What SDSS Misses: A Pilot Program to Find More Low Mass Galaxies
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Background: Numerical simulations formulated on the ΛCDM cosmology make clear predictions of the number of halos of given mass. While it is argued that the lowest mass halos may not be able to retain their baryons in the presence of reionization, stripping or feedback, we cannot understand how some of the more "massive satellites", which should survive reionization, can remain "missing"; there should be a factor of ∼10x more. This conundrum is referred to as the "Too Big to Fail" problem (Boylan-Kolchin, Bullock & Kaplinghat 2011), and seems to hold not only in the Local Group but also in the field (Klypin+ 2014; Papastergis+ 2014). Observations of low mass galaxies can test whether the theoretical expectations for the decline in baryon fraction are realized in nature and to what degree. Constraining baryon feedback by studying the properties of low mass galaxies not only yields clues on galaxy formation, but offers the potential to test the properties of dark matter on small scales (e.g. Papastergis+ 2012), which is otherwise degenerate with feedback.

Because of the Malmquist bias, the low mass population quickly disappears with distance from us in optical flux-limited spectroscopic surveys such as the Sloan Digital Sky Survey (SDSS). Surveys like the 2MASS redshift survey (Huchra+ 2012) also incompletely sample the nearby volume. On the other hand, the (observable) baryon content of low mass star-forming galaxies is *dominated* by HI, and at relatively nearby distances (D < 80 Mpc), that population is more accessible to detection in HI. Obtaining a more complete census of the nearby low mass population is critical in order both to trace large scale structure in regions not well-sampled (or covered at all) by the SDSS and to explore systematically the halo regime where the baryon-to-dark matter fraction plummets.

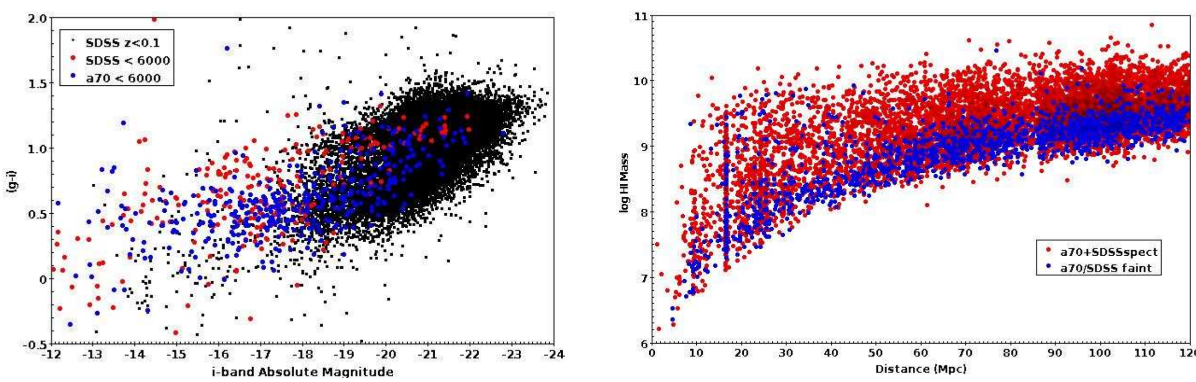

Figure 1: Left: Color-magnitude diagram of objects in the western region targeted by this proposal (Fig. 2). Black points show all galaxies in the SDSS spectroscopic sample with $z < 0.1$; red points denote the subset of those with cz < 6000 km s^{-1}, while blue points trace galaxies included in the 70% ALFALFA source catalog (α.70) also with cz < 6000 km s^{-1}. Note that the HI population is dominated by blue, low luminosity galaxies and avoids the red sequence. Right: Near-distance Spanhauer diagram showing separately the α.70 galaxies brighter (red) and fainter (blue) than the SDSS spectroscopic selection criterion. The feature at 17Mpc is the Virgo Cluster; the one at ∼85 Mpc arises from a harmonic of the San Juan airport radar.

Low Mass Gas-Rich Galaxies: The ALFALFA survey is obtaining a census of gas-bearing objects over a sufficient cosmological volume that robust measures of the HI mass, velocity and correlation functions can be extracted from it. Preliminary results have already been published (e.g., Martin+ 2012; Papastergis+ 2013; Moorman+ 2014). The population of galaxies detected by ALFALFA (Fig. 1) follows well-defined scaling relations at the high mass end (Huang+ 2012b), but the scatter in these relations grows at the low mass/luminosity end. Some of that scatter arises, as noted by Huang+ (2012a), because only at the nearest distances can ALFALFA detect both gas-rich and gas-poor dwarfs. Some also arises because of issues with the SDSS photometric pipeline, distance uncertainties. and bursty star formation histories. As seen in the right panel of Fig. 1, ALFALFA begins to sample the population which is too faint optically to be included in the SDSS spectroscopic sample but which *does* have SDSS photometry. Our aim here is to sample more completely the low mass, low luminosity ($M_i > -18$) star-forming galaxies in the nearby volume (D < 80 Mpc) via their HI line emission.

