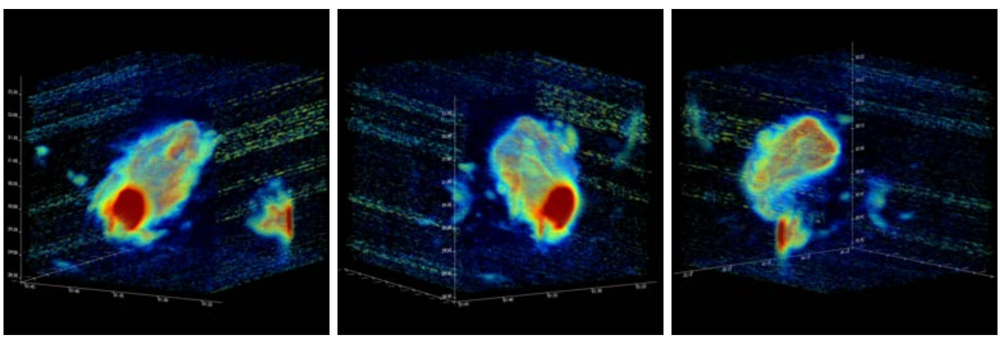
Extragalactic Neutral Hydrogen Studies at Arecibo Observatory

Executive Summary

Introduction

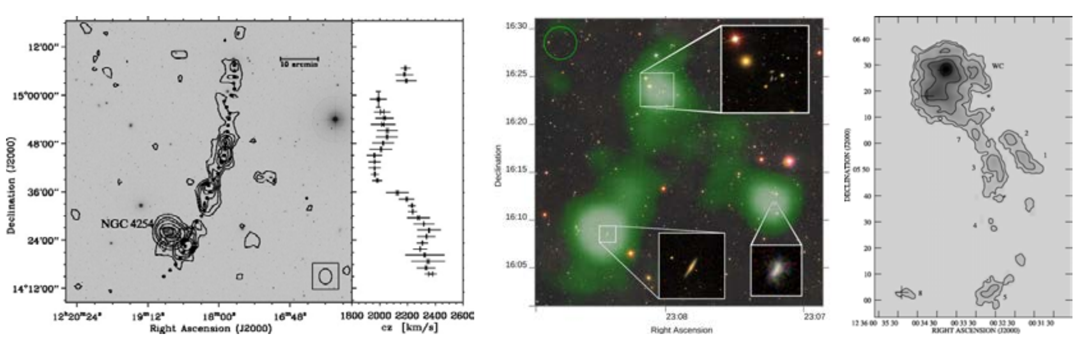
Hydrogen is the most common and basic element in the universe and is the main fuel for nuclear fusion in stars. It is found in three main forms: neutral atomic hydrogen (HI), ionized hydrogen (HII), and molecular hydrogen (H_2). Of these, the dominant – and most detectable – form found in galaxies is HI, which is present in all galaxies with active star formation.

The HI line at 21-cm enables radio astronomers to trace both the distribution and, through the shift in frequency due to the Doppler effect, the velocity structure of neutral hydrogen in and around galaxies. This gives a 3D map that can be used for many purposes, including examining galaxy-galaxy interactions, discovering new galaxies, and searching for evidence of 'cold-mode accretion' that could solve the problem of how galaxies continue to fuel new star formation.



3D HI map of Messier 33 from the Arecibo Galaxy Environment Survey. Image: Rhys Taylor

Arecibo brings its unrivalled sensitivity to bear on these problems. It has the largest collecting area of any current telescope (larger than any planned instrument to which the US community will have open access) and two highly-complementary receivers regularly used for HI observations: The L-band wide (LBW) receiver, used to observe single points on the sky at high sensitivity, and the Arecibo L-band Feed Array (ALFA), a seven-pixel array used for mapping.



HI streams & bridges in ALFA surveys reveal galaxy interactions: From left: 250 kpc tail on NGC 4254 in the Virgo cluster (Haynes, Giovanelli & Kent 2007); 800 kpc bridge in the field (Taylor et al. 2014b); 500 kpc tail on the NGC 4532/DDO 137 pair in the Virgo cluster (Koopmann et al. 2008).

