A Coordinated High Galactic Latitude Drift Survey for EALFA
A First Allocation towards an ALFA Legacy Survey

Overview:
Arecibo is the world’s most sensitive radio telescope at L-band. In addition to that sensitivity advantage, extragalactic HI surveys with ALFA offer important and significant improvements in angular and spectral resolution over the other major wide area surveys such as HIPASS and HIJASS. To break ground into new science areas, extragalactic HI surveys with ALFA must exploit those capabilities to explore larger volumes with greater sensitivity than have previous surveys. A comparison of major blind HI surveys and those proposed here is presented in Table A1.1. For example, a single pass (12 s/beam) drift scan survey with the ALFA system offers 6 times the sensitivity of HIPASS with 4 times better angular resolution (FWHM); multiple (N) passes in drift mode offer further sensitivity advantage as $\sqrt{N}$. As discussed in Appendix 2, the coverage of wide area is the most efficient means of increasing the volume sampled locally and hence, there is a best-advantage balance between solid angle and sensitivity. A coordinated survey combining wide areal coverage with varying sensitivity promises to deliver a legacy survey that will be of use to a broad community of investigators and serves as a strategic approach to a number of EALFA science objectives. Deeper surveys to be proposed when a wider bandwidth spectrometer becomes available and when commensal observing is enabled will address other critical E-ALFA science goals but are not discussed herein.

This request proposes an initial allotment of observing time with the ALFA to begin a coordinated, multifaceted E-ALFA high galactic latitude drift-scan survey, covering a portion of the sky illustrated in Figure 1, which incorporates portions of several wide-area surveys discussed in the E-ALFA whitepaper of July 2003: the shallow (12 s/beam) all-sky survey (the All-Sky Fast ALFA survey, dubbed “ALFALFA”) and the medium deep (60 s/beam) environmental survey. The latter is designed to compare regimes of differing cosmic density, including the Virgo cluster and a complementary region in the opposite direction (the Virgo-anti-Virgo ALFA survey, dubbed “VAVÁ” after a talented Brazilian soccer player). A further deeper extension (300 s/beam) covering a portion of the Virgo cluster survey will follow later upon evaluation of the results of the initial observations when the 2nd generation ALFA spectrometer becomes available. Definitions of the adopted survey acronyms and basic parameters is given in Table 1. This proposal presents a coordinated strategy for maximizing observing efficiency in the high $|b|$ region of the Arecibo sky using a simple limited-azimuth drift scan technique. A wide-area high latitude shallow survey is of interest to the G-ALFA consortium once commensal observing becomes possible and may also be useful for the statistical characterization of radio transients.

When completed late in this decade, the high galactic latitude portion of the shallow survey, ALFALFA_{hh}, will survey 6000 deg^2 and will detect some 16000 extragalactic HI sources. It is specifically designed to probe the faint end of the HI mass function (HIMF) in the very local universe and will provide a complete census of HI in the surveyed sky area, making it especially useful in conjunction with other wide area surveys such as SDSS, 2MASS, GALEX, etc. Covering some 1600 deg^2, VAVÁ_{60}, will address numerous issues associated with the nature of high velocity clouds, the origin and evolutionary history of dwarf galaxies, local large scale structure and environmental influences on HI content. VAVÁ will also allow for a test of whether the HIMF is universal or rather depends on local environment. In conjunction with optical studies of comparable volumes, ALFALFA and VAVÁ will explore the “missing satellite problem”, the apparent contradiction between the number of low mass halos observed in the Local and surrounding groups with that predicted from numerical simulations.

Because the observations will be conducted using the limited-azimuth drift scan technique to be tested this summer under ALFA precursor proposal A1946 and require only the WAPPs, an allocation of telescope time to initiate this coordinated survey is requested as soon as ALFA is commissioned. The proposed strategy is designed to provide the foundation for further proposals for E-ALFA, to produce early science results and to allow testing of both hardware and software in support of the full surveys as well as the deeper E-ALFA programs. The current proposal requests an initial allocation of telescope time based on current estimates of sensitivity, detection rates and resource levels. We understand that allocation of time will be reviewed periodically and will be granted only upon mutual agreement in light of demonstrated progress and competitive review. We request the right to alter our strategy, without prejudice, depending on instrument performance, initial results and other circumstances.
Table 1. Survey Acronyms and Specifications

<table>
<thead>
<tr>
<th>Name</th>
<th>t_{int}</th>
<th>Sky coverage</th>
<th>Total time</th>
<th>Definition</th>
</tr>
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<tr>
<td>ALFALFA</td>
<td>12</td>
<td>12000°</td>
<td>4000°</td>
<td>All Arecibo Sky, including ALFALFA_{bb}</td>
</tr>
<tr>
<td>ALFALFA_{bb}</td>
<td>12</td>
<td>6600°</td>
<td>2000°</td>
<td>high</td>
</tr>
<tr>
<td>VAVA_{60}</td>
<td>60</td>
<td>1600°</td>
<td>1900°</td>
<td>00°:20′&lt; R.A. &lt; 02°:20′, 8° &lt; Dec. &lt; +32° 10° &lt; R.A. &lt; 11°, 13° &lt; R.A. &lt; 14°, +08° &lt; Dec. &lt; +16° 11° &lt; R.A. &lt; 13°, +04° &lt; Dec. &lt; +28°</td>
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<tr>
<td>VAVA_{300}</td>
<td>300</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
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</tbody>
</table>

a Does not include overhead for followup Arecibo observations, including both reliability checks and anticipated discovery followup.
b Includes ALFALFA_{bb}

Requested Initial Telescope Time Allotment:

The current request for an initial allotment of telescope time is designed to initiate the coordinated, combined ALFALFA_{bb} and VAVA_{60} surveys in a manner that allows evaluation of survey strategy efficacy, produces early science results, and lays the groundwork for further E-ALFA observations. A possible program, totalling about 1300 hours spread over two years as summarized in Table 2, will fulfill a first installment of the ALFALFA and VAVA surveys. The proposed 2-year program will achieve:

- The mapping with 12 s/beam of nearly 1500 deg², more than 3 times the coverage of the Arecibo Dual Beam Survey (ADBS: Rosenberg & Schneider 2000).
- The mapping with 60 s/beam of 468 deg² in the Leo-to-Virgo region, covering an 8°-wide swath perpendicular to the supergalactic plane, crossing the heart of Virgo and including the complete sky area included in the Leo I survey of Karachentsev & Karachentseva (2003).
- The mapping with 60 s/beam of 234 deg² in the anti-Virgo region, with complete coverage of the region around M33 and the NGC 784 group of dwarfs.

Determination of the faint end of the HIMF and its dependence on environment will require completion of the full surveys, but this initial allocation will allow early science results in several important areas including: a first blind census across Virgo with rms = 1 mJy/beam, giving a 5σ detection limit of M_HI > 6.6 x 10^6 M_☉ at the cluster distance (assuming a width W = 30 km s⁻¹); a complete search for HVCs around M33; the identification of gas-rich galaxies in the NGC 784 and Leo I groups; the mapping of the environments of 12 gas-rich galaxies with D_{UGC} > 7; a first attempt at a large blind survey for HI absorbers.

Table 2. Initial 2-year strategy for combined survey

<table>
<thead>
<tr>
<th>Year</th>
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<th>Request</th>
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<tr>
<td></td>
<td>22° &lt; RA &lt; 03°</td>
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<td>5 hrs x 17 days</td>
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<tr>
<td></td>
<td>00°:20′ &lt; RA &lt; 02°:20′</td>
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<td>4 x 2 hrs x 17 days</td>
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<td>followup</td>
<td>50 hrs</td>
</tr>
</tbody>
</table>

Here “single” refers to a first drift scan pass of the targeted region, giving 12 s/beam. “four” refers to four similar passes of the same region which when summed and added to the first pass delivers a total integration time of 60 s/beam. The single drift constitutes ALFALFA, the sum of five, VAVA_{60}.
Figure 1: Proposed sky coverage for the combined drift scan survey in the anti-Virgo (upper) and Virgo (lower) directions. The cyan lines mark the lines of $b = -20^\circ$ (upper) and $+20^\circ$ (lower) while the green lines trace SGL = $-10^\circ$, $0^\circ$ and $+10^\circ$. The area to be covered by ALFALFA in single drift mode (12s/beam) is traced in by red lines showing the 9 bands of “tiles”. The region outlined in blue will be covered by a total of five passes (60s/beam) as part of VAVA. Blue filled circles mark galaxies with observed heliocentric recessional velocities $cz < 700 \text{km s}^{-1}$; open magenta circles denote objects believed to lie with 10 Mpc (Karachentsev et al. 2004) based largely on primary distances.

