ALFALFA: The Arecibo Legacy Fast ALFA Survey

0. Overview

Arecibo is the world's most sensitive radio telescope at L–band. In addition to that all–important sensitivity advantage, Arecibo equipped with ALFA offers important and significant improvements in angular and spectral resolution over the available major wide area extragalactic HI line 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 the previous surveys. As discussed in Appendix A, wide areal coverage is the most efficient means of increasing the volume sampled locally. An extragalactic survey covering the high galactic latitude sky visible from Arecibo will produce an extensive database of HI spectra that will be of use to a broad community of investigators, including many interested in the correlative mining of multiwavelength datasets; we thus dub this program the *Arecibo Legacy Fast ALFA* survey: ALFALFA. A comparison of major blind HI surveys and ALFALFA is presented in Table B.1. A 2–pass drift survey will deliver 1.6 mJy/channel sensitivity (at 18 km s^{-1}), 8 times better than HIPASS and with 4 times better angular resolution (FWHM). In addition to its broad applications, such a wide area HI survey will serve as a strategic approach to a number of focussed E-ALFA science objectives. In coordination with this survey, deeper studies of selected regions, some of which await the second generation E-ALFA spectrometer, will address other critical E-ALFA science goals that are not discussed herein.

When completed in 4–5 years, ALFALFA will survey 7000 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 synergy with other wide area surveys such as SDSS, 2MASS, GALEX, etc. In conjunction with optical studies of comparable volumes, ALFALFA 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. ALFALFA will also provide the basis for studies of the dynamics of galaxies within the Local and nearby superclusters, will allow measurement of the HI diameter function, and will enable a first wide-area blind search for local HI tidal features, HI absorbers at $z < 0.06$ and OH megamasers in the redshift range $0.16 < z < 0.25$.

This request proposes an initial allotment of observing time with ALFA to begin ALFALFA as a 2–pass, 28 sec/beam E–ALFA high galactic latitude drift-scan survey. This program will exploit a simple fixed-azimuth drift scan — *minimum intrusion* — technique, an approach used by others in the past, refined through extensive single pixel test observations in 2003-4 (AO programs A1705, A1763 and A1849) and finally implemented for ALFA in precursor observations in Aug-Sep 2004 (A1946). A 2–pass strategy will greatly aid in the rejection of spurious signals and rfi, thus minimizing the need for follow-up confirmation observations, will even out the scallopping in the maps that arises from unequal pixel gain, and offers the opportunity to use the same dataset for the statistical characterization of continuum transients. A wide–area high latitude survey is of interest to the G-ALFA and P-ALFA consortia once commensal observing becomes possible; expressions of interest in commensality have been obtained from G-ALFA and P-ALFA team leaders. The current WAPP capability is well matched to ALFALFA's goals. Restriction to the 100 MHz from 1335 to 1435 MHz minimizes the vulnerability of the observing program to RFI, particularly severe below 1335 MHz.

During the course of our ALFA precursor observations, we have demonstrated through their results (see *http://www.astro.cornell.edu/∼haynes/pre204/drift.htm*) that the fixed azimuth drift scan technique produces well calibrated, bandpass flattened datasets. We have already invested significant effort in developing software in the IDL environment for data processing and for signal detection. We have established a collaboration with the US National Virtual Observatory that will allow public access to the resultant data products on the shortest possible timescale. Other efforts by members of our proposal team will focus on complementary and follow-up multiwavelength observations, on development of velocity flow models, clustering algorithms and numerical simulations, and on the development of educational and public outreach materials. Students at both the graduate and undergraduate level are already involved in conducting the observations and in analyzing survey data and their scientific implications.

1. Sky Coverage & Telescope Time Request

ALFALFA will cover 7074 square degrees of the high galactic latitude sky accessible to the Arecibo telescope, i.e. the regions between 0° and 36° in Declination (subdivided into 9 bands of tiles, each 4° wide; see Section 4 for details), 07^h30^m to 16^h30^m and 22^h to 03^h in Right Ascension. The full region of the survey will be mapped in drift mode, following a 2–pass strategy (i.e. each Declination band will be scanned at two different epochs, separated by a few months) with the ALFA system, requiring a total of 4130 hours of telescope time. The completion of the full survey is projected to require 5 years. With the present proposal, we request time for the first year of ALFALFA, which will aim to cover 8° (2 of the 9 "tile" bands as described in Appendix C) in Declination in 2–pass mode. The request for the period 1 Feb 2005 to 31 Jan 2006 is of 990 hours of telescope time, with the ALFA array and the WAPPs backend; allowing for setup time (not including ALFA cover removal time after S and 430 MHz dual beam transmitter sessions), we request:

- 66 night time observing sessions respectively between (a) LST=07^h10^m and LST=16^h40^m and between (b) LST=21^h40^m and LST=03^h10^m.

It is of paramount importance that at least half of the sessions of interval (a) be scheduled in the months of February and March and at least half of the sessions of interval (b) be scheduled in the months of August and September. For details, see Section 4.

ALFALFA will provide the reference frame, starting point and photometric standard for other extragalactic ALFA surveys. It is thus desirable, for effective and timely science fall–out, that ALFALFA gets started decisively. ALFALFA will use the WAPPs as a backend system throughout the survey. Extensive precursor tests have been carried out with the system, which by 1 Feb 2005 is expected to be fully ready to go.

Cataloguing a complete census of HI locally, pinning down the HIMF to the lowest masses and conducting the blind absorption and OH megamaser surveys will require completion of the full 5-year program, but this initial allocation will allow early science results in several important areas including: the mapping with 28 s/beam of nearly 1600 deg^2, more than 3 times the coverage with twice the sensitivity of the Arecibo Dual Beam Survey (ADBS: Rosenberg & Schneider 2000); a first blind census across the center of Virgo, giving a 5σ detection limit of $M_{HI} > 10^7 M_\odot$ 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.

2. Science Goals

The upgrade of the surface of the Arecibo antenna in the mid-1970's initiated a new era of extragalactic 21 cm HI line studies which exploited the big dish's collecting area and superior ancillary instrumentation (low noise amplifiers; broadband, flexible multi-bit spectrometers). 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 ALFA, the Arecibo legacy of extragalactic HI studies will continue, probing regimes untouched by other surveys and 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). Here we briefly outline the main science objectives of the E-ALFA wide area high galactic latitude program.

2.1 A Legacy Survey: HI in the Nearby Universe The survey design and its strategy as proposed here have evolved from numerical simulations (c.f. Giovanelli 2003; Masters *et al.* 2004), in which we use a cosmic density map provided by the PSCz density reconstruction (Branchini *et al.* 1999) gridded with 0.9375 h^{-1} Mpc spacing in the inner 60 h^{-1} Mpc, and at twice that value between 60 and 120 h^{-1} Mpc; the map is smoothed with a Gaussian filter of 3.2 h^{-1} Mpc. The density map is complemented by a peculiar velocity map, which allows us to infer more accurate estimates of the distances than those derived purely from redshifts. Two different HIMFs (those derived by Zwaan *et al.* 1997 and Rosenberg & Schneider 2002; the Zwaan *et al.* 2003 HIMF has values intermediate between the former two) are used to populate the map with HI "clouds", which we then proceed to "detect". HI sizes and velocity widths are assigned using empirical scaling relations obtained from our own HI survey data and Broeils & Rhee (1997), with realistic scatter and spectral baseline instability. Disk inclinations and pointing offsets are randomized. We have inspected a wide grid of survey parameters, including different scenarios of suppression of gas infall onto low mass halos due to reionization. Experiments made with the single pixel L-narrow receiver in 2003 and preliminary inspection of our recent A1946 precursor observations confirm the efficacy of these simulations in practical observing conditions (c.f. the presentations by RG at the first E-ALFA Workshop in Mar 2003 and at the 3rd G-ALFA Workshop in Aug 2004, posted on the NAIC-ALFA website).

