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HI Cosmology in the Local Universe with ALFALFA

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Abstract. The Arecibo Legacy Fast ALFA (ALFALFA) survey is an ongoing second generation blind extragalactic HI survey exploiting Arecibo's superior sensitivity, angular resolution and digital technology to conduct a census of the local HI universe over a cosmologically significant volume. As of mid-2007, ∼4500 good quality extragalactic HI line sources have been extracted in ∼15% of the final survey area. ALFALFA is detecting HI masses as low as $10^6 M_\odot$ and as high as $10^{10.8} M_\odot$ with positional accuracies typically better than $20''$, allowing immediate identification of the most probable optical counterparts. Only 3% of all extragalactic HI sources and fewer than 1% of detections with $M_{HI} > 10^{9.5} M_\odot$ cannot be identified with a stellar component. First ALFALFA results already suggest, in agreement with previous studies, that there does not appear to be a cosmologically significant population of optically dark but HI rich galaxies. ALFALFA promises a wealthy dataset for the exploration of many issues in near-field cosmology and galaxy evolution studies, setting the stage for their extension to higher redshifts with the Square Kilometer Array (SKA).

1. Introduction

21 cm HI line observations over the years have provided critical understanding of the nature of galaxies and the processes which govern their evolution. HI line studies address a host of fundamental cosmological questions (the number density, distribution and nature of optically–dark and low mass halos) and issues of galaxy formation and evolution (sizes of HI disks, history of tidal interactions and mergers, low z absorber cross section, origin of dwarf galaxies, nature of high velocity clouds). The program for the current symposium *"Frontiers of Astrophysics"*, marking the 50th anniversary of NRAO, illustrates the continued promise of HI line investigations not only for the exploration of galaxies and large scale structure but also for new applications which will explore entirely uncharted cosmic volumes, the "Dark Ages". Surveys of redshifted HI for cosmological purposes are main drivers of the Square Kilometer Array (SKA).

However, it is important to keep in mind that, in comparison with the view gleaned from optical redshift catalogs, our understanding of $z = 0$ cosmology through the eyes of the 21 cm line is still immature. The HI equivalent of the optical luminosity function (OLF), the HI Mass Function (HIMF), is still derived from only a few thousand objects. Among recent estimates of the HIMF are those presented by Zwaan *et al* (1997), Rosenberg & Schneider (2002), Zwaan *et al* (2003) and Springob *et al* (2005). The latter is based on a compilation of HI observations of ∼9000 optically selected galaxies, further restricted by HI line flux and optical diameter to a complete subsample containing 2200 objects.

The other determinations are based on blind HI surveys and thus have no bias against the low luminosity and low surface brightness galaxies which may be underrepresented in optical galaxy catalogs. However, all of these studies suffer from limitations associated with small number statistics, systematics and the effects of cosmic variance, especially at both the low and high mass ends. Of particular note, the lowest mass objects are detected only very nearby; determination of the low mass HIFM slope is not only limited by small number statistics but also by large uncertainties in the HI masses derived using redshift distances (Masters, Haynes & Giovanelli 2004). Because of volume limitations, the high mass end is likewise poorly sampled. Since the most massive objects will be the HI lampposts detected at high redshift in large numbers by the SKA and its precursor instruments, it is critical to understand the nature and distribution of their local counterparts.

Here, I introduce and review the promise of the on-going Arecibo Legacy Fast ALFA (ALFALFA) survey to yield cosmologically significant results on the number and distribution of optically-dark and low mass halos and on the determination of the $z = 0$ HIMF, the HI correlation function and its bias parameter.

2. ALFALFA: A Second Generation Blind HI Survey

Just as the introduction of wide field CCDs revolutionized the survey capabilities of optical and infrared telescopes, HI line astronomy is undergoing a similar renaissance with the advent of multi-beam receivers on the large single-dish telescopes, enabling blind HI surveys that cover wide areas. Table 1 summarizes the principal characteristics of major blind HI surveys. Most recently, the 305 m antenna has been equipped with a 7-beam system known as ALFA, the Arecibo L-band Feed Array, which is being used to conduct wide area surveys in galactic, extragalactic and pulsar research. The local extragalactic sky visible to Arecibo is rich, containing the central longitudes of the Supergalactic Plane in and around the Virgo cluster, the main ridge of the Pisces–Perseus Supercluster, and the extensive filaments connecting A1367, Coma and Hercules. Included in Table 1 are two surveys currently exploiting ALFA, namely ALFALFA and a somewhat deeper targeted survey covering a much smaller area, the Arecibo Galaxy Environments Survey (AGES; Auld *et al* 2006).