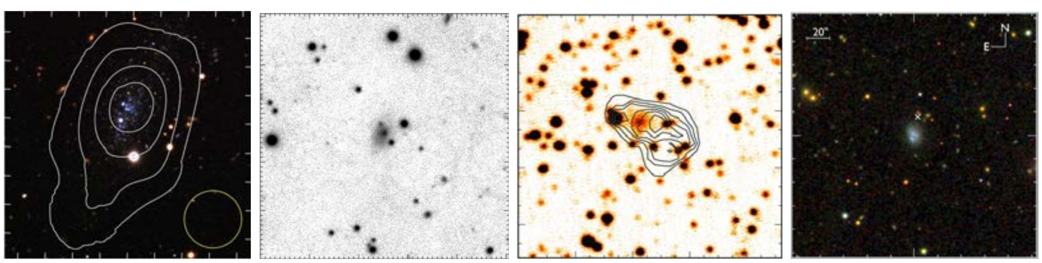
Over the past decade, ALFA has been used very successfully to carry out four extragalactic neutral hydrogen surveys. Three of these were designed with a 'wedding cake' strategy in mind with a wide-area, relatively shallow survey (the Arecibo Legacy Fast ALFA survey; ALFALFA), a smaller-area, moderately deep survey (the Arecibo Galaxy Environment Survey; AGES), and a very small-area, ultra-deep survey (the Arecibo Ultra Deep Survey; AUDS). The fourth, the ALFA Zone of Avoidance survey (ALFA ZOA) targets areas behind the plane of our Galaxy that are inaccessible to optical or infra-red surveys due to extinction and stellar crowding.

LBW and previous single-pixel HI receivers at Arecibo have also been used for a number of successful surveys and for many smaller projects. Ongoing work with LBW includes the Galex-Arecibo-SDSS Survey (GASS) and HI measurements for the REsolved Spectroscopy Of a Local VolumE survey (RESOLVE).

Future Work at Arecibo

Arecibo is in a position to address key science questions identified by the 2010 Decadal Survey panels on the Galactic Neighborhood and on Galaxies Across Cosmic Time via HI surveys.

A 40-beam phased array feed would give Arecibo a mapping speed for HI in the local universe similar to that planned for the SKA precursor telescopes. This would allow Arecibo to address questions such as whether small gas-rich dwarfs, analogous to the Local Group's Leo T, are common in nearby galaxy groups (addressing the 'missing satellites' problem), and what happens at the faint end of the HI mass function in the Virgo Cluster.



Nearby dwarf galaxies found in ALFA surveys point the way to the Leo T analogs that will be discovered in future surveys. From left: Leo P (Giovanelli et al. 2013; VLA contours shown); AGES J030039+254656 (Minchin et al. 2010); ALFA ZOA J1952+1428 (McIntyre et al. 2011; VLA contours shown); AF7448 001 (Taylor et al. 2014a). These dwarfs also demonstrate the way in which Arecibo works as part of the astronomy ecosystem, feeding science to the VLA.

A new L-band receiver with a lower system temperature and a higher redshift (lower frequency) bandpass limit than the current L-band wide could give a sensitivity boost equivalent to doubling the size of the telescope. It would allow a wide variety of projects, including studies of individual galaxies at z = 0.2 - 0.25, integrated HI signals from groups beyond z = 0.25, and absorption systems over a wide span of redshift space. A lower (sub 1 GHz) receiver would enable work at $z > 0.5$ (if the RFI environment allows) and a new spectrometer would give better dynamic range and RFI mitigation than the aging WAPP spectrometers.

Extragalactic Neutral Hydrogen Studies at Arecibo Observatory

Robert Minchin & Members of the Community

1. Extragalactic Neutral Hydrogen Science

Extragalactic HI studies span the science addressed by two of the Astro 2010 Decadal Survey panels: the Panel on the Galactic Neighborhood (GAN) and the Panel on Galaxies Across Cosmic Time (GCT). The GAN report emphasizes the importance of HI studies as part of multi-wavelength observations of galaxies, which it described as "required to characterize the ISM-IGM complexity".