Based on our simulations and the A1946 precursor observations, ALFALFA is expected to detect more than 16000 objects, sampling a wide range of hosts from local, very low HI mass dwarfs to gas-rich massive galaxies seen to $z \sim 0.06$. HI spectra provide redshifts, HI masses and rotational widths for normal galaxies, trace the history of tidal events and provide quantitative measures of the potential for future star formation via comparative HI contents. As a blind HI survey, ALFALFA will not be biased towards the high surface brightness galaxies typically found in optical galaxy catalogs and moreover, in contrast to HIPASS and HIJASS, will have adequate angular and spectral resolution to be used on its own, without the need for followup observations to determine identifications, positions and, in many cases, characteristic HI sizes. The wide areal coverage of ALFALFA overlaps with several other major surveys, most notably the Sloan Digital Sky Survey (SDSS), 2MASS and the NVSS. The catalog products of ALFALFA will be invaluable for multiwavelength data mining by a wide spectrum of astronomers, far beyond those currently engaged in the ALFALFA survey itself. A key element of this program is to provide broad application, legacy data products that will maximize the science fallout.

2.2 The HI Mass Function and the "Missing Satellite Problem" One of the principal discrepancies between cold dark matter (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". 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. By determining both, limits can be set on the number of low mass halos containing measurable stellar or gaseous components. 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 HIMF is the probability distribution over HI mass of detectable HI line signals in a survey sensitive to the global neutral hydrogen within a system. The most recent estimates of the HIMF have been presented by Zwaan *et al.* (1997; Z97), Rosenberg & Schneider (2002; RS02), Zwaan *et al.* (2003; Z03) and Springob *et al.* (2004). The latter is derived from a compilation of some 9000 optically selected galaxies, further restricted by HI line flux and optical diameter to a complete subsample containing 2200 galaxies. The other determinations are based on blind HI surveys and thus have no bias against the low luminosity and low optical surface brightness galaxies which may be underrepresented in optical galaxy catalogs. The Z03 HIMF is based on the HIPASS survey (Koribalski *et al.* 2004; Meyer *et al.* 2004), 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 $M_{HI} = 10^7~M_\odot$ that disagree by an order of magnitude, the RS02 HIMF having the steeper slope. All three HI blind surveys sample a lower mass limit just below $M_{HI} = 10^8~M_\odot$, for $H_\circ = 70$ km s^{-1}Mpc^{-1} (a value that will be assumed throughout, while for Virgo we adopt a distance D=16 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 $M_{HI} < 10^8~M_\odot$.

As pointed out by Kratsov *et al.* (2004), models of the formation of large scale structure must explain not only the number of satellites found in the Local Group, but also their clustering characteristics: whereas the dSphs are found concentrated with ∼300 kpc of their host giant galaxies, the irregulars are spread throughout, both near and far from the giants (Grebel 2004). The origin of this segregation as well as the fundamental differences among the dwarf populations are thus important issues for galaxy formation theories. The possible variation in the HIMF with local galaxy density or velocity dispersion can provide a statistical measure of the impact of environment mechanisms on the gas as galaxies evolve.

Surveys using ALFA will explore two fundamental aspects of the HIMF: its low mass slope, which has a direct bearing on the "missing satellite problem", and its behavior with varying galaxy environment. To date, studies of the possible environmental dependence of the HIMF have been limited to comparisons of the HIMF derived for galaxies in the Virgo cluster with those in the field (Hoffman *et al.* 1992; Briggs & Rao 1993; RS02; Davies *et al.* 2004; Gavazzi *et al.* 2004) but suffer from poor statistics and incompleteness. The results marginally suggest that the HIMF in Virgo is missing the low HI mass dwarfs found in the field or is at least flatter at the faint end than the field HIMF.

The science program of the E-ALFA consortium as illustrated in the E-ALFA white paper has, as one of its main goals, the robust determination of the HIMF over a range of independent volumes characterized by varying cosmic density. No single survey is likely to explore all the relevant parameter space. Achieving adequate detection statistics for objects in the 10^6–10^8 $M_\odot$ range requires a balance of survey areal coverage and survey depth in order to sample adequate volume. Studying a wide range of environments likewise necessitates tradeoffs of depth and area. In combination with the deeper surveys proposed under the AGES (Arecibo Galaxy Environments Survey) program, ALFALFA will allow exploration of a wide range of possible HIMF scenarios. It will focus on studies of the lowest mass objects in the very nearby universe ($M_{HI} < 10^7$ $M_\odot$, $D < 15$ Mpc) within the Local Supercluster but will also explore variations of the global HIMF, suggested by Springob *et al.* (2004) by sampling, at higher masses, across the range of local densities that characterize the rich clusters like A262, A1367 and Coma, their supercluster filaments and the voids between them.

We emphasize that since the lowest HI masses will be found only very locally, ALFALFA must cover a very large solid angle in order to survey adequate volume at D < 15 Mpc. ALFALFA as proposed will detect between 60 and 300 objects with $M_{HI} < 10^{7.5}$ depending on whether the HIMF follows Z97 or RS02. Both the legacy aspect and the local volume requirement thus dictate the need to survey 7000 deg^2.

2.3 Galaxy Evolution and Dynamics within Local Large Scale Structures The large scale distribution of galaxies in the local universe is concentrated in a structure (Lahav *et al.* 2000) first recognized by de Vaucouleurs and today designated as the Supergalactic Plane. At its center, the Virgo cluster is the nearest rich cluster to us. Overall, the galaxy distribution in that direction has been shown to trace a filamentary structure (West & Blakeslee 2000; Gavazzi *et al.* 1999; Solanes *et al.* 2002) elongated along the line of sight. Galaxies in the cluster core are known to be HI–deficient due to interaction with the hot intracluster gas, while galaxies in the cluster periphery, foreground and background are not. Including its several principal concentrations, the cluster extends about 14° over the sky (Binggeli, Popescu & Tammann 1993). The solid angle subtended by this region samples the highest densities in the local Universe, and thus constitutes the obvious choice for the study of the HIMF in a high density environment. A region of comparable volume but low density, surveyed to comparable sensitivity, is required to provide a reference. The regions with lowest cosmic density at comparable distance are, unsurpringly, in the anti–Virgo direction. Optimization of the Arecibo sky coverage and zenith angle dependence of sensitivity suggests an anti–Virgo region centered near $1^h.5$ in R.A., +24° in Dec. This region includes a large section of the largest, nearby cosmic "void"; averaged over a solid angle of ∼ 0.25 sterad, the anti–Virgo region between 0 and 3000 km s^{-1} is underdense by a factor of ∼6 with respect to the Virgo region in the same distance range. The comparative study of the HI and other properties of the galaxies in these two regions will yield clues on the procesess of environmental influence on galaxy evolution. HI contents will be compared, the dwarf population will traced over wide ranges of cosmic density, and a first truly blind survey for HI tidal remnants will be made.

A wide area Virgo survey will provide a database of unprecedented breadth for the investigation of the origin of gas deficiency in that cluster which will complement nicely the targeted, higher spatial resolution HI line synthesis study of Virgo galaxies currently being undertaken with the Very Large Array (PI: J. Kenney). It will also improve the dynamical understanding of the cluster and its surrounding groups, as well as of the processes associated with the evolution of large–scale structure, by providing a rich redshift data base of low optical luminosity gas–rich dwarfs not only within the cluster core but also in its broad surroundings.