ALFALFA is a two-pass, fixed azimuth spectral line survey which aims to map 7000 deg^2 of high galactic latitude sky over the HI velocity range from -1600 to $+18000$ km s^{-1}. Exploiting the big dish's large collecting area and small beam size, ALFALFA is specifically designed to probe the faint end of the HI mass function, a goal for which sky coverage is critical (Giovanelli *et al* 2005a). It exploits a "minimum intrusion" technique designed to maximize data quality (Giovanelli *et al* 2005b) and an automated Fourier domain signal extraction algorithm (Saintonge 2007a). ALFALFA has 8$\times$ the sensitivity, 4$\times$ the angular resolution, 3$\times$ the spectral resolution, and 1.6$\times$ the total bandwidth of HIPASS, the HI Parkes All-Sky Survey (Zwaan *et al* 2004; Meyer *et al* 2004). With a median redshift of only $\sim$2800 km s^{-1}, HIPASS did not sample adequate extragalactic volume to yield a cosmologically "fair sample". Furthermore, the large beamsize (15$'$) of the Parkes telescope made identification of optical coun-

Table 1. Comparison of Major Blind HI Surveys

Survey	Beam ($'$)	Area (deg^2)	δV (km s^{-1})	rms^a (^{a})	V_{median} (km s^{-1})	N_{det}	Ref
AHISS	3.3	13	16	0.7	4800	65	b
ADBS	3.3	430	34	3.3	3300	265	c
WSRT	49.	1800	17	18	4000	155	d
HIPASS	15.	30000	18	13	2800	5000	e,f
HI-ZOA	15.	1840	18	13	2800	110	g
HIDEEP	15.	32	18	3.2	5000	129	h
HIJASS	12.	1115	18	13	[i]	222	i
J-Virgo	12.	32	18	4	1900	31	j
AGES	3.5	200	11	0.7	12000	...	k
ALFALFA	3.5	7000	11	1.7	7800	>25000	l

[a] mJy per beam at 18 km s^{-1} resolution; [b] Zwaan *et al* (1997); [c] Rosenberg & Schneider (2000); [d] Braun, Thilker & Walterbos (2003); [e] Meyer *et al* (2004); [f] Wong *et al* (2006); [g] Henning *et al* (2000); [h] Minchin *et al* (2003); [i] Lang *et al* (2003), HIJASS has a gap in velocity coverage between 4500-7500 km s^{-1}, caused by RFI; [j] Davies *et al* (2004); [k] Auld *et al* (2006); [l] Giovanelli *et al* (2007).

terparts often uncertain without followup HI synthesis observations (Oosterloo *et al* 2007). The centroiding accuracy of ALFALFA is on average 24$''$ (20$''$ median) for all sources with signal-to-noise ratio > 6.5 so that identification of the most probably stellar counterpart is an integral part of the ALFALFA cataloging process. Its median redshift is ~7800 km s^{-1}, nearly 3× that of HIPASS.

Initial results from ALFALFA precursor observations were published by Giovanelli *et al* (2005b), and two catalogs of HI detections from the survey itself are published (Giovanelli *et al* 2007) or submitted (Saintonge *et al* 2007). Catalogs, spectra and associated data are being made available from the Cornell Digital HI Archive *http://arecibo.tc.cornell.edu/hiarchive/*. The first catalog (Giovanelli *et al* 2007) covering $11^h44^m <$ R.A. $< 14^h00^m$, $+12° <$ Decl. $< +16°$, contains 730 HI detections and their most probable optical counterparts. In comparison, HIPASS detected only 40 HI sources in the same region, two of which are unconfirmed by ALFALFA. Although this region of the sky has been heavily surveyed by previous targeted observations based on optical flux– or size–limited samples, 69% of the extracted sources are newly reported HI detections, an indication that previous criteria for identifying potentially HI–rich targets have neglected most of the HI-rich population.