Survey Strategy: Low mass halos are only detectable nearby, where their statistical sampling is quickly limited by Malmquist bias and cosmic variance. We aim to sample galaxies in a volume suited to overcome both issues, that is, far enough that distance uncertainties do not dominate but near enough that we can overcome Malmquist bias with moderate integration times. As discussed by Giovanelli+ (2005), solid angle coverage is critical to understanding a population of relatively low mass: *once such a mass is detectable at an astrophysically-interesting distance, it is more strategic to increase the solid angle coverage than the depth of a survey.* A survey to probe the low HI mass range over sufficient volume requires greater sensitivity than ALFALFA *and* a solid angle coverage substantially larger than that of AGES (~ 200 deg^2; Auld+ 2006). To sample more completely the range of HI masses $7.8 < \log \mathrm{M}_{HI}/\mathrm{M}_\odot < 8.5$ within 80 Mpc, we have considered the option of undertaking a drift scan survey similar to ALFALFA but covering > 1000 deg^2 with a longer integration time; such a survey would require many thousands of hours with ALFA to achieve adequate solid angle coverage. Since we have already shown (Haynes+ 2011) that *nearly all objects of log* $M_{HI}/M_\odot > 8.0$ *contain detectable starlight,* most of the volume covered by any such survey would discover no new galaxies. Instead, after a careful analysis of simulations of various such surveys, we believe that a more efficient approach is to conduct targeted LBW observations of objects carefully culled from the extensive SDSS photometric database, and model completeness based on the known systematics of ALFALFA and SDSS. Hence, we propose to carry out a *pilot* program designed to test with adequate statistical significance whether we can identify low mass gas rich galaxies in the volume out to D ~ 80 Mpc. If this target program proves successful, we will propose in the future to continue this program over a wider area, including the large area of the Arecibo fall sky not included in the SDSS spectroscopic survey. Such a future HI line survey with Arecibo would make an important contribution to our understanding of the number, distribution and baryon content of low mass star-forming galaxies in the local universe, a population underrepresented in the SDSS. The objects studied as part of this project will also be targeted for interferometric and optical followup to study their halo kinematics and stellar populations.

Identifying Candidate Low Mass Galaxies from the SDSS: We propose to use what we have learned from ALFALFA and its correspondence to the SDSS (Huang+ 2012b) to identify and measure the HI masses of objects which fall below the ALFALFA detection limit because their HI masses are too small at their distances. In this pilot experiment, we wish to test our SDSS selection to see if it works to find objects in the HI mass range $7.8 < \log \mathrm{M}_H/\mathrm{M}_\odot < 8.5$ at distances between 30 and 80 Mpc. For this pilot experiment, we have tried to increase the probability of finding targets of the proper HI mass and distance by observing two sky regions known to have overdensities, but *not* rich clusters, in these redshift ranges. The regions are shown in Fig. 2.

The target galaxies have been identified in the SDSS DR10 database according to two criteria:

- Objects identified in the SDSS photometric sample according to their apparent magnitude, color, surface brightness and concentration but which are too faint to be included in the SDSS spectroscopic sample and which are *not* detected by ALFALFA. (*Photometric-only sample*: 109 targets; 73 in western region, 36 in eastern.)
- Brighter objects of similar color, surface brightness and concentration with SDSS spectroscopic redshifts. For these, we predict that their HI masses lie below the ALFALFA detection limit *at their distances*, but their HI content is otherwise normal (i.e. they are not HI deficient, luminous galaxies). (*Spectroscopic sample*: 54 targets; 38 and 16, respectively)

For the photometric-only selection, we use the SDSS-DR10 database to search for objects with good photometry in all bands and classified as "galaxies" (extended sources). We require the surface brightness profiles to be disk-dominated and set limits on the color and concentration; individual inspection of each candidate target leads to the rejection of objects which are clearly bogus (bright stars, multiple photometric objects) and ones which may be confused with other sources in the Arecibo beam. A representative sample of objects selected by the above criteria is shown in Fig. 3.