**Science justification: The HI Mass Function**

While the cold dark matter (CDM) paradigm has been very successful in predicting many properties of the large scale distribution of galaxies and their scaling properties, areas of conflict between theory and observations still remain. In particular, CDM theory describes the growth of structure through the merger of small halos formed in large numbers early-on. Although the small halos serve as the building blocks of larger hierarchical units, galaxies and clusters, many low mass objects are nonetheless expected to survive to the present epoch.

One of the principal discrepancies between CDM 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; Moore et al. 1999b), referred to as the “missing satellite problem”. As pointed out by Kratsov et al. (2004), models must explain not only the number of satellites found in the Local Group, but also their radial distribution: whereas the dSphs are found concentrated with $\sim$300 kpc of their host giant galaxies, the irregulars are spread throughout, both near and far from the giants (Grebel 2004).

The logarithmic slope of the faint end of the galaxy mass function predicted by CDM simulations is close
to the value of \( \alpha = -1.8 \) that arises analytically from the Press-Schechter formalism (Press & Schechter 1974; Bardeen et al. 1986). Because the mass function itself is difficult to determine directly, current efforts focus on estimation of the faint end of the optical luminosity function (LF) and, of direct relevance to this proposal, of the HIMF. Thus, limits can be set on the number of low mass halos containing measurable stellar or gaseous components.

The most recent estimates of the HIMF have been presented by Zwaan et al. (1997; Z97), Rosenberg & Schneider (2002; RS02) and Zwaan et al. (2003; Z03). The Z03 HIMF is based on the Parkes Multi-Beam HI Survey (HIPASS), while the RS02 and Z97 HIMFs are both based on drift scan surveys conducted at Arecibo during the period of its recent upgrade. The faint end slope of those determinations of the HIMF vary between \(-1.20\) and \(-1.53\), yielding extrapolations below \( M_{HI} = 10^6 \, M_\odot \) that disagree by an order of magnitude, the RS02 HIMF having the steeper slope. All three surveys sample a lower mass limit just below \( M_{HI} = 10^8 \, M_\odot \), for \( H_0 = 70 \, \text{km s}^{-1}\,\text{Mpc}^{-1} \) (a value that will be assumed throughout, while for Virgo we adopt a distance \( D=16 \, \text{Mpc} \)). No galaxies were detected by RS02 or Z97 with \( M_{HI} < 10^7 \, M_\odot \), while 3 are claimed by Z03, and only a small number of detections have \( M_{HI} < 10^6 \, M_\odot \).

**Determining the Shape of the HI Mass Function:** There are two major questions of interest when looking at the HIMF: the shape of the low mass end and the behavior of the HIMF with environment. The shape of the low mass end of the HIMF and its corollary, the cosmological mass density of HI, are important parameters in the modelling of the formation and evolution of galaxies. The change in the HIMF with environment provides a statistical measure of the environment’s effect on the gas as galaxies evolve.

Determining the shape of the low mass end of the HIMF requires well determined masses for enough galaxies to provide decent statistics in the \( 10^6 - 10^7 \, M_\odot \) range. Blind 21 cm surveys are the way to determine these parameters in an unbiased way, but past surveys have suffered from extremely poor statistics. HIPASS was the first 21 cm survey to have significant galaxy detection statistics (4315 in the HICAT; Meyer et al. 2004), but like the other surveys, HIPASS is limited by angular and velocity resolution, sensitivity, and the number of independent volumes of space surveyed adequately at the low mass end.

**ALFALFA and the Determining the Low Mass End:** The vast improvement in the statistics provided by the ALFALFA survey will allow us to resolve the controversy over the faint-end slope of the HIMF. ALFALFA will put us in range of the numbers of objects obtained in optical galaxy surveys rather than where we have been with HI surveys with only a handful of galaxies in each mass bin below \( 10^6 \, M_\odot \).

Counterpoint: The ALFALFA survey will only detect the \( 10^6 - 10^7 \, M_\odot \) sources within about 12 Mpc with a peak in the detection distribution at about 9 Mpc. At these distances, the HI mass determinations are extremely uncertain because of the inadequacies of distances determined from current flow models. In addition, these low mass sources will all be from a small number of independent volumes so we may not achieve a fair sampling of space. A deeper survey will improve on (but not solve) these issues (but the statistics especially at slightly higher masses where the HIMF is really pinned down will be smaller). Note that for the lowest masses, we’re stuck in the Local Supercluster.

**VAVÁ and Determining the Change in the HI Mass Function with Environment:** Optical luminosity functions show large variations with environment, with steeper faint end slopes being in clusters (e.g., Lobo et al. 1997). Most studies of environmental dependences of the optical luminosity function do not address objects of the lowest masses, but rather consider only halos of \( M > 10^{10} \, M_\odot \) (Mo et al. 2004). Recently large numbers of faint cluster galaxies have been identified in the Virgo cluster (Sabatini et al. 2003) leading to a cluster luminosity function that is consistent with standard CDM models, but very different from the global luminosity function derived by 2dF and Sloan. In a recent survey of six groups of varying density including Virgo, Trentham & Tully (2002) found a mean slope of \(-1.19 \pm 0.03\), significantly flatter than predicted by CDM scenarios. Additionally, they examined the fraction of the total dwarf population that are dE/dSph and found it to vary with the degree of dynamical evolution of their environment (see also Trentham, Tully & Verheijen 2001). Outside of Virgo, further evidence for environmental differences in the optical LF has also been presented by numerous authors, among them Zabludoff & Mulchaey (2000), Girardi et al. (2003) and Flint, Bolte & Mendes de Oliveira (2003).
Previous studies of the HIMF have concentrated on determining an “average” shape of the field mass function. However, we know that galaxy environment affects the gas content of galaxies through star formation, tidal interactions, and merging. Because of these processes we would not expect the HIMF to be the same in all environments, but the relationship between the HIMF and environment can not be studied with the small samples that have been available. Only with the much larger number of galaxies detected in a range of environments will we be able to probe the change in the HIMF with environment and begin to study how it is affected by the processes that transform galaxies.

The choice of a Virgo and anti-Virgo region in the VAVÁ survey allows us to probe these different environments while providing a database for a Virgo study (discussed below). First suggestions that the HIMF in Virgo might be different from that seen in the field was suggested by Hoffman et al. (1992) and Briggs & Rao (1993), both of whom suggested that the HIMF in Virgo below $10^8 M_\odot$ is depressed relative to that found in the field. Further evidence of such an environmental dependence comes from the Arecibo Dual-Beam Survey (Rosenberg & Schneider 2002) which indicates that the HIMF is much flatter in the Virgo Cluster than in the field. By considering the relationship between the optical and the HI, we will be able to assess the relative importance of star formation and gas stripping as a means of consuming the gas.

**A Deeper Survey and the Shape of the HI Mass Function:** The limiting distance for observing a HI mass scales like $\sqrt{T_{\text{int}}}$ so an increase from 60 s/beam to 300 s/beam gains only a factor of 2.2 in limiting distance. At the same time, it becomes much harder to survey a wide area, since for the same total survey time, you can achieve only $\sim 1/5$th the areal coverage. The volume surveyed in constant total observing time actually drops as the integration time increases. Going deeper is an expensive way of targeting the low mass end of the HIMF and may require prohibitively long total survey times before an interesting volume can be reached.

At the same time, such a survey may have an advantage in determining environmental dependencies, since at 300 s/beam it would be possible to probe the lower mass bins at the distance of the Virgo Cluster. The objective would be to sample a large enough volume at the greater distance so that such surveys in different regions detect the same number of galaxies in the $10^6$ to $10^7 M_\odot$ bin. Such a survey would suffer in the statistics at higher masses but could be designed to better probe different environments. Deciding what relatively small sky area to cover becomes critically important. Results of the shallower surveys could point the way towards this objective.