At the time of this meeting, signal extraction has been completed for ~15% of the survey area with catalogs totaling ~4500 detections in preparation for publication in the second half of 2007. The largest contiguous region fully processed to date corresponds to a strip between $7.5^h <$ R.A. $< 16.5^h$, $12° <$ Decl. $< 16°$. A total of 2657 HI sources have been detected in that region which covers ~7.5% of the survey total solid angle. Figure 1 shows a cone diagram of the ALFALFA detections in this strip; the distribution of HI sources closely matches

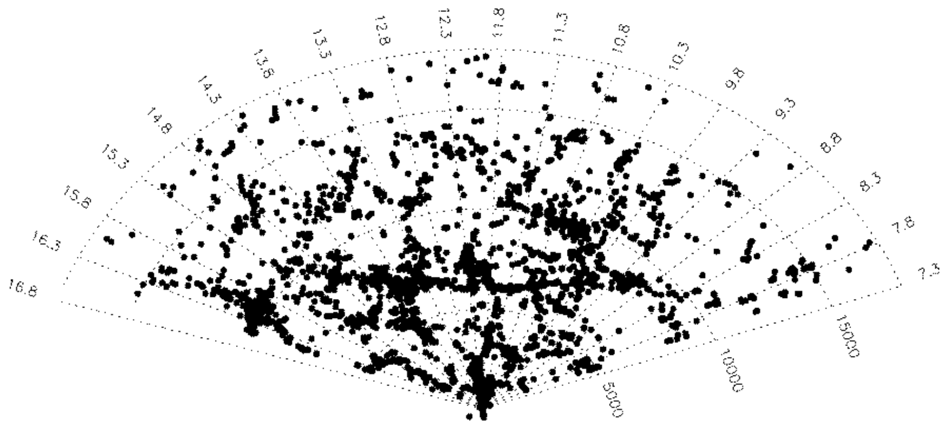

Figure 1. Cone plot 2657 HI sources detected by ALFALFA in the region R.A.=[7.5^h–16.5^h], Dec=[12°–16°], which represents 7.5% of the survey. Note that due to RFI, ALFALFA is effectively blind in the redshift range between approximately 15000 and 16000 km s^{-1}.

the complex features of large scale structure evident also from optical surveys. Figure 2 summarizes the characteristics of the HI detections in the same region. The statistical improvement of ALFALFA over HIPASS is clear from the Spänhauer diagram shown on the left; in fact, in the same region, HIPASS detected only 90 sources versus the 2700 found by ALFALFA. The diagrams on the right show the quality of the ALFALFA data and signal extraction technique: the S/N of detections exhibits no significant bias with respect to velocity width. Spectroscopic HI surveys are not simply flux limited; the flux limit is expected to increase as $W^{1/2}$ for low velocity widths and show a linear rise for the wider line profiles. Such a transition is observed near $\log W \simeq 2.5$. The ALFALFA flux limit is ~ 0.25 Jy km s^{-1} for narrow lines, rising to 1 Jy km s^{-1} for the broadest ones. The detection areal density of ∼5 sources deg^{-2}, with peaks $10 - 20\times$ higher in regions of groups and clusters suggests that the full ALFALFA survey may catalog as many as 30,000 HI sources, a higher yield than suggested by survey simulations based on estimates of the HIMF derived from previous surveys (Giovanelli *et al* 2005a).

3. ALFALFA and the Existence of Massive "Dark Galaxies"

A truly "dark galaxy" is a halo consisting only of dark matter. In some scenarios, it is possible that some optically dark objects may contain enough HI that a blind HI survey would detect them. A good example of a "dark" object is the southwestern component of the binary system known as HI1225+01. While the northeastern HI component hosts a small, star forming dwarf, the SW component has no detectable stellar counterpart. VLA observations reveal a velocity field implying rotation with $V_{rot} \simeq 14$ km s^{-1}, yielding a dynamical mass of 10^9 $M_\odot$ and thus $M_{dyn}/L > 200$ (Chengalur, Giovanelli & Haynes 1995). However, it is not an isolated object, being part of an apparent binary system.