Virgo is the only environment which is both near enough that distance estimates based on secondary methods can distinguish between infall and expansion regimes in the region around the cluster (the so-called "triple–valued region") and also massive enough to possess an extensive, well-populated infall region. In the case of Virgo, the infall domain extends 28° from the center of the cluster, so that a survey that can identify objects at turnaround must cover a very wide area. While the SDSS may provide the required photometric parameters for applications of the Tully-Fisher distance method, its $3''$ fibers cannot provide adequate rotational width measures. Thus ALFALFA, in combination with the SDSS database, will provide the basis for a unique study of the galaxy dynamics both in and around the Virgo cluster.

Other groups within the Local Supercluster will also be targets including: the Canes Venatici I Group at about 5 Mpc, the Leo I group at about 10 Mpc, the "groups of dwarfs" (Tully *et al.* 2002) around UGC 3974 (D = 5.4 Mpc) and NGC 784 (D = 4.4 Mpc), and the Canes Venatici II and Coma I groups at at 10–20 Mpc. There are $\sim$20 additional groups at velocities less than 1000 km s^{-1} which we should be able to study in great detail. Models of the structure of the Local Supercluster are being developed by KLM and by IDK and collaborators and will both contribute to and benefit from the ALFALFA survey.

Of particular note, 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}. 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. Rood & 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. The methodology developed by IDK & VEK to identify nearby dwarfs has already 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). To probe the dI population found by Karachentsev & Karachentseva (2004), a very wide field (> 120 deg^2), as provided by ALFALFA, must be studied.

2.4 The Extent and Origin of HI Disks Extended gas disks around galaxies represent a reservoir for future star formation activity. The study of the distribution of HI relative to that of the optical (stellar) disk allows the investigation of the relationship of gas to star formation and the discrimination of models of the origin of the observed truncation of stellar disks at 3 − 5 optical disk scale lengths based on gas density threshholds (Fall & Efstathiou 1989) versus those related to the maximum protogalaxy specific angular momentum (van der Kruit 1979). In contrast to other major wide area surveys such as HIPASS and HIJASS, some 500 gas-rich galaxies will be resolved by ALFA's $3.5'$ beam, allowing a quantitative measure of their characteristic HI sizes (Hewitt *et al.* 1984) and the derivation of the HI diameter function. In combination with optical photometry, ALFALFA will determine the fraction of galaxies with extended gas disks and enable studies of their host galaxies, their environment, morphology and the role of gas in their evolution. Of particular note, we hope to discover more extremely extended gas disks, such as those found in DDO 154 (Krumm & Burstein 1984), NGC 4449 (Bajaja *et al.* 1994), NGC 2915 (Meurer *et al.* 1996) and UGC 5288 (van Zee 2004) and extensive tidal features such as those seen in the Leo Triplet (Haynes, Giovanelli & Roberts 1979).

Additionally, ALFALFA will resolve extended HI in the vicinity of the 100 large ($D_{UGC} > 5'$) nearby galaxies that may have been missed by interferometric observations, allowing for a census of the neutral ISM on all spatial scales. In particular, the Arecibo telescope provides an ideal probe of the short spacings missed by the VLA in its more compact configurations. For the ALFALFA parameters $t_{int} = 28$ s/beam and channel bandwidth of 5 km s^{-1}, the antenna temperature detectable at the 5 limit is $T_a = 0.13$ K; for a source with a spectral width of 25 km s^{-1} which fills the beam, this limit corresponds to a minimum detectable column density of $N_{HI} = 6 \times 10^{18}$ cm^{-2}.

The column density regime probed by ALFALFA will characterize the broad-scale emission at the edges of galaxy disks, which are hypothesized to truncate at roughly the same value of N_{HI} (e.g. Corbelli & Salpeter 1993, Maloney 1993). The existence of a smooth HI component similar to that in DDO 154 (Hoffman *et al.* 2001) would also extend rotation curves further into the dark matter halo, allowing for more robust determination of the halo shape and concentration to contrast with cold dark matter paradigm predictions on galaxy scales (e.g. Dutton *et al.* 2004; Barnes *et al.* 2004).

ALFALFA will provide a census of the abundance and distribution of HI disks, providing the low redshift link to the damped Lyman α (DLA) absorption seen in quasar spectra. At higher redshift, the neutral gas mass traced by DLA absorption makes a greater contribution to the luminous baryonic mass than it does at the current epoch. ALFALFA will provide important clues to such gas disk evolution. While the HIMFs derived from all surveys to date suggest that large galaxies contribute the majority of the local HI mass density, it also seems that massive galaxies do not dominate the cross section for DLA absorption (Rosenberg & Schneider 2001; Rao & Turnshek 1998). Recent observations with the GMRT of resolved low z DLAs similarly has found that the absorption is associated with HI masses less than those characteristic of L^* galaxies (Chengalur & Kanekar 2002). To understand the DLA cross section at low redshifts requires study of the population of low mass but HI rich galaxies that are missing from optical catalogs. Followup optical studies of ADBS counterparts by JLR and JJS demonstrate that the earlier survey detected galaxies with absolute magnitudes of -16 at distances of 70 Mpc. ALFALFA should detect such objects in very large numbers, allowing not only robust estimates of their contribution to the local HI cross section, but also a measure of their clustering correlation amplitude and scale.

2.5 The Nature of High Velocity Clouds In addition to providing important clues on the extents and kinematics of HI gas around other galaxies, ALFALFA will allow a wide area study of gas in and around the Milky Way as a complement to, and in conjunction with, the G-ALFA surveys. In particular, ALFALFA will explore the nature of the local high velocity clouds (HVCs) of neutral hydrogen which may represent gas accretion onto our Galaxy (e.g., Tripp *et al.* 2003) but which also have been claimed to be more distant, the "missing satellites" in the Local Group (Blitz *et al.* 1999; Braun & Burton 1999). 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). ALFALFA will trace important high-velocity structures, such as the northern portions of the Magellanic Stream and Complex C at 4× better resolution than HIPASS. It will also be 8× 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; Quilis & Moore 2001) and or if they are *bona fide* dark matter–dominated Galactic satellites (e.g., Moore *et al.* 1999a).

The recent discovery of an extended, faint population of HI clouds within 50 kpc of M31 by Thilker *et al.* (2004) suggests a similar search for clouds around M33. At the Andromeda distance, the Thilker *et al.* clouds have masses between 10^5–10^7 $M_\odot$, and line widths of 15–80 km s^{-1}. While Arecibo can not reach as far north as M31, ALFALFA will cover part of the region containing the clouds discovered by Thilker *et al.* and their possible extension toward the region around M33. Wright's cloud (Wright 1979; Braun & Thilker 2004) was detected easily in our A1946 observations in Aug/Sep 2004.