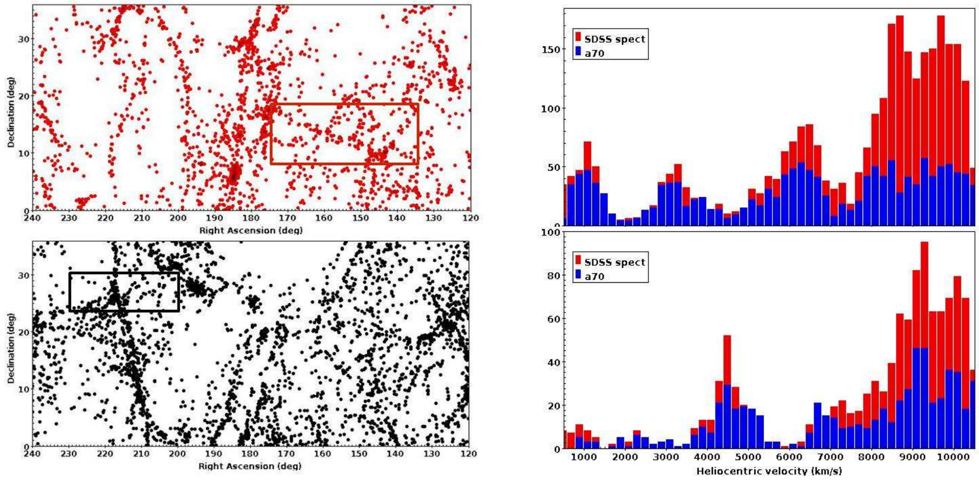

Figure 2: Left: Sky distribution of galaxies in the heliocentric velocity intervals 2000-4000 km s^{-1} (red; upper) and 4000-6000 km s^{-1} (black; lower). The areas targeted in this proposal are outlined in each panel. Right: Distribution of recessional velocities for galaxies for the SDSS spectroscopic sample (red) and ALFALFA HI detections (blue) in the same two sky areas, showing the local overdensities contained in each.

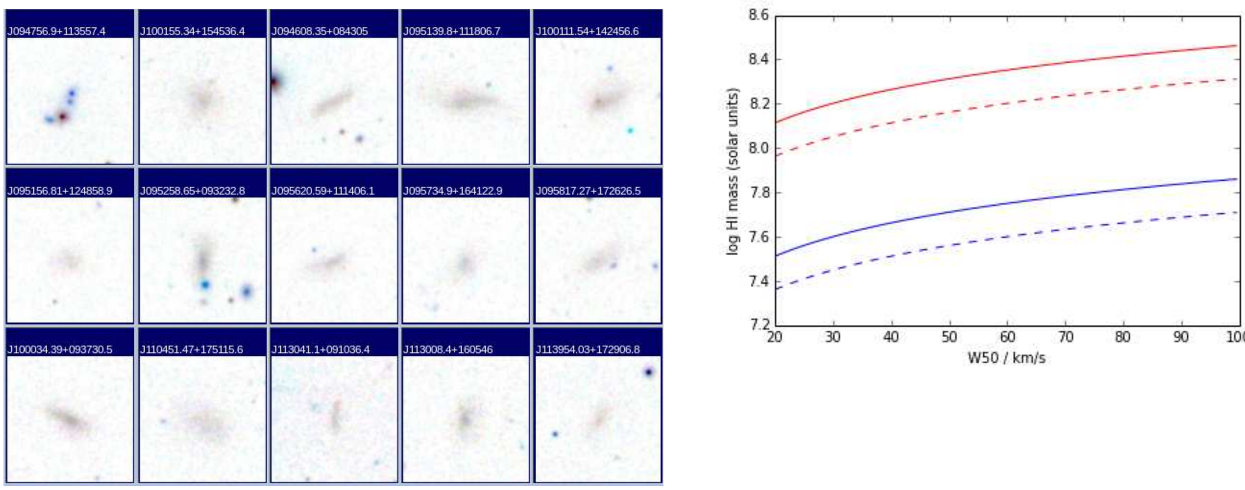

Figure 3: Left: SDSS images of representative targets returned from an SQL query of the SDSS photometric database. Such queries sometimes return unflagged suspect SDSS photometric objects (upper left object) which can be dismissed on visual inspection. The other objects on the top row are all detected by ALFALFA with c$z < 5000$ km s^{-1}. The remainder are targets of unknown redshift, selected on the basis of the SDSS photometry alone. Right: Estimated 5σ detection limit for single (solid lines) and double (dashed) ON-OFF pairs at 40 (blue) and 80 (red) Mpc for the proposed observing mode, assuming an rms of 1.2 mJy per 24.4 kHz channel after Hanning smoothing for a single ON-OFF pair.