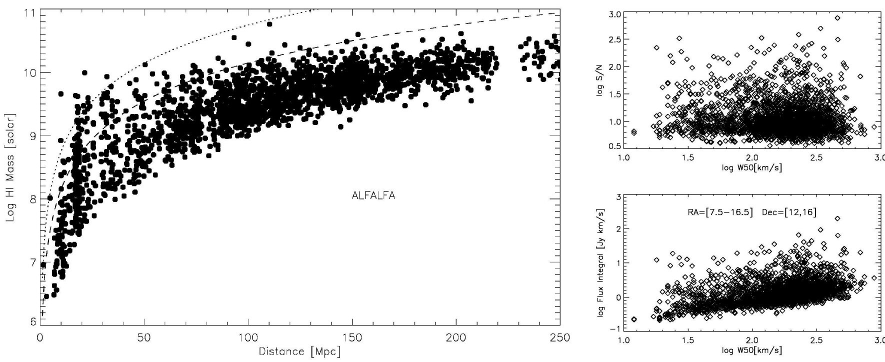

Figure 2. **Left:** Spänhauer diagram of the 2657 HI sources included in Figure 1. The two smooth lines identify respectively the completeness limit (dotted) and the detection limit (dashed) for sources of 200 km s^{-1} linewidth for the HIPASS survey. Note that due to RFI, ALFALFA is effectively blind in the redshift range between approximately 15000 and 16000 km s^{-1}. **Right:** Signal–to–noise ratio versus velocity width (top) and integrated HI line flux density versus velocity width for the same galaxies.

A candidate isolated massive dark galaxy VirgoHI21, was detected by Davies *et al* (2004) during the HI Jodrell All-Sky Survey (HIJASS) and corroborated by Arecibo and WSRT observations (Minchin *et al* 2007). VirgoHI21 lies some 100 kpc N of NGC 4254, M99, one of the brightest spiral galaxies in the Virgo Cluster. Well-known for its prominent optical lopsidedness and strong $m = 1$ spiral mode, NGC 4254 lies about 3°, or 1 Mpc at the Virgo distance, from M87 and appears to be moving at high speed relative to the cluster. It is, however, not HI deficient. As illustrated in Figure 3, the ALFALFA observations reported by Haynes *et al* (2007) show clearly the existence of a huge HI stream, in which VirgoHI21 is one condensation, extending ~ 250 kpc to the north of NGC 4254. The gas mass associated with the stream is a modest 6×10^8 $M_\odot$, or about 10% of the total HI associated with NGC 4254. One of the driving arguments for the interpretation of VirgoHI21 as an isolated massive dark galaxy is the gradient seen in the velocity field (Minchin *et al* 2007); as evident in Figure 3, this gradient is just part of the varying, large–scale velocity field along the stream. Duc & Bournaud (2007) have modeled the formation of a tidal tail closely resembling that seen in Figure 3 by a a very high speed encounter of NGC 4254 with another cluster member now located several degrees away. ALFALFA has discovered a number of other optically-dark HI clouds in the periphery of Virgo (Kent *et al* 2007; Kent, this volume) which may be of similar origin.

One of the principal results of HIPASS is the lack of HI detections without optical counterparts in those regions of the sky not obscured by the Galactic plane. ALFALFA will deliver much more stringent constraints on the existence of gas-rich dark galaxies through its sensitive, large volume coverage.