2.6 A Blind Survey for 21 cm Absorbers at $z < 0.06$ The background continuum source counts for this work at 1.4 GHz yield 2100 sources brighter than 0.4 Jy and 11400 sources brighter than 0.1 Jy, within the survey area proposed. 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 targeted sources and we adopt their results as "typical" (although the redshift range is considerable higher). Similarly, Darling *et al.* (2004) have detected HI in absorption in an "optically blind" search against continuum sources using the GBT. The HI features found in those surveys 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}. For a source of 0.5 Jy, a peak absorption of 10 mJy (5σ) corresponds to $\tau \sim 0.02$. The peak column density is given by $N_H \sim 1.82 \times 10^{18} T_{spin} \tau_{peak} \Delta V \ cm^{-2}$. For $T_{spin} \sim 100K$ and a velocity width of 100 km s^{-1}, $\tau_{peak} \sim 0.02$ corresponds to 3.6 x $10^{20} cm^{-2}$ with the obvious condition that narrower widths would probe lower column densities. Using the values for τ_{peak} and ΔV given in Table 1 of Vermeulen *et al.*, we estimate that ALFALFA will be be able to detect all but three of the lines found by those authors, assuming a frequency range match. ALFALFA will target low redshift absorbers not associated with the radio sources themselves.

A major difficulty with absorption studies is spectral baseline determination. A method commonly used averages sources of similar strength observed at comparable telescope configuration (possible for the limited azimuth drift mode considered here). We expect that standing waves will be broader than expected HI absorption lines, and that most rfi will be spectrally unresolved. To identify absorbers, we will 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 require extra effort, but will yield cosmologically interesting statistics based on such a "blind" HI absorption survey. Among others, JKD, EMM and CMS are interested in pursuing the absorption line study.

2.7 A Blind Survey for OH Megamasers at $0.16 < z < 0.25$ 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, half of which were discovered by JKD's Ph.D dissertation work (e.g. Darling & Giovanelli 2002) at Arecibo. Several of them are observed to have variable spectral features allowing superresolution and 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.

3. Synergy with other surveys

3.1 Targeted studies Issues associated with the star formation (SF) process in galaxies can greatly benefit from the combination of HI line spectra with optical broadband and Hα imaging. A great deal of complementary data are already available, and further work will be provided by a number of team members. NB will contribute imaging using the Wise Observatory where his group has access to a 40-inch reflector equipped with CCD cameras with broad-band and H-alpha filters. Through their guaranteed access, they will conduct follow-up observations of galaxies "discovered" by ALFALFA. GG and AB are planning a full Virgo cluster survey in B-band to explore the young stellar populations in galaxies found there. GG and MS are already keepers of the GOLDMine (*http://goldmine.mib.infn.it/*), a web based repository for a large database of optical and NIR imaging data on Virgo and nearby Abell clusters including A262, A1367 and Coma; further imaging will be undertaken for ALFALFA detections by GG at San Pedro Martir. Cornell (including NAIC) astronomers have access to the Palomar 5m telescope and will survey selected regions with the Wide Field Infrared Camera (J,H,K). Among others, LvZ, ES and JJS will hope to provide followup observations at WIYN, the MMT, etc.

3.2 Wide area surveys A number of ongoing major survey efforts will provide complementary datasets for correlative studies with ALFALFA. In the northern galactic cap, ALFALFA will enable a broad spectrum of studies of fundamental galaxy properties in conjunction with the Sloan Digital Sky Survey investigation of the same region which should be completed in 2007. ALFALFA will contribute HI masses and rotational widths as well as redshifts for low surface brightness gas-rich galaxies. The GALEX all–sky imaging survey (AIS) is currently covering part of the Virgo region in two UV bands. Most spirals, many BCDs, some Im and E will be detected. In addition there will be approx 20 deeper fields (MIS) covering approx 20 $\deg^2$. The MIS will include the central 12 $\deg^2$ plus numerous other key galaxies. AB is a scientific associate of GALEX and should have access to the survey data by the end of 2005.

3.3 VLA HI line Currently, a large, targeted survey of HI in Virgo cluster galaxies is being conducted with the VLA (P.I. Jeff Kenney). A database of relevant VLA observations will be established and maintained by LvZ and ES who will lead the followup observations of interesting ALFALFA detections.

3.4 HST-ACS Several HST surveys using the Advanced Camera for Surveys will provide deep images that can be searched for very faint objects. For example, 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, unlike other dSphs, it appears to be isolated. Also, the ACS Virgo Survey targets 100 galaxies in the central regions of Virgo which can likewise be searched for additional faint objects. Among others, KLM plans to explore the Virgo survey ACS fields, and IDK has an on-going ACS program to determine primary distances to very nearby galaxies.

3.5 Future space possibilities Members of the team also play special roles in future space missions for which ALFALFA followup can be planned. NB is the PI of the TAUVEX space telescope array, slated to operate starting in 2006; he will plan follow-up, deep UV observations of ALFALFA targets with TAUVEX, enabling the characterization of the SF in the target galaxies as well as a measure of their dust content. Likewise, AB is a scientific associate of both the ASTRO-F (2005-8) and HERSCHEL (2007–) missions, giving access to their far infrared instruments.

4. Survey Strategy

The ALFALFA survey strategy has been developed over the last two years through single pixel and ALFA precursor experiments. E-ALFA memos on the development of survey strategy are listed in Appendix D.

4.1 Spectral Coverage & Sampling Rate The WAPP backend system, with 16 boards of 100 MHz bandwidth and 4096 spectral channels each, for a spectral resolution of 25 KHz (~ 5 km s^{-1} near 1420 MHz for the HI line), is an excellent match to the science goals of ALFALFA. The bandpass will be centered at 1385 MHz for all beams, yielding effective coverage between -2000 and +18000 km s^{-1} for HI, including the rest frequency of several RRLs and the redshift range (0.16,0.25) for the main OH lines. Based on extensive experience, we intend to record data at a 1 Hz rate, which allows for effective identification of rfi. The raw data rate will thus be ~ 0.26 MB/sec.

4.2 Sky Tiling As described in Appendix C and E-ALFA memo #040209, we subdivide the Arecibo sky within $0° <$ Dec. $< 36°$ into 648 *tiles* of 20^m in RA by 4° in Dec. Mapping a tile in drift mode will require 17 drifts of ALFA, spaced $\sim 14'$ in Dec. for single–pass coverage, and twice as many drifts for double–pass. The second drift will be offset from the first so that the Dec. sampling will be $\sim 1'$, better than Nyquist, with negligible Dec. "scallopping" of the gain over the map except for that introduced by beam 0, which will be optimally distributed across the map (see E-ALFA memo #040803). The tile size was chosen to constitute a data block that can reasonably be handled for data processing in an efficient manner by current desktop computers. The generation of raw data will proceed at the rate of ~ 1 GB/hr, and a single 1200 sec drift across a tile will be ~ 315 MB. Such a data block is well suited for one of the most computer intensive parts of the reduction pipeline, that of bandpass subtraction. The data for a full tile, after polarization averaging and regridding, can fit within the 2–4 GB memory of current desktops.

4.3 Drift Mode The proposed survey will be carried out in drift mode. For most of the survey, the azimuth arm will be parked along the local meridian, the zenith angle determining the declination to be mapped (a tiny rate will be applied to maintain drifts along fixed epoch, rather than current declination; this is a necessary measure, since the survey will extend over several years). For 8 of the 9 band of tiles, the azimuth and rotation angle of the feed array will be the same. Only the band of tiles centered at Dec.=18° will require a nearly E-W orientation for the azimuth arm. This strategy will greatly simplify the disentangling of main beam, side- and coma-lobe contributions to the maps (which fortunately for us, will largely consist of small angular size features, unlike e.g. G-ALFA). Characterization of ALFA parameters needs thus to be made on a greatly reduced volume of parameter space. The most important advantage of a drift mode strategy is however another: *minimum intrusion.* With no moving telescope parts, constant gain and system temperature along a drift are obtained; standing waves will change exclusively as driven by the sidereal rate; beam characteristics remain fixed; bandpass subtraction is optimized. Moreover, we plan to apply no Doppler tracking of the LO, to push further the "minimum intrusion policy". The results of our precursor experiment clearly show the superior quality of the data obtained under this approach.