The report of the Astro 2010 Panel on Radio Millimeter, and Submillimeter (RMS) Astronomy from the Ground identified three questions posed by the GAN and GCT panels that can be addressed with Arecibo (all included in the "Understanding the Cosmic Order" section of the main Astro 2010 report):

- How do baryons cycle in and out of galaxies, and what do they do while they are there? (GCT 2)
- What are the flows of matter and energy in the circumgalactic medium? (GAN 1)
- What controls the mass-energy-chemical cycles within galaxies? (GAN 2)

There are two modes in which Arecibo can participate in surveys addressed at answering these questions:

1. Blind HI surveys, where sources are identified by their neutral hydrogen content
2. Pointed HI surveys, where sources have been previously identified at other wavelengths

Both types of survey have been carried out successfully at Arecibo in the past. The recent ALFA projects, ALFALFA (Giovanelli et al. 2005), AGES (Auld et al. 2006), AUDS (Freudling et al. 2011) and ALFA ZOA (Henning et al. 2010), are examples of blind HI surveys, while there is a long history of pointed surveys including GASS (Catinella et al. 2010), RESOLVE (Kanappan et al 2013), SFI++ (Springob et al. 2007), and the work on cosmic distances and large scale structure that led to the award of the Henry Draper medal to Haynes & Giovanelli. This current generation of surveys is provoking much interest in the community, with the main survey papers for both ALFALFA (Giovanelli et al. 2005) and GASS (Catinella et al. 2010) having received over 100 citations.

It should be noted that large surveys also provide quantities of data that can be used to answer topical questions not imagined at the start of the survey. For example, Papastergis et al. (2014) used ALFALFA data to investigate whether there is a 'too big to fail' problem in the field. 'Too big to fail' was first noted in the Local Group by Boylan-Kolchin et al. (2011), many years after ALFALFA started, and has rapidly become a hot topic in local universe cosmology.

Another great advantage of surveys at Arecibo is the commensal observing approach, pioneered at Arecibo. This means that other projects run at the same time as the extragalactic HI surveys: a Galactic HI survey runs alongside ALFALFA and AGES, a pulsar survey and a galactic radio recombination line survey run alongside ALFA ZOA, while SETI and a survey for fast radio bursts run whenever ALFA is observing. This strategy led to the discovery of the first fast radio burst found outside of Australia (Spitler et al. 2014) – in data taken during observations for the ALFA ZOA extragalactic HI survey.

Two different metrics measure the performance in carrying out these different kinds of survey. For blind surveys, mapping speed is the critical measure; while for pointed surveys raw sensitivity is most important. The compromises necessary in making a survey instrument mean that array receivers, which deliver the best mapping speed, do not normally deliver the best raw sensitivity: The L-band wide (LBW) receiver at Arecibo has a higher gain, lower system temperature, and higher bandwidth than ALFA, for example:

Receiver	Gain (K/Jy)	Tsys (K)	Bandwidth (GHz)
ALFA (7 pixel)	10	30	1.225 –1.525
LBW (single pixel)	11	27	1.15 – 1.73

2. Future challenges

The ALFA surveys have been very productive (over 80 refereed papers submitted as of October 2014), but are now ramping down their observations. ALFALFA and AUDS have been completed (although are now entering the period where a lot of science is emerging from the data), while AGES is near finishing. As a result, more LBW projects (including survey follow-up observations) are getting time on the telescope. While ALFA has been primarily used by large survey teams, LBW serves mainly smaller 'PI' projects that span a wide range of scientific interests.

In the near future, ALFA's survey capabilities will be overtaken by those of MeerKAT, ASKAP, FAST, and the WSRT equipped with APERTIF. Feasibility studies have been carried out for a possible 40-beam phased-array feed at Arecibo (as recommended by the Astro 2010 RMS panel), known as AO40. Giovanelli (2008) found that such a feed, with a T_{sys} of 50K, would be competitive with the SKA precursors; recent studies with a cryogenically cooled 19-element phased-array feed on the telescope have shown that a much lower T_{sys} is possible, giving mapping speeds around four times faster than currently with ALFA.