**Science justification: The Virgo Cluster and its Surroundings:**

The Virgo Cluster is the largest nearby cluster of galaxies and is the obvious place to study the individual and statistical properties of galaxies in the cluster environment. The cluster is probably still assembling itself from a number of smaller sub-groupings though in the central regions galaxy interactions will have been common because of the relatively short crossing time $\approx 0.1 \ H_0^{-1}$. Virgo is the nearest X-ray cluster indicating that there is a substantial inter-galactic gas that the galaxies move through and presumably this is what modifies the gas content of cluster galaxies compared to those in the field. Almost all previously published work on the HI properties of the cluster galaxies has been obtained from pointed observations of optically identified sources. The VAVÁ survey will provide a blind 21cm survey of the cluster region, allowing us to take an unbiased look at the gas distribution in the survey galaxies. To perform this science with survey of $\sim 300$ s/beam would require additional time than to make a shallower survey of most of the cluster region while deeply surveying only a section of the cluster.

Seen from a 25 years perspective, HI observations of galaxies have provided us with some of the most powerful diagnostics on the evolution of local late-type galaxies, and in particular on the role of the environment in regulating their fate. The pioneering work of Haynes & Giovanelli (1984) served to quantify the amount of HI that normal, isolated spiral galaxies have within their disks as a function of their optical size (and Hubble type). It then became natural to define an “HI deficiency” parameter, quantifying how much HI an individual galaxy contains with respect to the expected quantity defined above. A series of HI studies on nearby clusters of galaxies, made possible by the superior sensitivity of the Arecibo telescope, triggered by the work
of Giovannelli & Haynes (1985), continuing with Chincarini et al. (1983), Gavazzi (1987, 1989), Hoffman et al. (1989) just to mention few, culminated with the work of Solanes et al. (2001). They concurred establishing that spiral galaxies in rich clusters, otherwise normal in their optical morphology, have systematically positive HI deficiency parameters, i.e. a significantly reduced HI content (see the review by Haynes, Giovannelli & Chincarini 1984). The pattern of HI deficiency found in spiral galaxies that are members to rich, X-ray luminous clusters was interpreted as due to ram-pressure stripping suffered by the fast moving galaxies through the dense intergalactic medium. A high HI deficiency parameter, indicating that a galaxy is subject to the severe pressure conditions that are found in the hostile cluster environment, became perhaps the best probe for the cluster membership, allowing to quantify whether a particular galaxy has or it has not yet past through the dense IGM. The HI deficiency parameter is yet perhaps the most valuable environmental indicator.

The Virgo cluster, due to its proximity to us (17 Mpc), has received most attention in HI studies. The pioneering works of Helou et al. (1981) and of Haynes & Giovannelli (1986), culminating with the study of dwarf galaxies by Hoffman et al. (1989) provided evidence for extremely HI deficient mixed with HI normal galaxies in this cluster. This, in conjunction with distance estimates from the Tully-Fisher (1977) relation inspired 3-D studies of the Virgo cluster which brought to circumstantial evidence for significant infall onto this cluster (Tully & Shaya, 1984; Gavazzi et al. 1999, 2002). If the study of the global HI properties of Virgo galaxies were entirely carried out with the Arecibo dish, detailed HI mapping of a dozen galaxies was obtained at the VLA (Cayatte et al. 1990), providing evidence that HI ablation occurs outside-in, producing a spatial truncation of the HI disks. Follow-up imaging in the light of the $H\alpha$ line provided evidence that both the global intensity and the radial distribution of the star forming regions in these galaxies follow the neutral hydrogen, not the molecular gas distribution Gavazzi et al. (2002 and in preparation), showing that a direct link exists between the HI reservoir and the present star formation activity.

All available data on the Virgo cluster galaxies are collected and distributed world-wide through the WWW site "GOLDmine" (http://goldmine.mib.infn.it). At HI, the completeness of the data-base is remarkable. Out of the 411 late-type (>Sa) galaxies listed in the VCC (Binggeli et al. 1995) and classified as members or possible members with $m_p < 20.0$ mag, 322 (78%) have been detected in HI and all of the remaining galaxies rely on significant upper limits. Similar numbers are 261/291 or 90% for $m_p < 16.0$ mag. Typically, these HI observations were carried out with 1.0 mJy (rms) corresponding roughly to mass limits of $10^7 M_\odot$; this is comparable to the rms per beam limit for 18 km s$^{-1}$ resolution that VAV\textsuperscript{60} will achieve.

- **Cluster structure:** Previous observations of Virgo indicate a complex substructure within the region and evidence for infalling groups or clouds (Binggeli et al. 1993). Given that the infalling population is likely to be gas-rich compared to the established cluster population, the best way of studying and distinguishing between the different sub-groupings is to consider the structure in redshift as a function of HI mass. Overall, the galaxy distribution in that direction has been shown to trace a filamentary structure (West & Blakeslee 2000; Solanes et al. 2002) elongated along the line of sight.

- **Beyond the cluster edge:** An HI survey of the cluster would also cover the void behind Virgo. Recent high-resolution simulations in a flat, Λ dominated Universe (Gottlober et al. 2003) indicate that the voids in the Λ galaxy distributions contain low-mass halos. Their prediction is that a typical void with a diameter of ~ 20h$^{-1}$ Mpc would contain ~ 10$^5$ objects with mass greater than 10$^7$ M$\odot$. Given the sensitivity limit of ~ 10$^8$ M$\odot$ for objects behind the Virgo cluster, we expect to detect a few hundred of these objects whose presence in the void and whose dynamical properties would place significant constraints on modern cosmological models. A deeper survey would do even better at probing the void behind the cluster for this purpose.

**Science justification: Additional Science Goals:**

While the focus of the ALFALFA and VAV\textsuperscript{60} surveys is the study of the HMF, concentrating on determining the low mass end and its possible variation with environment and a detailed study of the Virgo cluster region,
there are many other interesting science results that will emerge from the proposed survey. We discuss several of those other science goals below.

**Discovering Isolated HI Clouds:** With any new survey there is always the chance of discovering new objects. A blind survey like the one we are proposing has the potential to reveal new kinds of object. One puzzle for numerical modelers of galaxy formation is that the process has been so efficient. Most of the gas seems to reside in the big bright galaxies. Yet, QSO absorption line studies indicate many absorption line systems that do not appear to be associated with bright galaxies. The VAVÁ survey will provide a deep survey for HI clouds not associated with optical sources.

A 300 s/beam survey will provide a much greater opportunity here as we really probe much lower in mass than any other large survey has done to date. But the issue is how much sky area needs to be covered in order to achieve the required statistics.

**HI in Nearby Galaxies:** In contrast to other major wide area surveys such as HIPASS and HIJASS, a large number of galaxies detected by ALFALFA and VAVÁ will be resolved by Arecibo’s 3.5’ beam. Consequently, ALFALFA and VAVÁ will resolve extended HI in the vicinity of large ($D_{UGC} > 7'$) nearby galaxies that may have been missed by interferometric observations.

For the ALFALFA parameters $t_{int} = 12$ s/beam and $CBW = 5$ km/s$^{-1}$, the antenna temperature detectable at the 5σ limit is $T_{o} = 0.2$ K, corresponding to a minimum detectable column density $N_{HI}^{5\sigma}$. For a uniform source that fills the beam and assuming a characteristic spectral width of 25 km/s$^{-1}$, $T_{o}^{5\sigma}$ may be converted to a minimum detectable column density $N_{HI}^{5\sigma} \sim 10^{19}$ cm$^{-2}$, for VAVÁ$_{60}$, $N_{HI}^{5\sigma}$ decreases by a factor of $\sqrt{5}$. While the column densities actually reached depend on the source morphology and the data reduction details, VAVÁ$_{60}$ will likely probe the extended HI emission in nearby galaxies at the $10^{18}$ cm$^{-2} < N_{HI}^{5\sigma} < 10^{19}$ cm$^{-2}$ level.