Drift mode observations, combined with the calibration scheme described below, yield maximally efficient use of telescope time, providing high photometric quality with practically zero overhead.

4.4 Double–Pass As shown in Appendix A, the volume sampled at any HI mass limit, for a survey of fixed total duration, diminishes as the integration time per point t_s increases, as $t_s^{-1/4}$. Once a threshold sensitivity is reached, it is thus more advantageous to increase the solid angle of the survey than its depth. As discussed in E-ALFA memo #040702, the loss of volume sampled by going from a 1– to a 2–pass survey is 19%. Several advantages of a 2–pass strategy offset that loss, however: (1) separation of cosmic emission from rfi will be greatly aided; (2) as shown in E-ALFA memo #040702, the denser sampling will allow statistical separation of spurious from cosmic signals to lower values of S/N; (3) if the two passes are separated several months in time, confirmation of signal candidates can be obtained by verifying that they are separated in radial velocity by $30\cos(\Delta\theta)$ /kms, where $\Delta\theta$ is the change in the angle between the line of sight to the detection candidate and the velocity vector of Earth on its heliocentric orbit; (4) variability in continuum sources can be measured, and transients can be identified, allowing commensality with other groups (J. Cordes will lead a "transient chase" observing team that will piggy–back on ALFALFA); (5) it now appears likely that, given the singular design of the ALFA hardware, maintenance will be difficult and as a result ALFA may normally operate at less than 100% capacity. Loss of a beam in single–pass would result in grievous holes in sky coverage; a 2–pass strategy would greatly attenuate the resulting damage to the survey.

For the reasons listed above, the 378 tiles of high galactic latitude Arecibo sky, between 0° and 36° in Declination, 07^h30^m to 16^h30^m and 22^h to 03^h in Right Ascension, will be covered in two drift passes. In order to optimize topocentric Doppler shift, the two passes must be separated by 3–9 months in time. Coordinated interaction between team and telescope scheduler will be necessary.

4.5 Deeper Drift Scan Studies A subsection of the survey region will be covered with higher sensitivity, through an 8–pass drift strategy that will increase sensitivity by a factor of 2 and provide higher sampling density with respect to the wide–angle, 2–pass approach. A discussion of the optimal spacing of multiple pass surveys is presented in E-ALFA memo #040803. The 8–pass region will include central parts of the Local Supercluster, crossing the Virgo cluster, as well as its outer, anti–Virgo parts. The exact region near Virgo, to be covered in this mode, remains to be decided on the basis of the outcome of the 2–pass approach. Coordination will be made between this and the deeper study to be proposed under the AGES program.

4.6 Calibration Monitoring of T_{sys} will rely on firing a noise diode for 1 sec, every ~ 200 sec, without interruption of a scan and thus no significant 'loss of sky'. This scheme was tested during A1946 precursor observations in Aug 2004; we identified a number of timing problems in the AO data taking system, which are currently being fixed. We have also cross–calibrated T_{sys} of the various beams (see E-ALFA memo #040920), using a technique which yields beam-to-beam fidelity to better than 1%; that technique is now implemented as part of our reduction pipeline and will be automatically applied to each data set. For each drift, 10 continuum strips will be obtained, each averaged over adjacent sections of ~ 10 MHz bandwidth: this will provide us with a record of continuum fluxes and "local" (over the 1335–1435 MHz region) indications of the sources' spectral indices α.

Once a map of a tile is completed, a catalog of positions, L–band fluxes and local α of all continuum sources within the tile will be produced, and compared with those of a published catalog (e.g. the NVSS). This will allow very precise calibration of our photometry (the slope of a flux–to–flux regression line), and an identification of variable sources (over a timescale of years). The software for this calibration scheme has already been written and is being tested on the A1946 percursor data set.

We underscore that ALFALFA will provide a photometric standard of unprecedented quality for other surveys and all extragalactic HI work.

5. Data Management, Reduction, Public Access and Outreach

Numerous memos listed in Appendix D address issues related with data management, reduction and access. Data will be processed within the IDL environment, taking advantage of the substantial, already existing AO–based software developed by Phil Perillat. All spectral data units will have the same IDL 'structure' format, that of the so–called 'm' structure, independent of the processing stage. This greatly facilitates handling, conversion to FITS format at any stage of reduction and export. Substantial experience has been developed within our group in the data management and processing in this environment. Our processing pipeline, fully developed by us, has been tested with the A1946 precursor run. We have been able to obtain conversion from FITS to IDL, noise calibration, bandpass subtraction, continuum source extraction and baselining of data sets in real time, i.e. in less than the time necessary to gather the data.

5.1 Data Products

- Data will be taken as a sequence of drift scans, each containing 900 1–sec records; each record contains 16 spectra of 4096 spectral channels, corresponding to the 7 beams × 2 pols plus 2 spare boards. Scans will follow each other with only 1–2 sec of 'dead time' in between, for minimal 'loss of sky'. Drift scans are the main processing unit. During or soon after data taking, drift scans will be converted from FITS (form delivered by data taking software) to IDL, noise–calibrated, bandpass subtracted and baselined. A detailed record of the processing is kept in ancillary files and both spectral line and continuum structures are inspected and validated by an observer. We refer to these as **Level 1** data products. The FITS files (**Level 0** data products) will be maintained in storage at the Observatory. While their distribution will remain restricted, access for technical tests by Observatory staff and other individuals will be possible, in coordination with the observing team. Already as the first E-ALFA team on the telescope (A1946), we have provided sample data to members of the community for the benefit of their development effort.

- After a tile has been fully sampled by drifts at different declinations, we will proceed to producing a regridded, smoothed spectral map cube, a continuum map, a re–calibration of the data by using a flux catalog of the sources within the continuum map and to extracting spectral line sources. Gridded, smoothed spectral line data cubes, flux–calibrated, baselined spectra and continuum maps of a tile are **Level 2** data products.

- As multiple passes are available for a given tile, coadded spectral data cubes and information on continuum source variability will be provided, as **Level 3** data products of the survey.

- Catalogs of cleaned, calibrated, confirmed, extracted signals are the final **Level 4** data products.

5.2 Public Access and Outreach ALFALFA will be the deepest, highest resolution extragalactic HI survey ever conducted over a comparable 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 the local Universe in this part of the sky, the instrument of choice to select targets for deeper mapping, a vehicle for follow-up work for a much larger community than that which usually observes at Arecibo. We fully intend the data products of ALFALFA to become available to the community in a prompt, useful and robust manner.

First, rather than through few widely spaced data releases, we plan to make ALFALFA data available to the community on a continuous basis, in order to assure timeliness and optimize scientific fallout. Compatibly with telescope time allocations, we intend to coordinate prioritization of tiles to be completed with the scientific needs of other groups. During data taking, progress will be posted on the web on a weekly basis, as will be full plans for each observing run. Validation checks of data from each observing run will be promptly posted as well, no later than *one month* after completion of each observing run, as it has already been our practice with A1946 observations (see our group website). Higher level data products will be released for public access through the web no later than *6 months* after validation of the given tile data set. Postings will thus be regulated by previous telescope time allocations, which will, presumably, be affected by the timeliness of our data releases.

Access tools will be provided largely through the portals of the US NVO. Note that we have received NSF support for the specific purpose of training students towards providing access to ALFALFA products through NVO nodes; that in early 2004 we have initiated contacts with the NVO leadership through focussed visits at JHU and STScI, receiving training and commitments of further support; and that 3 Cornell graduate students from our group have attended the Aspen NVO School in Sep04. One of us (MPH) is a member of the NVO Advisory Committee and will be presenting specifics of the ALFALFA/NVO effort at the Jan05 AAS Meeting.