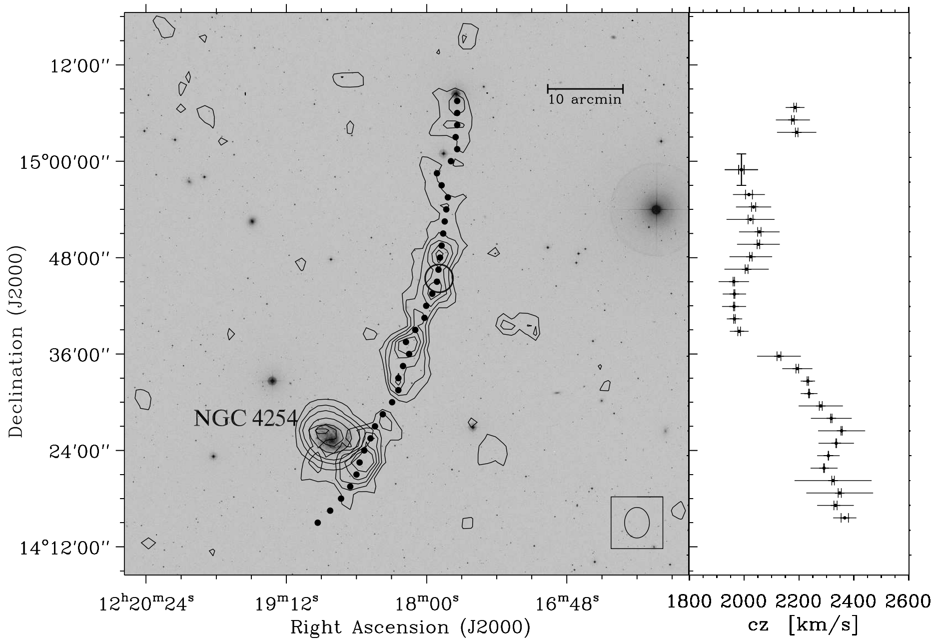

Figure 3. Left: HI flux contours extracted from the ALFALFA survey dataset, superposed on a DSS2 Blue image. The 36 filled dots indicate the locations of successive deeper L-band wide (LBW) receiver pointings (Haynes *et al* 2007). The contours centered on NGC 4254 are at 10, 15, 20, 30, and 40 Jy beam^{-1} km s^{-1}, integrated from 2259 to 2621 km s^{-1}. The contours for the HI stream are at 0.35, 0.52, 0.70, 0.87, and 1.0 Jy beam^{-1} km s^{-1}, integrated from 1946 to 2259 km s^{-1}. The 3′ circle in mid stream indicates the position of VirgoHI21 (Minchin *et al* 2007). Right: The velocity of the HI emission peak as seen in LBW pointings.

4. ALFALFA and the "Missing Satellite Problem"

One of the principal discrepancies between cold dark matter theory and current observations revolves around the large difference between the number of dwarf dark matter halos seen around giant halos in numerical simulations based on CDM and the observed dwarf satellite population in the Local Group (Kauffmann *et al* 1993; Klypin *et al* 1999), referred to as the "missing satellite problem". Previous determinations of the HIMF below 10^8 $M_\odot$ (Zwaan *et al* 1997; Rosenberg & Schneider 2002; Zwaan *et al* 2003) suffer severely from small number statistics and from the systematics associated with distance uncertainties and large scale inhomogeneities (Masters, Haynes & Giovanelli 2004). ALFALFA is specifically designed to survey enough solid angle to detect several hundred objects with $M_{HI} < 10^{7.5}$ and thus provide a robust determination of the low HI mass slope of the HIMF. Already, ALFALFA has detected more galaxies with masses less than $M_{HI} < 10^{7.5}$ $M_\odot$ than included in all of the previous HI blind surveys combined.

For her Ph.D. thesis, Amélie Saintonge (2007b) has undertaken a first study of some of the lowest HI mass galaxies detected early in the ALFALFA survey.

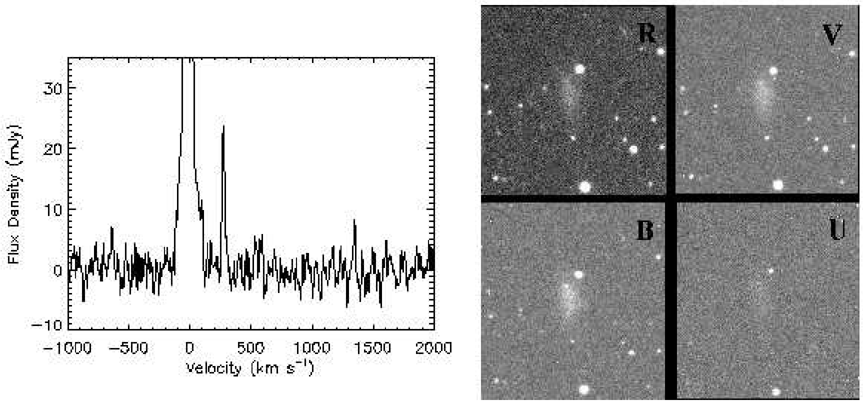

Figure 4. Left: ALFALFA spectrum of AGC 112521 (HI0141+27). Right: Broad-band images (courtesy of L. van Zee) using the WIYN 0.9m telescope of the optical counterpart, a newly-discovered low surface brightness dwarf member of the NGC 672 group.