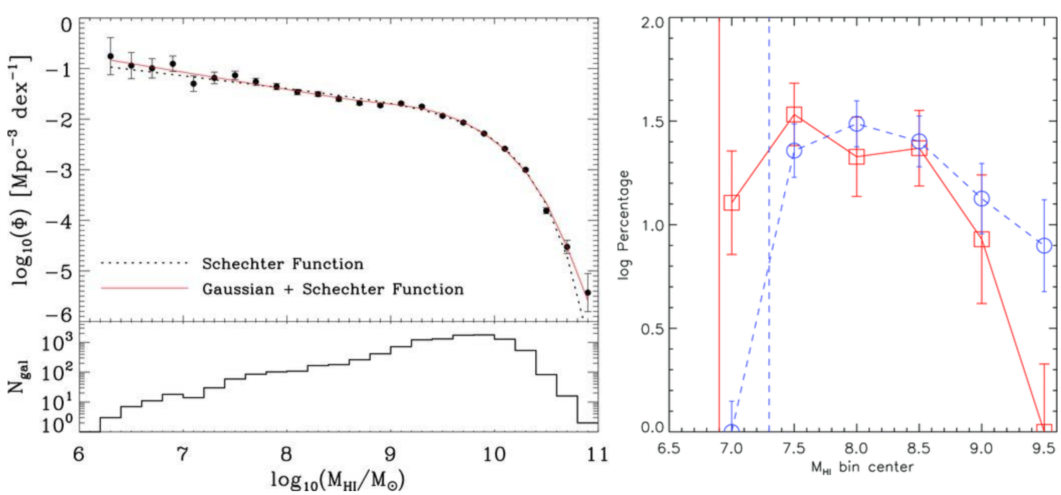
Arecibo's raw sensitivity is also challenged by FAST and (in the longer term) by SKA1. It should be noted that neither of these instruments, as currently planned, are open skies (policies for FAST are not yet set, there is a possibility that a limited amount of time will be open to the international community in the future; for the SKA US access will be via collaboration with SKA-member country PIs). However, LBW is now an old instrument. A new L-band single-pixel receiver with a lab T_{sys} of ~10K (so delivering ~20K on the sky) would reduce integration times to 50-60% of what is currently needed, equivalent to a 70 - 100% increase in surface area.

3. Future HI survey science

While the proposed 40-beam phased-array feed, AO40, will match the SKA precursors for mapping speed, the interferometers will have greater resolution, giving an advantage at high redshift where they can disentangle sources more easily but a disadvantage at low redshift where weak sources may be lost due to the signal being spread across multiple pixels. It therefore makes sense for AO40 surveys to concentrate on science that can be done with relatively wide, relatively shallow surveys, leaving the deep, higher-redshift surveys to the interferometers.

3.1 Possible AO40 projects:

- Key project: Minihalos in nearby groups (See Giovanelli 2009, Haynes et al. 2011, and the 2011 ASAP white paper on extragalactic astronomy for details):
  - Look for objects similar to Leo T ($M_{HI} = 3 \times 10^5 M_\odot$)
  - Covering 200 sq. deg. (same as the current AGES area) with an order of magnitude more sensitivity than ALFALFA would take ~5000h (similar to the total for ALFALFA) using an AGES-like chase-and-drift strategy. (An ALFALFA-like fixed-drift strategy would not be suitable.)
- Wider and deeper surveys of the Virgo Cluster to explore the faint end of the cluster HI mass function:
  - Extended survey at AGES depth:
    - Build on existing AGES coverage (20 sq. deg. in main Virgo Cluster field; Taylor et al. 2012).
    - Could be started with ALFA then switched to AO40 when that becomes available
    - 100 sq. deg. region would require ~1100h with ALFA or ~280h with AO40 (including the 20 sq. deg. already covered by AGES).
  - Deep field (Giovanelli 2007, Giovanelli 2008):
    - Small section of Virgo Cluster to 10 times the integration time of AGES.
    - Would require ~700h with AO40 for a 20 sq. deg. region.
- Continued surveying of the Zone of Avoidance:
  - As with ALFA ZOA, in conjunction with Pulsar and Galactic RRL surveys.
  - Would find galaxies only visible by the HI signal and map large scale structure behind the Milky Way.



HI Mass Functions. Left: The field from ALFALFA (Martin et al. 2010). Right: The Virgo Cluster from the deeper AGES (red) and the wider ALFALFA (blue) surveys (Taylor et al. 2013).