Contacts with J. Alonso of the AO Visitor Center have been made, to produce display materials to illustrate ALFALFA's science goals and projected impact.

6. Survey Management

A subset of the E-ALFA consortium, the ALFALFA project team represents a broad group of individuals combining a wide range of experience and expertise. Active members of the ALFALFA project team, their affiliations and expected contributions are listed in Appendix E. Issues of survey planning and management are discussed here.

6.1 Organization & Governance The effective management of a multinational, multidisciplinary, multiyear survey effort will require a higher level of organization than any previous, even large, observing programs carried out at Arecibo. The first step in that direction was the coordinated separation of E-ALFA into several survey projects, and the formation of a Coordinating Committee which includes the P.I.s of those projects (*http://www.astro.cornell.edu/∼haynes/ealfa_cc/*). The organization of ALFALFA includes:

- 1. The P.I., who will act as an interface with NAIC and the other E-ALFA projects.
- 2. An *Oversight Committee*, formed by the P.I. and 5 other members, including a doctoral student, at least one representative of foreign institutions and at least 3 representatives of U.S. institutions. The OC will deal with issues related to science task assignments to team subgroups, coordination with other survey teams, commensality, membership, funding and conflict resolution. It will also oversee the activities of several ALFALFA subgroups, namely:
- 3. An *Observing, Data Validation and Bookkeeping* task group, responsible for coordinating the observing effort within the team and the telescope scheduling with NAIC, in charge of Level 1 data validation, rfi monitoring and alleviation issues and responsible for the overall bookkeeping effort of the survey.
- 4. A *Data Processing* task group, in charge of coordinating the processing of the data, from telescope output to calibration, bandpass subtraction, baselining, regridding, and related software development. This group will also deal with the implementation of software for the production of higher level data products, automatic signal extraction algorithms, cleaning, specialized gridding techniques, cross-referencing with multiwavelength catalogs, in close collaboration with:
- 5. A *Public Access* task group, which will guarantee the development and implementation of the tools necessary for robust and effective access to the survey products by the community, both through specialized channels and through the NVO.
- 6. An *Education and Outreach* group, which will develop outreach materials to be implemented both at AO and at participating institutions, and will organize workshops with student participation at both the undergraduate and graduate levels.
- 7. A *Follow–up and Coordinated Multiwavelength Observations* group, which will organize and coordinate observations in support of ALFALFA by members of the team.

6.2 Commensality Three different sets of scientific interests will also be served, in a commensal fashion, by ALFALFA. First, the 2–pass strategy discussed above will provide data for studies of radio continuum source variability on months (separation between the two passes) and years (with reference to existing catalogs) scales, a local (within a 100 MHz bandwidth) spectral index, and information on other continuum transients. Second, as soon as the P-ALFA backend is completed, it will be possible to split the front end signal and separately sample it at high time resolution, using the data for the search of high galactic latitude pulsars and giant pulses from extragalactic sources. Third, the G-ALFA spectrometer, already completed, will be used to analyze at high spectral resolution our IF signal for the study of high latitude galactic HI. Letters of intent from J. Cordes (P-ALFA) and T. Bania (G-ALFA) have been received. Formalization of the exact parameters by which commensal observations will be monitored have not yet been provided by NAIC. We of course intend to fully abide by those and will work towards facilitating their implementation.

6.3 Milestones While a survey of this nature will produce results more regularly after acquisition of a significant body of observations, we can already anticipate milestones which can be used to measure our ability to tackle the many facets of ALFALFA during the first year. Among them are:

- Soon after we hear a positive decision on this proposal, we will officially designate the governance of the survey effort, as described in section 6.1.
- We intend to submit for publication a paper that will illustrate the goals and scientific impact of ALFALFA, as well as include the results of the precursor A1946 observations.
- By early 2005, a list of Ph.D. theses that will be based on ALFALFA data products will be made known.
- Assuming that the beginning of the observations for ALFALFA will take place in Feb–Mar 2005 as requested, we expect completion of data taking for a full tile by Summer 2005 and posting of the related public access data by the end of 2005.
- A successful demonstration of our ability to deliver on this proposal will be most likely required by October 1, 2005, the time by which a request for continued allocation of telescope time will be submitted. Under an optimistic scenario for the allocation of telescope time, preliminary, but fully processed Level 2 data sets will be available for inspection by a skeptical review panel before then.

6.4 Funding The funding avenues available for observers at NAIC are limited and are not well tailored to enable long–term, legacy programs like ALFALFA. Nonetheless, sufficient guarantees exist to justify a request for telescope time that will extend for several years. First, the senior members of the ALFALFA team have a succesful record of independent funding; second, they have demonstrated their ability to bring to completion large–scale observing projects in the past, gathering the resources necessary to bring them to completion; third, they have already obtained substantial support for the initiation of the efforts associated with the survey. Notably, a 3–year grant was awarded by NSF in 2003 to RG (P.I.) and MPH (co–P.I.), to carry out a set of ALFA precursor observations and to initiate a wide angle drift survey of most of the AO sky (ALFALFA) and a deeper survey of the Virgo/anti–Virgo region. In 2004, a 1–year grant was awarded to RG, to initiate preparation of an ALFA/HI node within the NVO environment, and a grant was awarded to RK towards the organization of ALFALFA–related outreach efforts in undergraduate institutions. A grant proposal to the Brinson Foundation for ALFALFA work by MPH was invited and is pending. Other requests are currently being planned or pending by several members of the team, both at the individual level and in a coordinated manner, taking advantage of binational funding options. RG and MPH are devoting the bulk of their sabbatical leaves, in AY 2004-5, to ALFALFA activities. While normal NSF grant cycles are not well matched with a 5–yr survey effort, the current circumstances are witness of strong commitment to the effort by senior team members.

6.5 Student Participation Graduate student participation in the activities of the survey and those leading to it is conspicuous. Precursor observations involved direct participation of 6 graduate students. The current membership of the ALFALFA team involves 6 graduate students; this number is expected to grow. RK has been granted NSF resources to host an E-ALFA Undergraduate Workshop at Union College in Spring 2005, to initiate planned outreach activities involving undergraduate students.

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Appendix A: Scaling Relations

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

$$M_{HI}/M_{\odot} = 2.356 \times 10^5 D^2_{Mpc} \int S(V) dV \tag{1}$$

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

$$M_{HI}/M_{\odot} \simeq 2.356 \times 10^5 D^2_{Mpc} S_{peak} W_{kms} \tag{2}$$

where S_{peak} is the line peak flux and W_{kms} its velocity width in km s^{-1}. For detection, $S/N = f_\beta S_{peak}/S_{noise}$ 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_{noise} can be obtained from the radiometer equation

$$S_{rms} = \frac{T_{sys}/G}{\sqrt{2 \times CBW \times t_s \times f}} \tag{3}$$

where T_{sys}/G is the system temperature divided by the system gain (for the ALFA feeds, T_{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_{smo}, the switching technique applied for bandpass stabilization, f_{switch}, and other observational details, i.e. $f = f_{switch} f_{smo} f_{other}$. For the data taking schemes under consideration, $f_{switch} f_{other} \simeq 1$, while $f_{smo} \propto W_{smo}$, where W_{smo} is the width of a spectral smoothing function.

