFALFA would require some 4000 hours of AO40 time. Projected along the line of sight to the central regions of the Local Group (LG), such a survey would permit detection of LG sources with as little as  $5 \times 10^3 M_{\odot}$  and unprecedented column density sensitivity (near  $3 \times 10^{17}$  cm<sup>-2</sup>) in resolved sources in the LG and High Velocity Cloud complexes.

## FUTURE EXTRAGALACTIC TARGETED HI SURVEYS

HI can be currently detected in emission from extragalactic objects out to a  $z \sim 1/3$ , with dwell times of order of 10 ksec at AO. HI sources at distances > 200 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 in the HI line is best done via targeted, rather than blind searches.

GASS is an approved, targeted Arecibo 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 are 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 ~15% will be provided by ALFALFA. A possible extension to GASS++, which would include objects to  $z \simeq 0.3$  (a lookback time of about 4 Gyr), would be able to survey significant predicted changes in scaling laws of disks, relying on the uniquely high quality of the kinematic information in the HI data.

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 ([4],[5],[6]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 1–7 Gyr. The observational characterization of that function is of special importance, with respect to SKA plans for the "Billion HI Galaxy" surveys, the measurement of baryon acoustic oscillations and the elucidation of the nature of dark energy. As pointed out before, in spite of its large collecting area, sensitivity issues and confusion prevent the effective use of the Arecibo telescope for observations of individual galaxies at even higher redshift. However, 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<sub> $\odot$ </sub> spread over a width of 1500 km s<sup>-1</sup> could in principle be detectable in less than 10 hours with the Arecibo telescope. 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 for such a HI Cluster Integral, HIClint, survey.

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