4. Future HI science with single-pixel receivers

4.1 Science with a new L-band receiver

A new single-pixel L-band receiver could deliver a halving of the time necessary to carry out observations to a given sensitivity. This will enable current science to be carried out more efficiently and will allow observations to be carried out to lower noise levels, revealing sources not currently visible. It is likely that most sources observed with this receiver (as with the current LBW) will be previously identified at other wavelengths, although it will also be useful for follow-up observations of HI sources detected in blind HI surveys either with ALFA or AO40, or at other telescopes.

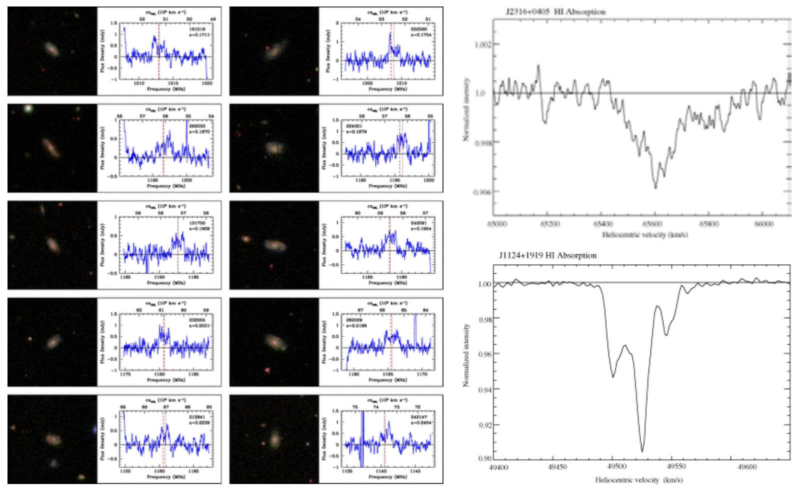
This would be an all-purpose receiver, playing to Arecibo's strength of great raw sensitivity and open to PI projects from the whole community, rather than a dedicated survey instrument used mainly by large teams. It would enable Arecibo to participate more effectively in multi-wavelength surveys and would support a balance of small PI projects and large campaigns.

- Recent examples of multi-wavelength observations where Arecibo has contributed HI measurements include GASS observations of galaxies selected by stellar mass, RESOLVE observations of a volume-limited sample of galaxies, and observations of dusty elliptical galaxies, very low mass galaxies, and galaxies with high specific star-formation rates.
- Arecibo is also a vital part of the astronomy ecosystem, its unequalled sensitivity making it the instrument of choice for preliminary observations that lead to science with other instruments such as the VLA. An example of this is recent observations of lensed galaxies at $z \sim 0.1$, a vital first step in selecting a gas-rich sample for VLA HI imaging that will (in combination with the lensing) reveal the dark matter sub-structure in these galaxies.

Ideally, a new L-band receiver would open up new redshift space at Arecibo, where galaxies can be observed through 'windows' in the RFI (the current LBW receiver is normally limited to $z < 0.23$, although it has been extended to $z \sim 0.25$ for specific projects by removal of some filters). This is a technique pioneered at Arecibo by Catinella et al. (2008) and Catinella & Cortese (2014) – the latter of which made the highest-redshift detection of HI emission to date – and would allow observations of galaxies and clusters of galaxies at high redshift. This would enable some interesting science:

- Targeting intermediate-redshift galaxies (out to $z \sim 0.3$) identified in the optical, following up on the work by Catinella et al., but using the greater sensitivity to push to lower masses (Giovanelli 2007; Giovanelli 2008).
- Observations of intermediate-redshift ($z \sim 0.25+$) clusters, where the Arecibo beam is well matched to the size of the cluster (Giovanelli 2008).
    - Would be much more sensitive to the integrated signal from clusters than is possible with the SKA precursors.
- HI absorption studies at higher redshifts.
    - Lower frequency bandpass limit means higher redshifts are accessible.

- More sensitivity gives a greater number of continuum sources against which absorption could be seen.



Left: emission lines at z = 0.2 from Catinella et al. (2008). Right: absorption lines at z = 0.22 and 0.16 from Gupta et al. (2006).

