

ALFALFA: The Search for (Almost) Dark Galaxies and their Space Distribution

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Summary. — The Arecibo Legacy Fast ALFA (ALFALFA) survey is designed to explore the $z = 0$ HI mass function (HIMF) over a cosmologically significant volume. ALFALFA will improve on previous determinations of the HIMF by its combination of depth, wide area and centroiding accuracy, the latter allowing, in most cases, immediate identification of the optical counterpart to each HI signal. ALFALFA will detect hundreds of galaxies with HI masses less than $10^{7.5} M_{\odot}$ and also greater than $10^{10.5} M_{\odot}$, and its final catalog will allow investigation of the dependence of the HIMF both on local density and on galaxy morphology. Already ALFALFA confirms previous suggestions that there is no cosmologically significant population of HI-rich dark galaxies. Fewer than 3% of all extragalactic HI sources and <1% of ones with $M_{HI} > 10^{9.5}$ cannot be identified with a stellar counterpart. Very preliminary results on the presence of gas-rich dwarfs in the void in front of the Pisces–Perseus supercluster suggest an underabundance of such objects compared to the predictions of numerical simulations. The objects with highest HI mass exhibit a range of morphologies and optical colors and surface brightnesses but all appear to be massive disk systems. The latter represent the population likely to dominate future studies of HI at higher redshift with the Square Kilometer Array.

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1. – Introduction

As discussed in the preceding paper by Giovanelli in this volume, the Arecibo Legacy Fast ALFA (ALFALFA: [1, 2, 3, 4]) survey is an on-going second generation HI blind mapping program that will produce a final catalog of more than 25000 HI detections at $cz < 0.06$. 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. With the installation in 2004 of its first “radio camera”, the 7-beam Arecibo L-band Feed Array (ALFA), the Arecibo legacy of extragalactic HI studies continues to probe regimes untouched by other surveys, addressing fundamental cosmological

questions (the number density, distribution and nature of 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). In addition to Arecibo's huge collecting area, the availability of several multi-bit and many-channel backends allows the *simultaneous* collection of multiple datasets covering different frequency intervals with different spectral resolution without loss of signal. The combination of Arecibo's unmatched sensitivity with its new wide area mapping capability and the efficiency of commensal observing offers tremendous potential for future scientific discovery in the coming years.

It is important to note that our current understanding of large scale structure and the galaxy population traced by HI redshift surveys is distinctly immature relative to that derived from O/IR redshift surveys. The previous major blind HI survey, the HI Parkes All-Sky Survey (HIPASS; [5]), surveyed 30000 deg^2 but detected only 5000 galaxies with a median redshift of $\sim 2800 \text{ km s}^{-1}$. As a second generation effort, ALFALFA will improve on these statistics dramatically. Although it will cover only 7000 deg^2 , ALFALFA promises a final catalog in excess of 25000 HI detections with a median redshift of $\sim 7800 \text{ km s}^{-1}$. Its detection rate is on average 4 to 5 galaxies per square degree; in high density regions, that rate rises to 20 or more. This improvement on HIPASS is driven partly by broader frequency coverage but mostly by the sheer sensitivity of Arecibo and by technical advances in signal processing and survey strategy. Furthermore, the Arecibo beam size advantage permits a centroiding accuracy generally better than $20''$ so that optical counterparts can be identified – or excluded – with high probability. While not designed for the detailed study of the HI distribution within galaxies and confusion limited in regions of highest local sky density, ALFALFA will yield a catalog of accurate HI line fluxes, systemic velocities and profile widths for gas-rich galaxies within $z < 0.06$, probing a volume a factor of 10 times greater than that sampled by HIPASS. Initiated in 2005, ALFALFA is expected to be completed in 2010-11. Because the survey is not complete, results are not yet definitive until more volume is sampled, but ALFALFA already promises to deliver robust measures of the HI mass function, the HI correlation function and its bias parameter over a cosmologically significant volume. Here, I discuss some of the open issues associated with the number density and distribution of gas-rich galaxies and summarize the ALFALFA potential to address them.