While the maximum ALFA science return for studies of nearby galaxies and their environments might lie in longer integrations and lower column densities, the range of $N_{HI}^{5\sigma}$ probed by VAVÁ$_{60}$ is nonetheless an interesting regime in which to examine broad-scale HI. Not only might we glean a new perspective on the broad-scale emission at these sensitivities for systems that fall in the VAVÁ$_{60}$ survey area, but the latter would also allow for the development of software to combine ALFA data products with interferometric observations of HI on smaller spatial scales. In particular, Arecibo observations are ideal for filling in missing short spacing visibilities of the VLA in its more compact configurations. Hybrid Arecibo + VLA maps of nearby systems would therefore provide a complete census of their HI content.

The requested initial VAVÁ$_{60}$ telescope time allotment includes 12 gas-rich galaxies with $D_{UGC} > 7'$ spanning a range of morphological types and environments, allowing for both early science results and the development of robust data manipulation software.

**Surveys of Nearby Groups and Clusters:** In addition to the study of the Virgo region with VAVÁ, there are a handful of nearby groups and clusters that we will be able to study in great detail, providing the best information on gas-rich galaxies in dense environments that we have to date.

One of the most significant groups that we will be able to study with this survey is the Canes Venatici I Group at about 5 Mpc. Only the southern half of the group is in the Arecibo declination range, but it is extremely rich in low HI mass systems. Given the relative orientations of the Arecibo strip and the Local Supercluster, there is another region where discovery rates would be expected to come close to what we expect in this region. The group is near enough that we will be able to detect galaxies down to $10^{9} M_{\odot}$, thereby allowing us to study low HI mass sources in high density regions.

Located at a mean distance of 10.4 Mpc, the Leo I (M 96) Group offers an attractive opportunity for exploring both the optical luminosity function and the HIMF in an intermediate density environment. Unlike the Local Group, Leo I is dominated by early type galaxies, yet it is still characterized by a low velocity dispersion. For 19 galaxies with measured redshifts, the dispersion in radial velocity is 130 km s$^{-1}$. The mean projected radius of the group is 352 kpc, its integrated luminosity is $6.7 \times 10^{10} L_{\odot}$, the virial mass-to-luminosity ratio
is 107 $M_\odot/L_\odot$, and the crossing time is 2.7 Gyr. Some signs of segregation according to morphological type and luminosity are evident as a function of distance from the group center, probably reflecting a measure of dynamical relaxation. The subsystem of bright galaxies in Leo I has a lower characteristic scale (250 kpc) and velocity dispersion (92 km s$^{-1}$), leading to a relatively low virial mass-to-luminosity ratio, 34 $M_\odot/L_\odot$, typical for the Local Group and the other nearest groups (Karachentsev & Karachentseva 2003). Based on an optical survey of 7 deg$^2$, Flint et al. (2001) conclude that Leo I is missing the population of intermediate luminosity dwarfs found elsewhere. Tremonti & Tully (2002) found that the luminosity function is especially flat in Leo, and they note further that there is some tendency for galaxies to subcluster. Furthermore, those authors found that the percentage of dwarfs that are dE rather than dI is much lower in Leo (0.4±0.2) than in Virgo (0.82±0.15) or Coma I (0.73±0.2), despite its significant number of bright early-type galaxies. Both of these works concentrated only on the central regions of Leo I where the galaxy density is highest. Recently, Karachentsev & Karachentseva (2003) have performed an optical survey of a large solid angle (120 square degrees) centered on the Leo I Group, which identified 36 probable dwarf members of the group, with typical apparent magnitudes $B_1 \sim 18 - 19''$. Their methodology has in the past uncovered considerable numbers of faint gas-rich members of other nearby groups (e.g., Karachentseva & Karachentsev 1998; Karachentseva et al. 1999, 2001; Makarov, Karachentsev & Burenkov 2003).

Lying in the region of the sky visible from Arecibo, the Leo I group has been the object of previous Arecibo HI studies. Two of the brightest galaxies in Leo I – NGC 3379, and NGC 3384 – are surrounded by a 200 kpc ring of HI gas (Schneider et al. 1983). Two possible scenarios for the origin of this cloud have been proposed. Bood & Williams (1985) suggested that the ring resulted from a collision between NGC 3384 and NGC 3368 some 500 Myr ago. After the discovery of several additional gas features, Schneider (1985) noted that the clouds appear to be stable against tidal disruption and proposed that they instead represent a remnant of the primordial gas cloud from which all of the group members formed. Recently uncovered kinematic signatures suggest that all of the brighter galaxies have been involved in past interactions (Sil'chenko et al. 2003).

Thus the Leo I region presents an interesting environment in which to study differences among the low luminosity dwarf populations: a region of low velocity dispersion but containing a local density enhancement that supports the presence of bright E/S0 galaxies. To probe the dI population found by Karachentsev & Karachentseva (2003), a very wide field should be studied. For these reasons, the Leo region is included in the first phase of the VAV survey, and should produce early science results.

Tully (2004) has pointed out that groups dominated by late type galaxies have typical $M/L_B \sim 90$ $M_\odot/$lsun and that among the very nearby groups, a few seem to contain no giant galaxies. Of these “groups of dwarfs”, two lie in the Arecibo declination range: the groups around UGC 3974 (D = 5.4 Mpc) and NGC 784 (D = 4.4 Mpc). Both are excellent prospects to contain low HI mass objects as yet unidentified.

In addition, we will survey the Canes Venatici II and Coma I groups at at 10-20 Mpc. At these distances we will not be able to detect the $10^6$ $M_\odot$ sources, but we will detect a large number of sources at a few $\times 10^7$ $M_\odot$ in these groups. We will also survey the major overdensities of the Pisces-Perseus supercluster, the Coma cluster, the A1367 cluster, and the Coma wall. There are also ~20 additional groups at velocities less than 1000 km s$^{-1}$ which we should be able to study in great detail.

**High Velocity Cloud Searches:** The ALFALFA Survey will greatly improve our understanding of how gas is accreted onto galaxies. High-velocity clouds (HVCs) of neutral hydrogen may represent gas accretion onto our Galaxy (e.g., Tripp et al. 2003). Previous surveys of HVCs have been of substantially lower resolution (15.5' at best) and/or were unable to trace the connection between HVCs and Galactic HI emission (Putman et al. 2002; Wakker & van Woerden 1991). This survey will trace important high-velocity structures, such as the Magellanic Stream and Complex C, at 5 times the resolution of previous surveys. It will also be 8 times more sensitive to unresolved small clouds, or ultra-compact HVCs (if any exist with central neutral column density above $\sim 10^{20}$ cm$^{-2}$). This will allow us to determine if HVCs are interacting with a diffuse halo medium (e.g., Brüns et al. 2000; Quillis & Moore 2001) and address if they may be Galactic satellites that are dark matter dominated (e.g., Moore et al. 1999a, Ap.J., 524, L19).

The recent discovery of an extended, faint population of HI clouds within 50 kpc of M31 by Thilker et
al. (2004) has brought a similar search for clouds around M33 to the foreground. At the Andromeda distance, the Thilker et al. clouds have masses between $10^6 - 10^7$ $M_\odot$, and line widths of $15 - 80$ km s$^{-1}$.

**Absorption Line Studies at High Redshift:** The background source counts for this work at 1.4 GHz gives:

- 190 sources/steradian (665 sources in the Arecibo range) brighter than 1 Jy
- 840 sources/steradian (2940 sources in the Arecibo range) brighter than 0.4 Jy
- 5600 sources/steradian (19600 sources in the Arecibo range) brighter than 0.1 Jy

A recent study by Vermeulen et al. (2004) searching for HI in absorption in compact sources with the WSRT found absorption in 1/3 of the targetted sources and we adopt their results as “typical” (although the redshift range is considerable higher). The HI features found in that survey show a range of optical depths from $\tau = 0.16$ to $\tau < 0.001$ and exhibit a variety of line profiles with widths as narrow as 10 km s$^{-1}$ but more typically $\sim 150$ km s$^{-1}$. There are 1144 NVSS sources with flux density greater than 500 mJy in the region of the sky covered by ALFALFA$_{hh}$. For a source of 500 mJy, a peak absorption of 10 mJy (5sigma) corresponds to $\tau \sim 0.02$. The peak column density is given by $N_H \sim 1.82 \times 10^{18} T_{\text{spin}} t_{\text{peak}} \Delta V$ cm$^{-2}$. For $T_{\text{spin}} \sim 100$K and a velocity width of 100 km s$^{-1}$, $t_{\text{peak}} \sim 0.02$ corresponds to $3.6 \times 10^{20}$cm$^{-2}$ with the obvious condition that narrower widths would probe lower column densities. Using the values for $t_{\text{peak}}$ and $\Delta V$ given in Table 1 of Vermeulen et al., we estimate that ALFALFA would be able to detect all but three of the lines found by those authors, although the frequency range does not match. ALFALFA would target lower redshift absorbers not associated with the radio source itself.