Observing strategy: The LBW pointed observations will consist of 5-min ON-OFF total power pairs with the interim correlator and 9-level sampling. For targets of known redshift, a 25 MHz bandwidth will be used; in search mode, we will reconfigure to cover 85 MHz by staggering the center frequencies of the four correlator boards. The right panel of Fig. 3 shows our estimate of the 5σ HI mass detection limit as a function of the line width for one or two ON-OFF pairs. Each target will be observed for one pair and the result examined to decide whether to continue for another pair; we assume about half the targets will require two pairs. Allowing for OFF source integration, noise diode calibration and observing overheads, our previous experience yields a practical observing rate of $\sim 4-5$ pairs/hour. The total number of targets (163) is determined by the need to perform a statistical analysis of the resulting detection rate as a function of distance and HI mass for, separately, the spectroscopic- and photometric-only samples.

Observing request: In this proposal, we request 6 sessions in the LST range from 08^h to 16^h and 3 sessions 08^h to 12^h30^m for a total of 61.5 hours. The Undergraduate ALFALFA Team (UAT) will be heavily involved in all aspects of this program, including evaluating the SDSS photometry, conducting the observations at Arecibo and analyzing the dataset. For the period covered by this proposal, we request time specifically during the January UAT workshop and the last two weeks of March, corresponding to "spring break" periods when members of the UAT can travel to Arecibo.

Productivity Report (not previously reported):

• A working catalog covering 70% of the final ALFALFA area and including the cross-reference of optical counterparts with the SDSS is now in beta-testing by the team.

• A working catalog covering the full final ALFALFA area over the range $cz < 3000$ km s^{-1} is almost complete; a second catalog of ultracompact high velocity clouds is being finalized.

• Greg Hallenbeck (Cornell) completed his Ph.D. (August 2014) and is now a faculty member in the Department of Physics and Astronomy at Union College.

• The reduction and analysis of the LBW data from A2752 (November 2013) was part of the summer research of Alison Farrish (Cornell '16) who is using ALFALFA, A2752 and the SDSS to explore the characteristics and distribution of galaxies in the Pisces-Perseus supercluster and its foreground void. Her summer project also included writing code to accumulate multiple ON-OFF pairs, now incorporated into the LBW reduction package used by other members of the UAT.

• 23 observing sessions for program A2853 were carried out by faculty and students from eight UAT institutions. Analysis of these data will be part of the senior thesis of Will Harney at Union in the 2014-15 academic year.

ALFALFA-based refereed publications (not previously reported):

• *Is There a "Too Big to Fail" Problem in the Field?*, Papastergis, E., Giovanelli, R., Haynes, M.P. & Shankar, F. 2014, A&A (submitted)

• *The HI Mass Function and Velocity Width Function of Void Galaxies in the Arecibo Legacy Fast ALFA Survey*, Moorman, C.M.†, Vogeley, M.S., Hoyle, F., Pan, D.C., Haynes, M.P. & Giovanelli, R. 2014, MNRAS (accepted)

• *HIghMass - High HI Mass, HI-rich Galaxies at z 0: Sample Definition, Optical and Hα Imaging, and Star Formation Properties*, Huang, S., Haynes, M.P., Giovanelli, R., Hallenbeck, G.†, Jones, M.G.†, Adams, E.A.K., Brinchmann, J., Chengalur, J.N, Hunt, L.K., Masters, K.L., Matsushita, S., Saintonge, A. & Spekkens, K. 2014, Ap.J. (accepted)

• *HIghMass - High HI Mass, HI-rich Galaxies at z 0: High-Resolution VLA Imaging of UGC 9037 and UGC 12506*, Hallenbeck, G.†, Huang, S., Haynes, M.P., Giovanelli, R., Adams, E.A.K., Brinchmann, J., Chengalur, J.N, Hunt, L.K., Masters, K.L., Saintonge, A. & Spekkens, K. 2014, A.J. (accepted)

• *An Extremely Optically Dim Tidal Feature in the Gas-rich Interacting Galaxy Group NGC 871/NGC 876/NGC 877*, Lee-Waddell, K.†, Spekkens, K., Cuillandre, J.-C., Sick, J., Cannon, J., Haynes, M.P., Chandra, P., Patra, N., Stierwalt, S. & Giovanelli, R. 2014, MNRAS 443, 3601

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