2. – ALFALFA and the Distribution of Gas-Rich Galaxies

It is well known that HI sources are typically associated with star-forming disk galaxies, many of which are of low optical surface brightness. Spirals in rich clusters, however, exhibit strong HI deficiency, so that in regions of high X-ray emissivity, gas depletion can reach as high as 90%. Thus it may come as no surprise that HI blind surveys may trace the low amplitude fluctuations in the large scale structure, as cluster populations are simply not included among the HI detections. Principal aims of ALFALFA are to explore quantitatively how widely dispersed is the HI population in comparison with structures traced by O/IR samples and what are the impacts of both morphology and density on the HI mass function.

Figure 2 shows a cone diagram of the status of redshift observations in a nearby slice of the sky covered by both ALFALFA and SDSS, focusing on the local volume out to $cz < 8000 \text{ km s}^{-1}$. The sky area extends from $07^h30^m < \text{R.A.} < 16^h30^m$ and $+08^\circ < \text{Decl.} < +16^\circ$. Different symbols show the locations of subsets with redshifts derived from optical observations only (red open circles), HI only (blue filled circles) and both

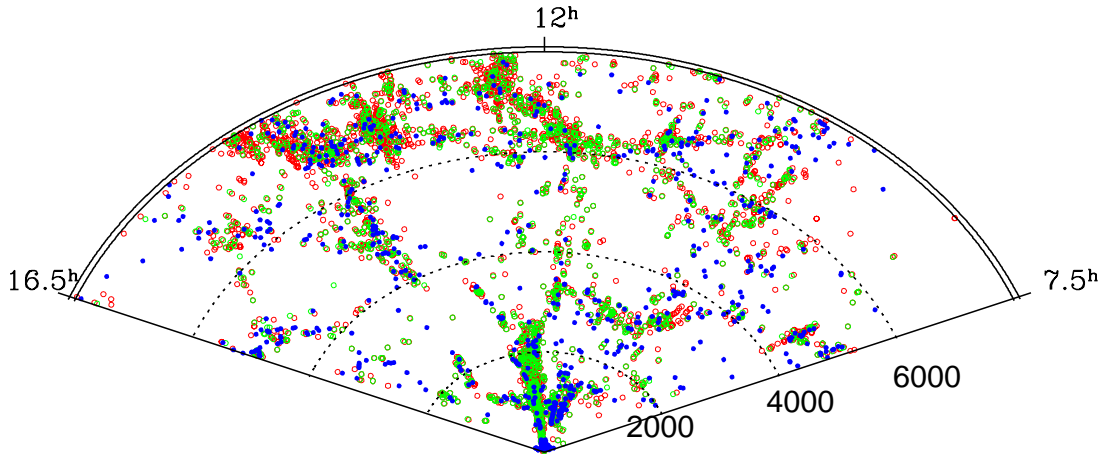


Fig. 1. – Radial distribution of 5670 galaxies with measured radial velocities $cz < 8000$ km s^{-1} in the ALFALFA strip from $07^{\text{h}}30^{\text{m}} < \text{R.A.} < 16^{\text{h}}30^{\text{m}}$ and $+08^{\circ} < \text{Decl.} < +16^{\circ}$. Different colors denote galaxies whose redshifts are drawn from, respectively, optical only (red), HI only (blue) and both (green). The HI-rich galaxies trace the same structures seen by optical surveys; the few “void” galaxies seen here are gas rich as expected. When complete, ALFALFA will provide a statistically complete picture of the local filament and void population.

(green open circles). The central region of this strip is dominated by the Leo and Virgo regions within the Local Supercluster at $cz < 2000$ km s^{-1} , while the eastern half shows the southern edge of the “Great Wall” and the filaments leading to Coma further to the north. Clearly the optical surveys, in this case mainly SDSS plus targeted surveys of groups and clusters, dominate the highest density regions, while the gas-rich galaxies trace the filamentary structures in more detail. Note that ALFALFA contributes a host of new redshifts at the nearer distances; these are typically low surface brightness, faint galaxies which populate the lowest density quartile.