The major difficulty with absorption studies is baseline removal. Probably the best method will be to use the average of other sources of similar strength and observing at comparable telescope configuration (possible for the limited azimuth drift mode considered here). While the resultant spectral baselines may not be great, we expect that standing waves may be broader than expected HI lines; likewise, rfi tends to be spectrally unresolved. We will then establish and follow a simple set of rules to assess whether or not a given spectral feature is RFI or real absorption. This aspect of the project will probably require a labor intensive extra effort, but could yield cosmologically interesting statistics based on such a "blind" HI absorption survey.

**Find Rare OH Megamasers near $z = 0.25$:** OH Megamasers (OHM) are powerful line sources observed in the L band, arising from the nuclear molecular regions in merging galaxy systems. Approximately 100 such sources are known to date. Several of them are observed to have variable spectral features allowing insight into the source structure and physics. Observations of OHMs hold the potential for tracing the merger history of the Universe since the sources are associated with merging galaxies. These surveys will detect OHMs at intermediate redshifts. These things are really bright so sensitivity should not be the important factor here which means that HIPASS should be able to identify any of these that an ALFA survey would also pick up.

**Synergy with other surveys:**

**Star-Formation in the Virgo Cluster** In the last 15 years N. Brosch and his graduate students, some of whom are now staff members at Tel Aviv University, concentrated on understanding the star formation (SF) process in galaxies. Given that SF in many “large” galaxies is driven by global processes, such as spiral density waves and others, this group based their study on dwarf galaxies where these do not operate. As there have been claims of neighborhood-dependent SF, mainly in the area of SF triggering, so that they selected their sample galaxies in a well-defined neighborhood, namely that of the Virgo Cluster. Targets include galaxies of late-type, to positively belong to the cluster, and to have SF “raw material” in the form of HI. Therefore, the selection was based on the Arecibo surveys of Hoffman and collaborators and included compact dwarfs (BCDs of high surface brightness [HSB]) as well as diffuse dwarfs (ImIII to ImV, following the classification of Binggeli et al., with low surface brightness [LSB]). These studies were performed mainly at the Wise Observatory in Israel, where Brosch’s group has access to a 40-inch reflector equipped with CCD cameras with broad-band and H-alpha filters. The latter cover the entire redshift range from rest to $\sim 10,000$ km s$^{-1}$ and have a bandwidth of $\sim 1,000$ km s$^{-1}$. Using broad-band surface photometry together
with H-alpha they have shown that they can characterize the underlying stellar populations in the target galaxies and can begin to understand how the SF happens.

In the next coming years, this group hopes to complete the data collection for the two complete samples of HSB and LSB and to add to this information from the GALEX UV survey. Some of the latter data will come from the GALEX All-Sky Imaging Survey (AIS) and, for a specific sub-sample, we requested special observations in the first GALEX AO. They also plan complementary VLA synthesis observations of some objects and, if the ALFA observations would be successful, they expect to ask for detailed VLA mapping of those objects where extended HI would be detected by VAVA.

As a follow-up on the ALFA observations we plan to perform imaging studies using our techniques of the broad-band and H-alpha imaging of the candidate neighbors of dwarf galaxies, as well as of the isolated HI clouds that would be detected. In this study there is no specific advantage in using a large telescope, unless one aims for high spatial resolution of fine features. Therefore, the advantage of having an easily accessible telescope with the required equipment, and a generous allocation of observing time, will be a great advantage in follow-up studies.

One important ingredient in our studies of SF processes lies in similar studies of a comparison sample of dwarf galaxies. To date, we have almost complete observations of a sample of very isolated compact galaxies. These have no catalogued neighbors to within ~3 Mpc or more thus, together with the Virgo sample, will be critical in evaluating the role of the long-distance interactions in triggering SF. We expect that the VAVA survey will yield more candidate “isolated” galaxies, both in the void behind Virgo and in the anti-Virgo direction, to add LSB galaxies to our samples.

**Optical: Virgo surveys**  G. Gavazzi and A. Boselli are considering the possibility of making a full cluster survey in the B band. There are several possible instruments that one should obviously consider, including: MEGACAM at the CFHT (FOV 1 deg)  WFC at the INT (FOV 0.5 deg; average seeing is however 1.5-2.0")  WFC at the ESO 2.2 (FOV 0.5 deg)  KPNO 4m (FOV 0.5 deg?)

The project is not prohibitive (some ten nights), however everybody knows how difficult it is to get time on nearby stuff. Should we ask a fraction of this time at every telescope? Can we rely on the pressure of the ALFA community?

**Optical: SDSS:**  The photometric portion of the SDSS has been completed and will be included in the public data releases by 2006. Funding for the spectroscopic complement is being requested; if granted, the spectroscopic data should be released in 2007.

**UV: GALEX**  The GALEX all sky survey AIS (all imaging survey) is currently covering Virgo in two bands: FUV (1350-1750 Å) to a limiting mag $m_{AB}$=20.5 and NUV (1750-2800 Å) to a limiting mag $m_{AB}$=20.5. Most spirals, many BCDs, some Im and E will be detected. In addition there will be approx 20 deeper fields (MIS) covering approx 20 deg$^2$ to a limiting mag $m_{AB}$=23.5. MIS will include the central 12 deg$^2$ plus some other key galaxies. A. Boselli is a scientific associate of GALEX and all data should be released by the end of 2005.

**UV: TAUVEX space telescope array**  N. Brosch is the PI of the TAUVEX space telescope array, a payload rather similar to GALEX and it comprises three bore-sighted 20-cm aperture telescopes. The field of view is ~one degree, the angular resolution is ~7 arcsec, and the spectral bands cover the range from Lyman alpha to 3000 Å. TAUVEX is slated to operate from the Indian Space Agency GSAT-4 satellite starting in 2006 for a three-year or longer mission, and its goal will be to secure deep UV observation that will reach one magnitude or deeper than the GALEX AIS. Brosch would like to see follow-up observations of VAVA targets with TAUVEX, to be combined with the ground-based UBVR and H-alpha data. This would allow not only the characterization of the SF in the target galaxies, but also a measure of their dust content.

**NIR: Palomar/WIRC:**  Cornell (including NAIC) astronomers have access to the Palomar 5m telescope
and are considering surveying selection regions with the Wide Field Infrared Camera (FOV 8.7\arcmin, 0.3\arcsec/pix; J,H,K).

**FIR: ASTRO-F**  The mission, scheduled for Aug 2005, will perform a 4 band (60, 75, 150, 175 \mu m) all sky survey with a resolution of 30-50\arcmin and a sensitivity approx 10-20 times IRAS. Virtually all Virgo spirals, many BCDs and Im will be detected at 60 mic. A second pointed MIR (10-20 \mu m) survey (P.I. A. Boselli) will cover the late-type dwarfs of Virgo. The ASTRO-F mission is planned to last 2 years and the data should be available by 2008. Finally ASTRO-F will perform an all sky survey at K (2.1 \mu m) (data release approx 2010) that should go significantly deeper than 2MASS due to better sky background. A. Boselli is a scientific associate of ASTRO-F.

**FIR: HERSHEYEL:** (planned for the end of 2007)  We are proposing a project aimed at observing with SPIRE (250-350-500 \mu m) and PACS (110-170 \mu m) the 100 galaxies studied by ISO plus all bright (m14) Spirals. A decision will be taken in Sept 2004 whether it will be a key-project or an open-time proposal. A. Boselli is a scientific associate of HERSHEYEL.