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

$$S/N = \frac{f_\beta S_{peak}}{S_{rms}} \simeq 3.6 \times 10^{-4} \frac{G}{T_{sys}} t_s^{1/2} \frac{M_{HI}}{M_{\odot}} D^{-2}_{Mpc} W^{-1/2}_{kms} > 5 \tag{4}$$

In practice, the smoothing of signals of $W_{kms} \simeq$ several hundred km s^{-1}does not reduce the noise in proportion to $\sqrt{W_{kms}}$ and, moreover, S_{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 $W_{smo} = 100$ km s^{-1}; thus, for $W_{kms} > 100$, $S/N \propto W^{-1}_{kms}$; (b) that for $W_{kms} \leq 100$ S_{peak} degrades as $W^{-1/4}_{kms}$, from its full value at $W_{kms} = 30$ to 0.74 of that at $W_{kms} = 100$; in this case $S/N \propto W^{-3/4}_{kms}$. Our detection criterion will then be:

$$8.4 f_\beta t_s^{1/2} \Big(\frac{M_{HI}}{10^6 M_{\odot}}\Big) D^{-2}_{Mpc} \Big(\frac{W_{kms}}{100}\Big)^{\gamma} > 5 \tag{5}$$

where $\gamma = -3/4$ for $W_{kms} \leq 100$ and $\gamma = -1$ for $W_{kms} > 100$. 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 $p = \big(e^{S/N - S_{1/2})/\eta} + 1\big)^{-1}$, where η 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 the simulations described in Section 2, we ignored all "detections" with $S/N < 5$ and only the "reliable" fraction of those with $S/N \geq 5$ is counted. See E-ALFA memo #040702 (Appendix D) for further details.

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

$$t_s \simeq \frac{1}{4} f_\beta^{-2} \Big(\frac{M_{HI}}{10^6 M_{\odot}}\Big)^{-2} (D_{Mpc})^4 \Big(\frac{W_{kms}}{100}\Big)^{-2\gamma} \tag{6}$$

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 $V_{beam} \propto \Omega_b D^3_{max}/3 \propto A^{1/2}$, 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 $V = \Omega D^3_{max}/3$, where Ω is the solid angle subtended by the survey. We can thus increase the number of detections either by sampling a larger solid angle Ω or by increasing $D_{max}(M_{HI})$. Now, the total time required to complete the survey is

$$t_{survey} \propto (\Omega/\Omega_b)t_s \tag{7}$$

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

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

and inverting:

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

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 Ω than to increase the depth of the survey $D_{max}(M_{HI})$.**

Appendix B: Comparison with Previous Surveys:

HIPASS and HIJASS cover the same area of sky that is visible at Arecibo, HIPASS south of Dec.= +25°, and HIJASS further to the north. However, in addition to the large increase in sensitivity, 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 those other surveys. The HIPASS follow-up 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 follow-up. 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.

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°x4° 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 the number of independent volumes surveyed. Table B.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.

Table B.1 Comparison of major blind HI surveys

Survey	Area (sqd)	Beam (′)	V_{max} (km/s)	$V_{res}{}^a$ (km/s)	t_s (s)	rms^b (mJy)	N_d	min $M_{HI}{}^c$ ($M_\odot$)	Ref
AHISS	65	3.3	-700 – 7400	16	var	0.7	65	$1.9 \mathrm{x} 10^6$	1
ADBS	430	3.3	-650 – 7980	34	12	3.6	265	$9.9 \mathrm{x} 10^6$	2
WSRT	1800	49.	-1000 – 6500	17	60	18	155	$4.9 \mathrm{x} 10^7$	3
Nancay CVn	800	4 x 20	-350 – 2350	10	80	7.5	33	$2.0 \mathrm{x} 10^7$	4
HIJASS	1115	12.	-1000 – 10000^d	18	400	13	222	$3.6 \mathrm{x} 10^7$	5
HIJASS-VIR	32	12.	500 – 2500	18	3500	4.	31	$1.1 \mathrm{x} 10^7$	6
HIDEEP	60	15.5	-1280 – 12700	18	9000	3.2	173	$8.8 \mathrm{x} 10^6$	7
HIZSS	1840	15.5	-1280 – 12700	27	200	15.	110	$4.1 \mathrm{x} 10^7$	8
HICAT	21341	15.5	300 – 12700	18	450	13.	4315	$3.6 \mathrm{x} 10^7$	9
HIPASS		15.5	300 – 12700	18	450	13.	(6000)	$3.6 \mathrm{x} 10^7$	10
AUDS	0.4	3.5	-960 – 47000^e	TBD	70 × 3600	0.02	(40)	$0.6 \mathrm{x} 10^5$	11
AGES	TBD	3.5	-960 – 47000^e	TBD	300	0.5	TBD	$1.4 \mathrm{x} 10^6$	12
ALFALFA	7000	3.5	-2000 – 18000	11	28	1.6	(16000)	$4.4 \mathrm{x} 10^6$	

[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 5σ detection with W = 30 km s^{-1}.
[d] Gap in velocity coverage between 4500–7500 km s^{-1} caused by rfi.
[e] Assumes second generation backend.

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: Current HIPASS survey, to Decl. $< +2°$; Meyer *et al.* (2004), Zwaan *et al.* (2004)
10: Final HIPASS survey (including northern extension)
11: Freudling *et al.* AUDS precursor proposal
12: Davies *et al.* AGES precursor proposal

Appendix C: Tiling the Sky with ALFALFA

For effective management and timely delivery of a nearly full (Arecibo) sky survey, 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 ALFA array (19° at the local meridian), it is possible to force the 7 beams to drift along equidistant Declination tracks. Because of the ellipticity of the illuminated area seen by the Gregorian, the spacing of the beams at the optimal rotation angle changes with Azimuth. Most of ALFALFA will be made with the Azimuth arm fixed in the N–S direction, and the beam separation will be constant: $125''$ ($2.1'$). To survey the Declinations near 18°, the Azimuth arm will need to be positioned near the E–W direction, and the bean spacings in Dec. will be smaller ($\simeq 1'.75$). The average FWHM of the (elliptical) beams is $\sim 215''$, so that a single–pass drift scan survey would yield an undersampled map in the Dec. direction. Adjacent drifts would be offset by $875''$ (14'.6). A 2–pass survey, with second–pass tracks interleaved between those of the first pass, would yield better than Nyquist Dec. sampling and nearly negligible Dec. scallopping of the gain through a map, except for that deriving from the higher gain of beam 0.

An important concern for a survey which may stretch data taking over several years is the impact of precession. Drift scans will track lines of current Declination. Two drifts of a few hours duration, taken a few years apart, will not yield tracks which are parallel to within a negligible fraction of the beamwidth. It will thus be necessary to implement a tiny Dec. rate on the data taking mode, or periodic readjustments of the Dec. will need to be applied, without interruption of the data taking. This request has been placed with the AO staff and will be implemented by end of 2004.

In single pass drift, ALFA can cover $\sim 7 \times 2.1' = 14'.6$. Seventeen (17) such strips will cover $14'.6 \times 17 \simeq 4°$ in Declination. This is a natural size for a tile, given its commensurability with standard coordinate units. For ease of handling with current desktop computers and in order for tiles to have a sensible aspect ratio, an RA extent of 20 minutes (tile size: ∼ 4° to 5°) is chosen. For a Declination coverage of 36°, the 24^h will occupy 648 tiles, each of approximately $20 \cos\delta$ square degrees, where δ is the declination of the tile. They are assigned to 9 "bands" in Dec. 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 and the two spare WAPP boards. For N=4096, which for a bandwidth of 100 MHz (3 levels) would yield ∼ 5.3 km s^{-1} channel separation, the data rate is ∼ 1 GB/hr.