All of them are nearby, optically faint and of low surface brightness. They exhibit a range of morphological clumpiness and rates of massive star formation. Various members of the ALFALFA consortium are pursuing multiwavelength observations including broad-band and Hα imaging, HI synthesis mapping and UV imaging with the GALEX satellite. Of a first sample targeted for follow-up Hα imaging, 15% do not show the presence of HII regions. While this work is still on-going, we present an illustrative example of the kind of newly catalogued system that ALFALFA finds. Figure 4 shows the ALFALFA HI spectrum of a new dwarf member of the NGC 672 group dubbed AGC 112521. This object was first detected in our ALFA-commissioning precursor observations (Giovanelli *et al* 2005b) and recovered in the early ALFALFA survey observations. As evident in Figure 4, the HI line emission from the galaxy is clearly detected at c$z = +274$ km s^{-1}, a narrow line full width at 50% of the peak emission of 26 km s^{-1} and a total HI line flux density of 0.68 Jy-km s^{-1} (Saintonge *et al* 2007). Assuming its membership in the NGC 672 group at a distance of 7.2 Mpc, the HI mass is 7.9×10^6 $M_\odot$. Its blue luminosity L_B derived from newly acquired images is similarly low: $L_B = 3.6 \times 10^6$ $L_\odot$, so that M_{HI}/L_B is 2.2. Adopting standard relations to convert multiband magnitudes into stellar mass, we find that nearly half of the baryonic matter is still in the form of gas.

With the promise of a final catalog of thousands of galaxies in the mass range $10^6 < M_{HI} < 10^8$ $M_\odot$, the study of these gas rich systems is a prime science driver of ALFALFA. Future ALFALFA studies will explore not only the low mass slope of the HI mass function and its possible dependence on environment, but also the distribution, morphology, star formation rate and chemical enrichment history of these low mass gas-rich dwarfs.

5. ALFALFA and the "Void Problem"

As pointed out by Peebles (2001), numerical simulations based on CDM predict that voids should contain large numbers of dwarf galaxies. For example, the voids in the simulations of Gottlöber *et al* (2003) are criss-crossed by dark matter filaments within which lie large numbers of very low amplitude inhomogeneities. In fact, those authors predict that a void with a diameter of $20h^{-1}$ Mpc should contain 1000 dark matter halos with masses of 10^9 $M_\odot$, and as many as 50 with masses ten times greater than that. Peebles suggests that the failure to identify such a void population raises one of the principal challenges to CDM models. Photoionization and baryonic blowout may suppress star formation or perhaps the retention of any baryons within the low mass halos, but it still is not clear that these processes are sufficient to explain the absence of galaxies in voids (Hoeft *et al* 2006).

Limits on the abundance and properties of void galaxies have been placed by previous optical and radio studies. Hoyle *et al* (2005) have used the SDSS dataset to show that the OLF of void galaxies has a fainter break luminosity L^* but a similar faint end slope to the overall SDSS luminosity function. In addition, they have shown that void galaxies are typically blue, disk-like and have high Hα equivalent widths, making them excellent targets for HI emission line surveys. Previous surveys for HI in voids have exploited the VLA to conduct blind HI surveys of the Pisces-Supercluster and its foreground void (Weinberg *et al* 1991; Szomoru *et al* 1994) and the Bootes void (Szomoru *et al* 1993; 1996). Szomoru *et al* (1993) did find an isolated galaxy in Bootes, but its mass of 5×10^9 $M_\odot$ and blue luminosity L_B of -18.6 exclude it as a true dwarf. In fact, those VLA surveys sampled a relatively small volume and were hampered by poor spectral resolution (42 km s^{-1}), not adequate to detect the lowest mass, narrowest HI signals.