**HI LINE: VLA:**  Currently, a large, targeted survey of HI in Virgo cluster galaxies is being conducted with the VLA (P.I. Jeff Kenney).

**HST-ACS:**  Several surveys using the ACS (FOV is 202\arcsec on a side) will provide deep images that can be searched for very faint objects. Recently, as part of the APPLES parallel project, Pasquali et al. (2004) have discovered’ a very faint dSph galaxy, dubbed APPLES 1, with properties similar to the dSphs in the Local Group. This object is particularly intriguing because it does appears to be isolated. The ACS Virgo Survey targets 100 galaxies in the central regions of Virgo; those fields likewise will be searched for additional faint objects.

**Observing program design**

Observations will to carried out in drift mode, so that gain, beam pattern and ALFA rotation angle remain constant through a given drift and, possibly for a whole declination strip. Calibration and data processing will be greatly simplified by this approach. We will test many of the technical challenges related to calibration schemes, impact of continuum sources, sidelobe contamination, rfi excision, gridding etc via observations to be scheduled under our precursor proposal A1946.

We assume that the coordinated ALFALFA and VAVÁ drift scan surveys will follow the “tiling the sky” plan outlined in Appendix 3 which is an amended version of that included in the drift scan precursor proposal. Note that a copy of the latter is available at [http://www.astro.cornell.edu/~haynes/pre204/drift.htm](http://www.astro.cornell.edu/~haynes/pre204/drift.htm).

To summarize, the Arecibo sky between 0\degree < Dec. < +36\degree is divided into 648 “tiles” of size 20'' in R.A. by 4'' in Dec. Each tile is constructed by combining 17 drift scan passes covering the same range of R.A. but offset by \sim14'' in Dec. A “band” is then a set of tiles that cover the same range of Dec. Individual beam tracks will be separated by \sim 2.1'' in Dec., slightly worse than Nyquist. Regions sampled with multiple drifts will offset tracks slightly in Dec., in order to reduce the ‘scallop’ in the sky coverage. Observations will typically cover a wide range in R.A. within a single band, with parameters related to the telescope configuration remaining fixed. This limited azimuth drift scan technique minimizes gain and side/coma lobe variations. The deeper observations that constitute VAVÁ will consist of N drifts, with N=5 for VAVÁ and possibly N=25 for VAVÁ. For the latter, it is also possible that observing techniques other than limited azimuth drift scanning may prove more practical; they will be investigated in a further precursor proposal to be submitted separately.

The size of a tile, \sim 5'' \times 4'', is chosen to constitute a data block that can reasonably be handled for data processing in an efficient manner by current desktop computers. A single drift composed of 7 beam strips, each the length of a tile (1200 sec), will be between 0.14 and 0.6 Gbytes, if sampled every second and for spectral dimensions of respectively 2048 and 8192 channels. Such a data block is well suited for one of the most processing-intensive parts of the reduction pipeline, that of bandpass correction. Simultaneous
residence of all data in a full tile–wide drift in memory is desirable, and can be handled by current desktop memories of 2–4 GBytes. The regridded data cube of a full tile will similarly be compatible with the size of the computer memory.

The proposed assignment of the 9 bands of tiles is summarized in Table A3.1. Note that drift scans within the band at Dec. = +18° require a restricted range of azimuth arm positions, as do those at the highest and lowest Dec. In order to maintain homogeneity of telescope parameters (e.g., gain and sidelobe structure), it may be desirable to carry out most drifts with the feed arm in the N–S direction, and only those in the band at Dec. = +18° with the feed arm near the E–W direction.

Calibration scheme and precursor tests: Our precursor proposal “Initial HI Survey Observations with ALFA in Drift Mode”, A1946 submitted by 25 members of the E-ALFA consortium received high rankings and has been placed in the “A” category. Observing time is expected to be scheduled in July–Aug 2004.

Follow-up Arecibo observations: In the out-years, additional time will be requested to allow for reliability checking, investigation of interesting phenomena and possibly deeper probes of some small regions. We anticipate that a 10% overhead will be required for reliability checking; the reality of this estimate will be tested via the precursor observations and will be revisited later.

Coordination with small ALFA projects: It is also assumed that small groups and individual investigators will also propose to use ALFA for small area surveys. It is hoped that in some measure these can be conducted in such a way as to add to the survey dataset in a homogeneous fashion, but the proprietary period will be respected for datasets constructed by individual investigators who win telescope time outside the survey program.

Possible second–pass ALFALFA survey: A second pass through the ALFALFA area of the sky, not included in the multiple–drift VAVÁ region, may be desirable to (a) increase detection reliability and (b) improve the sampling in the Dec. direction, by obtaining a second set of drifts ~1′ offset in Dec. from the first. In order to complete such second pass coverage, an additional ~1400 hours of telescope time would be necessary. This option may extend the survey schedule for an additional ~2 additional calendar years and will be revisited later.

Data management and dissemination

Basic requirements for data processing:

Software development for data processing:

Signal detection algorithms: Most of the previous surveys relied heavily on “by-eye” signal detection. The sensitivity offered by ALFA even in the ALFALFA survey is so great that relying on human detection is impractical. Therefore a major effort must go into developing robust signal detection algorithms that produce reliable and complete catalogs of sources.

Data product development:

Development of a Virtual Observatory Portal: Possible plan to be presented by Brian Kent.

Data release schedule:

A Legacy Survey for the Community

Because Arecibo is a multidisciplinary national facility, one objective of the ALFA consortia must be to produce “legacy surveys”, i.e., surveys that deliver data products in a manner that enables science beyond the scope of immediate consortium objectives and that are of interest to a wider body of the astronomical community. The coordinated survey discussed here will be the deepest, highest resolution extragalactic HI
survey ever conducted over this area of the sky and will provide a rich, homogeneous dataset, thus enabling many more uses by the broadest possible community as a complement to the work specifically proposed here.

The survey will be a starting point for anyone wanting to know the HI properties of a galaxy in this velocity range in this part of the sky. It will be also be a place to start a search for galaxies around low redshift Ly-α absorbers. As the first resource for this kind of work, it may also increase the interest in the larger community in the use of Arecibo for follow-up work on regions where the survey is not deep enough to answer the questions at hand.

Commensal High Galactic Latitude Observations with other Consortia

The G-ALFA consortium is interested in conducting a comparably shallow, all-sky survey but requiring considerably higher velocity resolution (≈ 0.2 km s⁻¹). The principal science drivers for the high galactic latitude G-ALFA HI programs include studies of interstellar turbulence, the cold neutral medium, the disk-halo connection, and the intermediate and high velocity cloud populations. We are in discussion with the leaders of the G-ALFA HI consortium about modes by which the separate E-ALFA and G-ALFA science objectives can be achieved under a common observing strategy and hope to be able to combine surveys once commensal observing becomes possible in early 2005.

Education and Outreach

- Graduate student involvement: *If possible, detail theses associated with 2 year plan.*
- Undergraduate student involvement:
- Course module development:
- AOVF display development:
- Website development:

Survey management plan

- Manpower resources: Observing team, software development team, algorithm development team, data product development team; survey evaluation team, etc.
- Resource commitment:
- Graduate student involvement:
- Undergraduate student involvement:
- Course module development:
- AOVF display development:
- Website development:

References Cited

Haynes, M. & Giovanelli, R., 1984, A.J., 89, 758
Appendix 1: Comparison with Previous Surveys:

HIPASS and HIJASS cover the same area of sky that is visible at Arecibo, HIPASS south of Dec. = $+25^\circ$, and HIJASS further to the north. However, in addition to the sensitivity considerations, ALFA surveys provide 2 direct benefits over the other two: improved angular and velocity resolution. The significant higher angular resolution (FWHM $\sim$3,5' for ALFA versus 12' for HIJASS and 15.5' for HIPASS) will help to limit the confusion of sources that plagued the other surveys. The HIPASS followup needed is enormous and therefore has been limited to the highest flux sources. It will be years before the sources are followed-up (if ever). An ALFA survey will be able to do science with the survey data directly, without time consuming interferometric follow-up. Additionally, the higher velocity resolution of ALFA will be useful in several ways: First, detecting edge-on galaxies with peak fluxes near the noise limit. The edge of a double peak spectrum is much sharper at higher velocity resolution which should make it easier to automatically detect these sources. Second, the higher velocity resolution will allow more accurate velocity and velocity width measurements, without the need for followup. Even the narrowest sources will be detected over several channels. Third, since most rfi is narrow band, the higher frequency resolution will be extremely useful in identifying and excising rfi. Improvements in detection statistics will be tested as part of the precursor proposal observations.