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 7–beam drift at a time. For an RA length comparable with the width of a single tile (all 7 tracks and both polarizations will be simultaneously processed), it is important for expediency that the raw data be loadable in memory, in 2 or 3 work copies, all at once. With currently available, inexpensive workstations with 2 GHz of memory, a 1 GB 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 can be compressed by a factor of about 3 in the RA dimension,to approximate one–quarter beam sampling. Sampling somewhat more generously than the Nyquist rate helps with the quality of the gridding process. Polarizations will 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 3 in the RA dimension, and polarizations added, a 34 drift (2–pass) map of a tile will be less than 2 GB with full spectral resolution, allowing for ease of copying and transferring the data.

The proposed areal coverage of ALFALFA includes 378 tiles. The exclusion of the low galactic latitude regions is clearly driven by (a) the realistic assessment that pulsar and other galactic surveys will put a premium on low latitude LST time and (b) the expectation that part of the low galactic latitude, extragalactic sky will be surveyed commensally with pulsar and other galactic surveys.

Appendix D: E-ALFA and Drift Survey Documents

During the course of preparing and executing the A1946 precursor observations, we have written and made available a number of memos and documents which discuss various strategies and options. We have also developed several web sites of interest not only to the group working on drift EALFA surveys, but other components of EALFA as well. We find this an efficient and effective way to communicate within E-ALFA and our team in particular and expect to continue to develop these websites as ALFALFA progresses. These sites are maintained and updated regularly at Cornell by MH, RG and members of the Cornell Extragalactic Group.

Last Update	Web address	Document/site
Sep04	* ~haynes/pre204/docs/memo040920.pdf	T_{sys} of ALFA beams
Sep04	* ~haynes/pre204/docs/comments040908.txt	Comments to NAIC staff after first A1946 precursor run
Sep04	* ~haynes/pre204/docs/lessons.pdf	Lessons learned from the first A1946 precursor run
Aug04	* ~galaxy/alfa_cima.htm	E-ALFA oriented CIMA cookbook
Aug04	* ~galaxy/alfafits.htm	E-ALFA oriented description of ALFA FITS file
Aug04	* ~galaxy/rotbeams.htm	ALFA rotation and beam spacing for off-meridian drifts
Aug04	* ~galaxy/docs/figbeams.pdf	Astronomer-friendly display of ALFA beams on the sky
Aug04	* ~haynes/pre204/docs/memo040803.pdf	Spacing of drift passes for E-ALFA surveys
Aug04	* ~haynes/pre204/docs/processing_b.pdf	Data processing stream for drift surveys
Aug04	* ~haynes/pre204/docs/book040812.pdf	Data organization and bookkeeping for drift surveys
Aug04	* ~haynes/pre204/docs/telecon040805.txt	Minutes of A1946 program telecon
Jul04	* ~haynes/pre204/docs/outline_cookbook.txt	Outline for data processing cookbook
Jul04	* ~haynes/pre204/docs/tasklist1.txt	Plan/Task list for A1946 Aug-Sep04 observing run
Jul04	* ~haynes/pre204/docs/a1946q1.txt	Questions/Requests to NAIC in preparation for A1946
Jul04	* ~haynes/pre204/docs/rg040702.pdf	Detection statistics, confirmation requirements and the advantages of a 2-pass strategy
May04	* ~haynes/pre204/docs/brkEALFAhandout.pdf	Possibilities for database archive and access
Jan04	http://alfa.naic.edu/extragal/A1849_cals.pdf	Calibration of drift scan observations

Last Update	Web address	Document/site
Sep04	* ~haynes/pre204/drift.htm	EALFA Drift survey web site
Aug04	* ~haynes/ealfa_cc/ealfa_cc.html	EALFA Coordinating Committee web site
Aug04	* ~haynes/wgs.html	EALFA Working Groups web site
May04	*/academics/courses/astro620/astro620.html	Web site for Cornell seminar course Astro 620, Spring 2004

* http://www.astro.cornell.edu/

Appendix E: ALFALFA Project Team

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

Name	Affiliation	Level of effort	Specific tasks
Alessandro Boselli	Marseilles	moderate	Complementary/followup observations
Noah Brosch	Wise Obs	significant	Complementary/followup observations
Barbara Catinella	NAIC-Arecibo	significant	Observing, RFI algorithm development
Vassilis Charmandaris	Cornell U.	moderate	Complementary observations
Jeremy Darling	OCIW	moderate	HI absorption lines, OH megamasers
Jonathan Davies	Cardiff	significant	Coordination with AGES
Diego Garcia Lambas	Cordoba	moderate	Complementary analysis, galaxy simulations
Giuseppe Gavazzi	Milano-Bicocca	significant	Complementary/followup observations
Carlo Giovanardi	Arcetri	moderate	Complementary analysis
Riccardo Giovanelli	Cornell U.	major	Observing strategy, survey management, software development, data analysis
Martha Haynes	Cornell U.	major	Observing strategy, survey management, web development, data analysis
Lyle Hoffman	Lafayette Coll.	significant	Observing strategy, software development, data analysis, follow-up
Leslie Hunt	Arcetri	moderate	AGN hosts, complementary observations
Angela Iovino	Milano-Brera	moderate	Complementary observations
Igor Karachentsev	SAO	moderate	Complementary analysis, primary distances
Valentina Karachentsev	Kiev	moderate	Complementary analysis, dwarf galaxies
* Brian Kent	Cornell U.	Ph.D. thesis	Observing, software development, data analysis, NVO portal development
Rebecca Koopmann	Union Coll.	significant	Observing, complementary observations, undergraduate education activities
Christian Marinoni	Milano-Brera	significant	Group algorithm development
* Karen Masters	Cornell U.	significant	Survey simulations, distance models, constrained N-body simulations
Robert Minchin	Cardiff	moderate	Software development, connection to AUDS
Emmanuel Momjian	NAIC-Arecibo	significant	Observing, data analysis, absorption lines
Erik Muller	NAIC-Arecibo	significant	Observing, HVC's, tidal streams
Carmen Pantoja	U. Puerto Rico	moderate	Observing, data analysis, follow-up, ZOA
Mary Putman	U. Michigan	significant	Observing, follow-up, HVC's
Jessica Rosenberg	Harvard-SAO CfA	significant	Observing, data analysis, HIMF
John Salzer	Wesleyan U.	moderate	Complementary optical observations, KISS data, emission line galaxies
* Amelie Saintonge	Cornell U.	Ph.D. thesis	Observing, software development, signal detection algorithm implementation, detection statistics
Marco Scodeggio	Milano-CNR	moderate	Database tools, clustering algorithms, complementary observations
Evan Skillman	U. Minnesota	moderate	Complementary observations, comparison with synthesis observations
Jose Solanes	U. Barcelona	moderate	Galaxy dynamical simulations, environmental effects
* Kristine Spekkens	Cornell U.	significant	Observing, survey strategy development, mapping algorithm development
* Christopher Springob	Cornell U.	significant	HI archive development, RFI excision algorithms, commensal observing
* Sabrina Stierwalt	Cornell U.	Ph.D. thesis	Observing, software development, HI size measure, data analysis, sidelobe modelling
Carlos Valotto	Cordoba	moderate	Complementary analysis, cluster simulations
Wim van Driel	Meudon	moderate	Observing
Liese van Zee	Indiana U.	moderate	Analysis of HI sizes, complementary optical and VLA observations, SMUDGES survey

* Student