Saintonge *et al* (2007) initiated a first, but limited, ALFALFA analysis of galaxies in the void in front of the Pisces-Perseus supercluster at $cz \sim 2000$ km s^{-1}. They detected no galaxies in a large volume of 460 Mpc^3, whereas a scaling of the predictions of Gottlöber *et al* (2003) under the assumption that the dark-to-HI mass ratio is 10:1 predicts that ALFALFA would have detected 38 HI sources. This very preliminary result for a single void in only 2% of the ALFALFA survey suggests that the discrepancy between the predicted and observed abundance of dwarf galaxies in voids cannot be reconciled by a population of gas rich dwarfs. More credible results will be available when the full ALFALFA survey is completed.

5.1. ALFALFA: Prelude to the SKA

Although they acknowledge the volume and resolution limitations of the HIPASS catalog, recent papers have explored the behavior of the galaxy distribution it traces by attempting to estimate its two–point correlation function $\xi(r)$. Meyer *et al* (2007) conclude that gas-rich galaxies are among the most weakly clustered galaxies known and suggest that the clustering scale length r_o depends strongly on rotational velocity, and thus, by implication, on the halo mass. In contrast, Basilakos *et al* (2007) argue that massive HIPASS galaxies show the same clustering properties as optically-selected ones, but that the low mass systems, M_{HI}

$< 10^9\ M_\odot$, show a nearly uniform distribution. Both of these studies are fraught with potential systematics because of the shallow depth of HIPASS, the potential impact of source confusion and the statistical limitations when its catalog is divided into subsets. As the follow-on to HIPASS, ALFALFA is specifically designed to overcome many of the limitations of the earlier survey, thereby allowing a robust determination of the HI-HI and HI-optical galaxy correlation functions and a quantitative study of the biasing of the HI population relative to optical or IR-selected samples and to the underlying density field.

One of the prime science drivers of the SKA is the undertaking of a billion galaxy redshift survey in the HI line over the redshift range $0 < z < 2.5$ to explore the evolution of the gas content of galaxies and constrain the dark energy equation of state through the measurement of baryon acoustic oscillations (Abdalla & Rawlings 2004). Even allowing for the likely increase in the gas content with z, only the most massive HI galaxies will be detected in emission at moderate redshift. As in the case of the low mass end of the HIMF, previous surveys have been too shallow to detect the most massive HI galaxies. ALFALFA has already detected more than twice as many massive galaxies with $M_{HI} > 10^{10.4}$ $M_\odot$ than all the previous HI blind surveys combined. These massive galaxies exhibit a range of morphologies, colors and nuclear concentration but all appear to be luminous disk systems. Many have stellar masses in the range corresponding to the "transition mass" ($M_{stars} \sim 3 \times 10^{10}\ M_\odot$) above which galaxies show a marked decrease in their present- to past-averaged star formation rates (Kauffmann *et al* 2003). ALFALFA will contribute its high mass detections to the GALEX–Arecibo–SDSS Survey (GASS; P.I.: D. Schiminovich), a new program to obtain measures of the HI content at a gas mass fraction as low as 1.5% of the stellar mass in a sample of 1000 galaxies chosen by optical-UV criteria to have stellar masses $> 10^{10}\ M_\odot$. The combination of multiwavelength data will provide new understanding of the physical processes that regulate gas accretion and its conversion into stars in massive systems. While ALFALFA+GASS will characterize the properties of galaxies at $z \sim 0$, ambitious future studies aimed at characterizing the evolution of galaxies over the last 4 Gyr should be possible in the next few years with Arecibo as well as the SKA precursor instruments.

6. Conclusions

ALFALFA is an ongoing survey with a detection catalog available in mid-2007 reflecting only about 15% of the final survey. Given its state, the full impact of ALFALFA is only beginning to become evident, but the survey promises now to yield > 25000 extragalactic HI detections when it is complete. It should yield robust measures of the HIMF, the HI-HI and HI-optical correlation functions and their bias parameters at $z = 0$, thereby establishing the present day constraints on HI cosmology. The ALFALFA team is an open consortium and interested parties are invited to follow the survey's progress via the ALFALFA website *http://egg.astro.cornell.edu/alfalfa*.

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