Both Meyer *et al.* [6] and Basilakos *et al.* [7] have derived the spatial correlation function $\xi(r)$ for the HIPASS catalog, employing different methods to account for large scale structure. On the one hand, Meyer *et al.* [6] conclude that the HI rich population represented by the HIPASS sample is extremely weakly clustered, though the clustering scale depends on the galaxy rotational velocity. In contrast, Basilakos *et al.* [7] claim that the massive HIPASS galaxies show the same clustering characteristics as optically selected samples, but that the low mass ($M_{\text{HI}} < 10^9 M_{\odot}$) systems show a nearly uniform distribution. A simple explanation for this apparent discrepancy in the analysis of the same sample is the lack of adequate volume sampling, the effect of which is to produce different results depending on the nature of corrections made in accounting for large scale structure.

As Peebles has discussed in this volume, current Λ CDM simulations predict that low amplitude filamentary structures criss-cross the voids. The galaxies corresponding to the halos in those filaments are expected to be low luminosity, star forming galaxies [8], excellent candidates for detection by ALFALFA. A first tantalizing result has been

obtained by Saintonge *et al.* [4] who analyzed the ALFALFA catalog covering a portion of the nearby void in front of the Pisces-Perseus Supercluster at $cz \sim 2000 \text{ km s}^{-1}$. Within a volume of 460 Mpc^{-3} , ALFALFA detects not a single galaxy. In contrast, we would have expected to detect 38 HI sources in such a volume based on scaling the predictions of Gottlöber *et al.* [9] with a dark-to-HI mass ratio of 10:1. It is not clear if this discrepancy, based on only 2% of the ALFALFA catalog, is real or just another example of the perils of volume limitations. Once sufficient volume is sample, ALFALFA will be able to place stringent constraints on the local void population and its possible challenge to the Λ CDM paradigm [10].

3. – ALFALFA, the HI Mass Function and “Missing Satellites”

Early studies of the HIMF [11, 12] showed its functional similarity to the optical luminosity function. Because of its relevance to the “missing satellite” problem, the faint (low mass) end slope, α , of the HIMF has been the focus of many previous studies, with widely varying results [13, 14, 15]. These previous studies were severely limited in their sampling of objects at both the low mass ($10^8 M_\odot$) and high mass ($10^{10} M_\odot$) ends. For example, the Rosenberg & Schneider [14] sample includes only a dozen galaxies with $M_{HI} < 10^8 M_\odot$; the HIPASS result [15] is based on ~ 30 such low mass objects. In addition to the statistical uncertainties associated with such small samples, the determination of the faint end slope is complicated by uncertainties in the distance estimates of these very nearby galaxies. For example, Masters *et al.* [16] have shown that the Hubble-law distance model employed by the HIPASS team [15] to their southern hemisphere-only sample yields a systematic underestimate of α .

ALFALFA will provide a factor of ten improvement in the volume sampling over HIPASS, important not only for taking proper account of the impact of large scale structure but also for separating the impacts of the morphological variation in HI content [17] and morphological segregation. Discussing particularly the issues associated with the derivation of the HIMF, Springob *et al.* [18] point out the critical need for large “fair” samples so that corrections can account not just for the fact that the space density varies with distance but also that the fractional volume of space occupied by regions of a particular density do also. Applications of HIMF derivations by methods which are not sensitive to large scale structure require understanding of the sample completeness, noise characteristics, RFI impact and signal extraction bias. Because of its combination of wide areal coverage, depth and angular resolution, ALFALFA will sample a sufficiently large volume of the local universe to yield a cosmologically fair sample.