As a flexible instrument, an L-band single-pixel receiver would be used for science that we have not even imagined. Astronomers working at any wavelength who want neutral gas information for their sample will be able to obtain it more quickly and efficiently. It should be noted that besides the HI science noted in this white paper, an improved L-band single-pixel receiver would also bring greater efficiency to OH molecular line studies and pulsar timing projects.

It is also worth noting that a high-quality LBW replacement would (in comparison to AO40) be cheap and fast to build and install, and would not require any investment in new IF/LO or backends (although it would be enhanced by these).

4.2 A sub-1 GHz 'L-Low' receiver

A new receiver below ~1.1 GHz would enable HI absorption and signal-stacking studies from z ~ 0.3 out to z ~ 1 (700 MHz), using Arecibo's large collecting area advantage over the SKA precursor telescopes to address the important question of the evolution of the cosmological mass density of neutral hydrogen at intermediate redshifts. This would require preliminary studies of the RFI in this spectral region and the development of RFI mitigation techniques. Such a receiver could also be very useful for pulsar timing and search projects.

4.3 Future back-end for single-pixel studies

While a new L-band single-pixel receiver would not require a new backend, the fact remains that the WAPPs are aging and parts are becoming obsolete. Once the current stock of spares at AO is exhausted, it will be very difficult to maintain the WAPPs, making it essential for AO to start looking at replacement options whether or not a new receiver is acquired.

For HI studies, not much improvement over the spectral-line performance of the WAPPs is necessary, although higher resolution can be useful for minimizing the impact of RFI. However studies (particularly at the higher-redshift, lower-frequency end of L-band) would be enhanced by a backend with better control of ringing and higher dynamic range, allowing it to be used in windows among heavy interference. It is possible this could be achieved using the ALFABurst/SERENDIP spectrometer.

Rejection/mitigation of RFI at high time resolution inside the new backend (prior to averaging) should also be investigated as this could greatly enhance high redshift work.

References

ASAP White Paper on Extragalactic Astronomy, 2011, "Arecibo Observatory's Essential Role in Extragalactic Astronomy through the Next Decade", Arecibo Science Advocacy Partnership: http://areciboscience.org/extragal.pdf

Astro 2010 Panel Reports, 2011, "Panel Reports–New Worlds, New Horizons in Astronomy and Astrophysics", National Academies Press: http://www.nap.edu/catalog.php?record_id=12982

Astro 2010 Report, 2011, "New Worlds, New Horizons in Astronomy and Astrophysics", National Academies Press: http://www.nap.edu/catalog.php?record_id=12951

Auld R. et al., 2006, MNRAS, 371, 1617: http://adsabs.harvard.edu/abs/2006MNRAS.371.1617A

Boylin-Kolchin M., Bullock J. S., Kaplinghat M., 2011, MNRAS, 415, 140: http://adsabs.harvard.edu/abs/2011MNRAS.415L..40B

Catinella B., Cortese L., 2014, MNRAS, accepted: http://arxiv.org/abs/1410.7464

Catinella B., Haynes M. P., Giovanelli R., Gardner J. P., Connolly A. J., 2008, ApJ, 685, L13: http://adsabs.harvard.edu/abs/2008ApJ...685L..13C

Catinella B. et al., 2010, MNRAS, 403, 683: http://adsabs.harvard.edu/abs/2010MNRAS.403..683C

Freudling W., Staveley-Smith L., Catinella B., Minchin R., Calabretta M., Momjian E., Zwaan M., Meyer M., O'Neil K., 2011, ApJ, 727, 40: http://adsabs.harvard.edu/abs/2011ApJ...727...40F

Giovanelli R. et al., 2013, 146, 15: http://adsabs.harvard.edu/abs/2013AJ....146...15G

Giovanelli R. et al., 2005, AJ, 130, 2598: http://adsabs.harvard.edu/abs/2005AJ....130.2598G

Giovanelli R., 2007, "Thoughts on the Future of HI Astronomy at Arecibo", white paper for 'Frontiers of Astronomy with the World's Largest Radio Telescope': http://www.naic.edu/~astro/frontiers/RIG.pdf