The HIJASS survey has a further serious limitation. Very bad rfi in the frequency band corresponding to $cz \sim 4500 - 7500$ km s$^{-1}$ range (within the range of much of the interesting large scale structure e.g., Pisces-Perseus, A1367-Coma–Great Wall). In addition, HIJASS is not scheduled to do any more observing in the Arecibo range (a 4$^\circ$ $\times$ 4$^\circ$ region in Virgo and a few other areas have been covered at this point) for the next few years.

The principal advantage that an Arecibo survey will have over previous surveys is depth and, depending on the survey strategy, the number of independent volumes surveyed. Table A1.1 includes a comparison of the major surveys, including those discussed here. For comparative purposes, the rms noise per beam quoted for each survey has been scaled to a velocity resolution of 18 km s$^{-1}$, the resolution of HIPASS.

**ADBS followup: what we might expect:** (words to be contributed by JJS)
Table A1.1  Comparison of major blind HI surveys (*NOT YET COMPLETE*)

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<th>Beam (')</th>
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<th>V_{max} (km/s)</th>
<th>V_{rms} (km/s)</th>
<th>t_s (s)</th>
<th>rms'' (mJy)</th>
<th>N_d</th>
<th>min M_{HI*} (M_{\odot})</th>
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<td>-650 – 7980</td>
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<td>11 60 0.94</td>
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<td>11 300 0.42</td>
<td>(2000)</td>
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\^a\ after Hanning smoothing.
\^b\ per beam, for W = 18 km s^{-1}. Note: ADBS gives 3–4 mJy for 7s, scaled to 12s and 18 km s^{-1}.
\^c\ at 10 Mpc, for 5\sigma detection with W = 30 km s^{-1}.
\^d\ Gap in velocity coverage between 4500–7500 km s^{-1} caused by rfi.

References:
1: Zwaan et al. (1997)
2: Rosenberg & Schneider (2002)
3: Braun et al. (2003)
4: Kraan–Korteweg et al. (1999)
5: Lang et al. (2003)
6: Davies et al. (2004)
7: Minchin et al. (2003)
8: Henning et al. (2000)
9: Meyer et al. (2004)
10: Freundling et al. UltraDeep precursor proposal
11: Probable 300–600 s/beam survey(s), including commensal ones (TBD)
Appendix 2: Scaling Relations

The HI mass of an optically thin source at distance $D_{\text{Mpc}}$, in solar units, is

$$M_{\text{HI}}/M_\odot = 2.356 \times 10^5 D_{\text{Mpc}}^2 \int S(V) dV$$  \hspace{1cm} (1)$$

where $S(V)$ is the HI line profile in Jy and $V$ is the Doppler velocity in km s$^{-1}$. To 1st order,

$$M_{\text{HI}}/M_\odot \approx 2.356 \times 10^6 D_{\text{Mpc}}^2 S_{\text{peak}} W_{\text{km s}^{-1}}$$  \hspace{1cm} (2)$$

where $S_{\text{peak}}$ is the line peak flux and $W_{\text{km s}^{-1}}$ its velocity width in km s$^{-1}$. For detection, $S/N = f_\beta S_{\text{peak}}/S_{\text{noise}}$ must exceed a threshold value, to be discussed; the parameter $f_\beta \leq 1$ quantifies the degree to which the source flux is diluted by the telescope’s beam. $S_{\text{noise}}$ can be obtained from the radiometer equation

$$S_{\text{rms}} = \frac{T_{\text{sys}}/G}{\sqrt{2 \times CBW \times t_s \times f}}$$  \hspace{1cm} (3)$$

where $T_{\text{sys}}/G$ is the system temperature divided by the system gain (for the ALFA feeds, $T_{\text{sys}}/G$ will vary between 2.65 and 3.40 Jy; here we adopt a flat value of 2.85 Jy; CBW is the channel bandwidth in Hz and $t_s$ the integration time in seconds. The factor 2 under the square root indicates that two independent polarization channels will be added. The digital backends will sample the signal at 9 levels, so clipping losses will be negligible. We assume $CBW = 25$ kHz, which at the frequency of the HI line is equivalent to 5.3 km s$^{-1}$. As for $f$, it is a factor that accounts for post-detection spectral smoothing of the signal, $f_{\text{smo}}$, the switching technique applied for bandpass stabilization, $f_{\text{switch}}$, and other observational details, i.e. $f = f_{\text{switch}} f_{\text{smo}} f_{\text{other}}$. For the data taking schemes under consideration, $f_{\text{switch}} f_{\text{other}} \simeq 1$, while $f_{\text{smo}} \propto W_{\text{smo}}$, where $W_{\text{smo}}$ is the width of a spectral smoothing function expressed in km s$^{-1}$.

The detection of a spectral line of width $W_{\text{km s}^{-1}}$ will, in principle, be optimized by smoothing the signal to a spectral resolution $W_{\text{smo}} \sim W_{\text{km s}^{-1}}$; in that case, $CBW = 25$ kHz and assuming $W_{\text{smo}} \simeq W_{\text{km s}^{-1}}$, a 5-sigma detection threshold will require

$$S/N = \frac{f_\beta S_{\text{peak}}}{S_{\text{rms}}} \approx 4.1 \times 10^{-4} \frac{G}{T_{\text{sys}}} t_s^{1/2} \frac{M_{\text{HI}}}{M_\odot} D_{\text{Mpc}}^{-2} W_{\text{km s}^{-1}}^{-1/2} > 5$$  \hspace{1cm} (4)$$

In practice, the smoothing of signals of $W_{\text{km s}^{-1}} \simeq$ several hundred km s$^{-1}$ does not reduce the noise in proportion to $\sqrt{W_{\text{km s}^{-1}}}$ and, moreover, $S_{\text{peak}}$ is depressed by such smoothing, for spectral shapes are by no means rectangular. The fact that the detection criterion described above applies well to narrow lines but not so to wider ones was also noted by RS02. Here we assume: (a) that the spectrum will be smoothed to a maximum of $W_{\text{smo}} = 100$ km s$^{-1}$; thus, for $W_{\text{km s}^{-1}} > 100$, $S/N \propto W_{\text{km s}^{-1}}^{-1}$; (b) that for $W_{\text{km s}^{-1}} \leq 100$ $S_{\text{peak}}$ degrades as $W_{\text{km s}^{-1}}^{-1/4}$, from its full value at $W_{\text{km s}^{-1}} = 30$ to 0.74 of that at $W_{\text{km s}^{-1}} = 100$; in this case $S/N \propto W_{\text{km s}^{-1}}^{-3/4}$. Our detection criterion will then be:

$$9.6 f_\beta^{1/2} \left( \frac{M_{\text{HI}}}{10^9 M_\odot} \right) \frac{D_{\text{Mpc}}^2}{100} \left( \frac{W_{\text{km s}^{-1}}}{100} \right)^{\gamma} > 5$$  \hspace{1cm} (5)$$

where $\gamma = -3/4$ for $W_{\text{km s}^{-1}} \leq 100$ and $\gamma = -1$ for $W_{\text{km s}^{-1}} > 100$. Many “detections” obtained near the threshold set by equation 5 will turn out to be spurious. The reliability of a detection will of course increase with increasing $S/N$. In our survey simulations, we model the probability $p$ that a “detection” obtained with a given $S/N$ be confirmed, with a smooth step function of the form $p = (e^{S/N - S_{1/2}/\eta} + 1)^{-1}$, where $\eta$ is set to 2.2 and $S_{1/2}$ — the value of the signal-to-noise ratio for which 50% of detections are confirmed — is set to 6, obtained by fitting the expression for $p$ to the data in Fig. 6 of Rosenberg & Schneider (2000). In our simulations, we ignore all “detections” with $S/N < 5$ and only the “reliable” fraction of those with $S/N \geq 5$ is counted.