Although dwarf galaxies constitute the majority of the galaxy population, large uncertainties surround their formation and evolutionary histories. The dwarf population follows a strong morphology-density relation, with the passively evolving systems always found within close proximity of massive galaxies, in contrast to the more widespread gas-rich, star forming population. ALFALFA will address many questions associated with the widely-dispersed gas-rich dwarf population: Where are the “missing satellites”? How are dwarfs affected by reionization? Is their evolution dominated by nearby massive neighbors? Are some dwarfs “young”, forming only now out of tidal debris? Environment-dependent mechanisms invoked to drive the morphological segregation include the tidal and ram pressure stripping as well as the formation of new dwarfs in the debris of tidal encounters. Indeed, some dwarfs may be recent entities, formed out of the tidal debris; these tidal dwarfs are distinctive in having little dark matter and higher heavier element abundances, than expected for their luminosities, an inheritance from their parent galax-

ies. An example is the “old” tidal dwarf candidate VCC 2062 [19] included also in the ALFALFA catalog.

Because of its wide areal coverage, sensitivity, and spectral resolution, ALFALFA is designed to probe the dwarf population over a wide range of environments, including local voids and the Virgo cluster. In addition to providing a robust determination of the low mass HIMF slope, the detailed study of the morphology, heavy element abundance, stellar population characteristics, kinematics and space distribution of these low mass objects will yield clues on their origin and cosmological importance. Already, ALFALFA has detected more galaxies with $M_{HI} < 10^8 M_{\odot}$ than all other HI surveys combined.

4. – ALFALFA, Massive Galaxies and Future Prospects with the SKA

The principal science questions which drive design of the Square Kilometer Array require major HI line surveys over a wide range of redshift. In fact, an advantage that HI line science has over other wavelengths is the potential to observe HI signals over the redshift window from $z = 0$ all the way back to the “dark ages”. The challenges to undertaking such studies should not be underestimated, however, both from observing time and signal-to-noise considerations as well as from the perspective of an ever-increasingly polluted radio interference environment. 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.

Previous blind HI surveys did not explore sufficient volumes to detect the highest HI mass galaxies nor to explore time evolution of the HIMF or the luminosity–rotation velocity scaling relation. Because of the bandwidth limitations of ALFA and its “fast” observing strategy, ALFALFA will not explore cosmic evolution, but it will establish the $z = 0$ abundance of high mass galaxies. Already, ALFALFA has detected more than twice as many objects with $M_{HI} > 2.5 \times 10^{10} M_{\odot}$ than all of the other previous blind HI surveys combined. Most of these appear to be luminous disk systems, some with comparable gas and stellar masses. These systems represent the most gas-rich massive disks and hence the ones most likely to be detected by current and near-term programs to detect HI at moderate redshifts. In combination with ALFALFA, the GALEX-Arecibo-SDSS Survey (GASS; D. Schiminovich, P.I.), scheduled to start in 2008, aims to measure the fractional gas content in 1000 massive disk galaxies (stellar mass $M_{*} \sim 10^{10}$) in order to explore the physical mechanisms by which galaxies acquire and retain their gas and convert it into stars and the influence on those processes of such factors as environment and AGN feedback.

5. – Conclusions

ALFALFA is an ongoing survey so that its impact is only beginning to become evident, but it promises to yield > 25000 extragalactic HI detections when it is complete. Its areal detection rate and centroiding accuracy are significant improvements over earlier surveys, and the vast majority of HI detections can be identified with optical counterpart with very high probability. Of the currently available ALFALFA catalog, fewer than 3% of all extragalactic HI sources and less than 1% of detections with $M_{HI} > 10^{9.5} M_{\odot}$ cannot be identified with a stellar component. When complete, ALFALFA will yield not only valuable measures of gas content and dynamical mass for several tens of thousands of individual galaxies but also robust measures of the HIMF, the HI-HI and HI-optical correlation functions and their bias parameters at $z = 0$. In combination with surveys at

other wavelengths, the products of ALFALFA will lay a firm footing for future studies of the evolution of these parameters over cosmic time. ALFALFA 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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