Giovanelli R., 2008, "Extragalactic HI Surveys at Arecibo: The Future", in 'The Evolution of Galaxies Through the Neutral Hydrogen Window', AIP Conf. Prof. 1035, 328: http://adsabs.harvard.edu/abs/2008AIPC.1035..328G

Giovanelli R., 2009, "Minihalos in and beyond the Local Group", white paper submitted to the Astro 2010 decadal survey: http://adsabs.harvard.edu/abs/2009astro2010S..95G

Gupta N., Salter C. J., Saikia D. J., Ghosh T., Jeyakumar S., 2006, MNRAS, 373, 972: http://adsabs.harvard.edu/abs/2006MNRAS.373..972G

Haynes M. P., Giovanelli R., Campbell D. B., Cortés-Medellín G., Koopmann R. A., & the ALFALFA team, 2011, "A Next-Generation Survey to Count Low Mass Dark Matter Halos in Nearby Galaxy Groups": http://egg.astro.cornell.edu/index.php/docs/ten2five.html

Haynes M. P., Giovanelli R., Kent B. R., ApJ, 665, L19: http://adsabs.harvard.edu/abs/2007ApJ...665L..19H

Henning P. A., Springob C. M., Minchin R. F., Momjian E., Catinella B., McIntyre T., Day F., Muller E., Koribalski B., Rosenberg J. L., Schneider S., Staveley-Smith L., van Driel W., 2010, AJ, 139, 2130: http://adsabs.harvard.edu/abs/2010AJ....139.2130H

Kannappan S. J., Stark D. V., Eckert K. D., Moffett A. J., Wei L. H., Pisano D. J., Baker A. J., Vogel S. N., Fabricant D. G., Laine S., Norris M. A., Jogee S., Lepore N., Hough L. E., Weinberg-Wolf J., 2013, ApJ, 777, 42: http://adsabs.harvard.edu/abs/2013ApJ...777...42K

Koopmann R. A., Giovanelli R., Haynes M. P., Kent B. R., Balonek T. J., Brosch N., Higdon J. L., Salzer J. J., Spector O., ApJ, 682, L85: http://adsabs.harvard.edu/abs/2008ApJ...682L..85K

McIntyre T. P., Minchin R. F., Momjian E., Henning P. A., Kaur A., Parton B., 2011, ApJ, 739, L26: http://adsabs.harvard.edu/abs/2011ApJ...739L..26M

Martin A. M., Papastergis E., Giovanelli R., Haynes M. P., Springob C. M., Stierwalt S., 2010, ApJ, 723, 1359: http://adsabs.harvard.edu/abs/2010ApJ...723.1359M

Minchin R. F., Momjian E., Auld R., Davies J. I., Valls-Gabaud D., Karachentsev I. D., Henning P. A., O'Neil K. L., Schneider S., Smith M. W. L., Stage M. D., Taylor R., van Driel W., 2010, AJ, 140, 1003: http://adsabs.harvard.edu/abs/2010AJ....140.1093M

Papastergis E., Giovanelli R., Haynes M., Shankar F., 2014, A&A, submitted: http://arxiv.org/abs/1407.4665

Spitler L., et al., ApJ, 790, 101: http://adsabs.harvard.edu/abs/2014ApJ...790..101S

Springob C. M., Masters K. L., Haynes M. P., Giovanelli R., Marinoni C., 2007, ApJS, 172, 599: http://adsabs.harvard.edu/abs/2007ApJS..172..599S

Taylor R., Minchin R. F., Herbst H., Smith R., 2014a, MNRAS, 442, L46: http://adsabs.harvard.edu/abs/2014MNRAS.442L..46T

Taylor R., Minchin R. F., Herbst H., Davies J. I., Rodriguez R., Vazquez C., 2014b, MNRAS, 443, 2634: http://adsabs.harvard.edu/abs/2014MNRAS.443.2634T

Taylor R., Davies J. I., Auld R., Minchin R. F., Smith R., 2013, MNRAS, 428, 459: http://adsabs.harvard.edu/abs/2013MNRAS.428..459T

Taylor R., Davies J. I., Auld R., Minchin R., 2012, MNRAS, 423, 787: http://adsabs.harvard.edu/abs/2012MNRAS.423..787T