It is useful to review the scaling relations relevant to the design of HI mapping surveys:
• The minimum integration time required to detect a source of HI mass $M_{HI}$ and width $W_{kms}$ at the distance $D_{Mpc}$ with ALFA is

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

i.e. the depth of a survey increases only as $t_s^{1/4}$. With equality of back-ends, the $t_s$ required to detect a given $M_{HI}$ at a given distance scales as the square of $G$, i.e. as the 4th power of the reflector diameter; Arecibo's diameter is between 4 and 4.5 times larger than that of the Jodrell Bank or Parkes telescopes.

• It is sometimes claimed that there is no advantage for a larger aperture telescope in carrying out wide angle surveys, because the lower sensitivity of a small telescope is made up by the larger solid angle sampled by its beam. That claim is incorrect. In fact, the beam of a telescope of collecting area $A$ is $\Omega_b \propto A^{-1}$, while the maximum distance at which a given HI mass can be detected is (cf. Eqn. 4) $D_{max} \propto G^{1/2}$. Since $G \propto A$, the volume sampled by one beam to the maximum distance $D_{max}$ is $V_{beam} \propto \Omega_b D_{max}^3 / 3 \propto A^{1/2}$, i.e. in a fixed time, a radio telescope samples a volume that scales with the reflector diameter, yielding a very significant comparative advantage for a large aperture.

• Assuming that clouds of mass $M_{HI}$ are randomly distributed in space out to the maximum distance at which they are detectable, $D_{max}(M_{HI})$, the number of clouds detected by a survey increases linearly with the sampled volume $V = \Omega_b D_{max}^3 / 3$, where $\Omega$ is the solid angle subtended by the survey. We can thus increase the number of detections either by sampling a larger solid angle $\Omega$ or by increasing $D_{max}(M_{HI})$. Now, the total time required to complete the survey is

$$t_{survey} \propto (\Omega/\Omega_b) t_s$$  \hspace{1cm} (7)

where $\Omega_b$ is the telescope beam. Since $D_{max}(M_{HI}) \propto t_s^{1/4}$, as shown in equation 6, we can write

$$V_{survey}(M_{HI}) \propto \Omega [D_{max}(M_{HI})]^3 \propto \Omega t_s^{3/4} \propto t_{survey} t_s^{-1/4}$$  \hspace{1cm} (8)

and inverting:

$$t_{survey} \propto V_{survey}(M_{HI}) D_{max}(M_{HI}) \propto V_{survey}(M_{HI}) t_s^{1/4},$$  \hspace{1cm} (9)

i.e. for a given surveyed volume $V_{survey}(M_{HI})$, once $M_{HI}$ is detectable at a cosmologically interesting distance, it is more advantageous to maximize $\Omega$ than to increase the depth of the survey $D_{max}(M_{HI})$. Thus, in order to reach the lowest mass for the HIMP, we intend to survey quickly the whole sky (the ALFALFA survey). To test for environmental differences, the VAVÁ survey proposed here necessarily requires not only longer integration to sample well the faint end slope at the distance of Virgo, but also the coverage of a significant area of sky. It is the need for both solid angle coverage and long integration time that makes a VAVÁ survey very demanding in terms of telescope time. The wide area coverage also makes VAVÁ very useful for scientific purposes other than the HIMP determination thus dictating its legacy status.
Appendix 3: Tiling the Sky with ALFALFA

In order to effectively manage a full (Arecibo) sky survey, that will cover \( \sim 12,000' \), it will be necessary to subdivide the sky in sectors, for each of which continuum maps and 3-d spectral data cubes can be processed and archived coherently. We shall refer to each of those sectors as a “tile”.

Rotating the array by \( \sim 22' \) will produce a power pattern with 7 equally spaced beams on the sky. The beam separation is 125" (2.1'), and the average FWHM of the (elliptical) beams is \( \sim 215'' \). The resultant Nyquist sampling interval perpendicular to the scan direction if 95'', so that a single drift scan pass will yield a slightly undersampled map in the Dec. direction. Adjacent drifts would be offset by 875'' (14.6)

Given this setup, a single ALFA “strip” will cover \( \sim 7 \times 2.1' = 14.6' \). Seventeen (17) such strips will cover 14.6' \( \times 17 = 4'1.1 \approx 4' \) in declination. This is a natural size for a tile, given its commensurability with standard coordinate units. In order for tiles to have a sensible aspect ratio, an RA extent of 20 minutes (tile size: \( \sim 4' \) to 5') is right. For a declination coverage of 36', the survey will consist of 648 tiles, each of approximately 20 \( \cos \delta \) square degrees, where \( \delta \) is the declination of the tile. They will be assigned to 9 “bands” in Dec. Gridding the map to half-beam grid point separation, each tile would consist of 200 \( \times 133 \) grid points, albeit keeping data to a tighter RA grid separation may be desirable. The spectral values will be written in 4 byte real format, so a single, one-polarization N-channel spectrum will be 4N bytes long.

Assuming the spectral processor dump rate to be 1 s (the beam will be oversampled in order to allow better rfi–excision capability), a single ALFA drift strip along the width of a tile will be 7 \( \times 2 \times 1200 \times 4N \) plus the space allocated to headers. The largest possible number of spectral channels envisaged for ALFALFA is \( N=8192 \), which for a bandwidth of 50 MHz (3 levels) would yield \( \sim 1.3 \) km s\(^{-1} \) channel separation and may make the data useful for a number of galactic studies, in addition to extragalactic ones. Other ALFALFA options are \( N=2048, 50 \) MHz bandwidth (9 levels) and \( N=4096, 100 \) MHz (3 levels). With \( N=8192 \), a single 7–beam strip across a tile will be 0.55 GBytes, plus headers, for the raw data. Other configurational options will be respectively 2 and 4 times smaller in size. In the calculations that follow, we shall assume the largest possible \( N=8192 \), which would enable galactic HI studies with the data.

An important consideration in setting the size of the raw data block units is connected to the computational constraints. The data will be bandpass-corrected one ALFA declination, 7–beam strip at a time. If the length of the strip is restricted to the width of a single tile, and assuming that all seven tracks and both polarizations will be simultaneously processed, it is important for expediency that the raw data be loadable in memory all at once. With currently available, inexpensive workstations with 2 GHz of memory, a 0.6 GByte data set has about the right size for efficient processing.

Bandpass correction and first-pass rfi excision will be applied to fully sampled ALFA strip segments of extent comparable with the tile width. After that, strips may be compressed by a factor of about 3 to 6 in the RA dimension, to approximate one-quarter to one half-beam sampling. Sampling somewhat more generously than the Nyquist rate helps with the quality of the gridding process. Polarizations may be added.

After all the declination strips pertaining to a tile will have been observed, bandpass corrected and rfi–excised to first order, a 3-d data cube can be constructed. Assuming, as mentioned above, that the data will have been compressed by a factor 4 in the RA dimension, each 7–beam strip will amount to about 0.045 GBytes, with full spectral resolution. A 17 strip map will amount to 0.77 GBytes. If it will be found that compressing strips in the RA direction before gridding is undesirable, then the data of a full tile may not fit in a 2 GB memory and may need to be broken into quadrants, and separately regridded.

The proposed areal coverage by tiles for the combined survey (expected to take 7–8 years) is detailed in Table A3.1. The sky distribution is illustrated in Figure 1.
Table A3.1. Approximate areal coverage after completion of combined survey

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<sup>a</sup> ALFALFA<sub>60</sub>: 6569 deg<sup>2</sup> at high galactic latitude, in single drift mode, 12 s/beam. The full ALFALFA survey will cover the 12000 deg<sup>2</sup> visible from Arecibo. A second pass of ALFALFA may be desirable at a later date.

<sup>b</sup> VAVÁ<sub>60</sub>: 1591 deg<sup>2</sup>, 5 separate drifts, giving 60 s/beam. Deeper coverage of a selected area covering 400 deg<sup>2</sup>, with 300 s/beam will target a subregion near the Virgo cluster, to be determined later (VAVÁ<sub>300</sub>).

Appendix 4: Survey Team

- List of persons committed to contributing to this effort, including affiliations, level of effort and task assignment