The ALFALFA Census of Gas-Bearing Galaxies at z=0

The Arecibo Legacy Fast ALFA (ALFALFA) Survey

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For the ALFALFA team

Cargese
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$\Omega_{\text{baryons}} = 0.045 \pm 0.004 \sim (1/6) \Omega_{\text{matter}}$

Coronal + diffuse IG gas $\sim 0.037$

Stars $\sim 0.003$

Cluster IGM $\sim 0.002$

Cold Gas $\sim 0.0008$ ($\sim 2/3$ atomic)

HI contributes a piffling fraction of cosmic matter in baryons

HI: a different view

Fukugita & Peebles 2004
HI?? Who cares??

\[ \Omega_{\text{baryons}} = 0.045 +/- 0.004 \sim (1/6) \Omega_{\text{matter}} \]

Coronal + diffuse IG gas \sim 0.037

Cluster IGM \sim 0.002

Stars \sim 0.003

Cold Gas \sim 0.0008 (~2/3 atomic)

HI contributes a piffling fraction of cosmic matter in baryons

Fukugita & Peebles 2004

HI: a different view

1. Virtually all star-forming galaxies contain HI
2. Many dwarf galaxies have \( M_{\text{HI}} > M_\ast \)
Why do we care?

• Easy to detect, simple physics → cold gas mass
• Good index of star formation fertility → future SF
• Comparative HI content => HI deficiency in clusters
• Excellent tracer of host dynamics → dark matter
• Useful Cosmology tool → TF relation, HIMF, BAO
• Interaction/tidal/merger tracer
• Can be dominant baryon form in low mass galaxies
ALFA is not a car...

It is a radio "camera"

Arecibo L-band Feed Array (ALFA)
An extragalactic spectral line survey

To cover 7000 sq deg of high galactic latitude sky

1345-1435 MHz (-2000 to +17500 km/s for HI line)

5 km/s resolution

2-pass, drift mode (total int. time per beam ~ 40 sec)

~2.3 mJy rms (per spectral pixel)

\[ M_{\text{HI}} \approx 10^5 M_\odot \text{in LG, } \approx 10^7 M_\odot \text{at Virgo} \]

4400 hrs of telescope time, 5+ years

Highly efficient: 99% open shutter

Oversees acquisition of TOGS (galactic HI) data

Started Feb 2005; as of Mar 12, 97% complete (779 runs)

ALFALFA, a Legacy Survey

The Arecibo Legacy Fast ALFA Survey

Main People Science Schedule Data Documentation Links Publications Undergrads

Non-experts News/Events Observing/Data Team

Overview

Check out the ALFALFA blog!

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. The lowest mass objects will only be detected nearby; 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...
The ALFALFA team: An open collaboration

Heavy student involvement:
- 7 PhDs to date
- 10 PhDs underway
- Dozens of undergrad thesis/summer projects

50 papers in refereed literature (appeared or submitted) with lots more on the way!
ALFA beams are 3.3 x 3.8

Almost z fixed azimuth drift mode

2nd pass offset from the first to give 1.05 ` sampling

ALFALFA survey strategy:
Keep it simple!

“Minimum intrusion”
99% open shutter time
ALFALFA observing status Mar 2012

- 779 observing runs, 4300 hours, most remotely
- 20,000 “good” detections in 50% of final area

“fall”

We hope to complete the legacy survey observations in Fall 2012.

ALFALFA also bears full responsibility for the observing for the commensal galactic HI program “TOGS” (Mary Putman, PI)

Followup “pointed” observations with LBW target most enigmatic objects (dark galaxies, OHM candidates, etc).

“spring”
ALFALFA: A 2\textsuperscript{nd} generation HI survey

- In comparison with opt/IR, the HI view is largely immature

- B.A. (Before ALFALFA), determinations of HIMF have:
  - been based only on few thousand objects
  - been strongly impacted by local large scale structure
  - included few objects with $\log M_{\text{HI}}/M_\odot < 8$
  - included few objects with $\log M_{\text{HI}}/M_\odot > 10$

- Nearly all star-forming galaxies contain HI
- At mid-low stellar masses, the gas fraction $M_{\text{HI}}/M_{\text{stars}}$ can be $> 1$.

ALFALFA:
- Designed to explore the HI mass function over a cosmologically significant volume with adequate statistics and dynamic range, roughly ~10X improvement over HIPASS.
- Fundamental aspect is Xcorrelation with other databases.
ALFALFA pipeline: “LOVEDATA”

- Developed in-house by faculty/grad students
- Designed for distributed desktop processing by “mortals”
  - Running at 40+ sites, Linux/MacOS
- IDL-based
- Datarate: 1GB/hour × 4400 hours
- Minimizes replication of full dataset (disk I/O slowest step)
- Both 2-D continuum map and 3-D line grid produced
  - Final astrometric and flux scaling tied to continuum sources in grid
- “Weights map” tracks missing data (RFI, dead beams etc)
- Source identification by matched filter algorithm
  - Final parameter extraction done by human
- Incorporates VO access to multiwavelength datasets/images
  - Most probably OC identified simultaneously
Why ALFALFA isn’t easy: RFI

- FAA radar
- galaxy
- harmonic
- MW HI
Flagging RFI: GPS NuDet
Continuum sources recorded
Mining ALFALFA

Signal extraction done in Fourier domain using matched filter algorithm (Saintonge 2007, AJ, 133, 2087)

HI flux density sensitivity depends on HI line width => but well-behaved

Amélie Saintonge (Cornell)
PhD thesis

Fabello+ 2010 MNRAS 411, 993

ALFALFA pipeline tracks RFI/continuum => Spectral stacking to dig deeper.

Silvia Fabello (MPA)
PhD thesis
Gridview: A creation of Brian Kent
Gridview: A creation of Brian Kent
Galcat: A creation of Brian Kent
Identifying Optical Counterparts

**ALFALFA** source centroids good to ~18” (depends on S/N)

**ALFALFA** catalogs include:
- the HI centroid position
- the position of the most probable OC
- OC’s SDSS PhotoObjID and SpecObjID (where applicable)

Of 15855 sources in α.40:
- 1013 have no OC
- 844 of those could be HVCs (or LG minihalos)
- 199 (<2%) extragalactic
- Of those, <50 are “isolated”

Haynes+ 2011 AJ 142, 170
ALFALFA Science Goals

1. **Census** of HI in the Local Universe over cosmologically significant volume

2. Determination of the faint end of the HI Mass Function and the abundance of low mass gas rich halos

3. **Environmental variation** in the HI Mass Function

4. Blind survey for HI tidal remnants

5. Determination of the HI Diameter Function

6. The low HI column density environment of galaxies

7. The nature of HVC’s around the MW (and beyond?)

8. HI absorbers and the link to Ly $\alpha$ absorbers

9. **OH Megamasers** at intermediate redshift $0.16 < z < 0.25$
HIPASS completeness limit
HIPASS detection limit
HIPASS bandwidth edge

ALFALFA covers adequate volume with adequate sensitivity
- 15000+ detections in 40% of final area
- 70% are "new"

In addition to sensitivity, bandwidth and velocity resolution, ALFALFA yields positions to < 20"
⇒ Identification of most probable optical counterpart (OC)

Continuum/RFI tracked
⇒ Allows stacking at arbitrary positions

\(\log_{10}(M_{HI}/M_\odot)\)

\(\alpha.40\) sample
Haynes+2011
AJ 142, 170

Virgo

FAA harmonic

FAA radar
- 7000 sqd of high galactic latitude sky with median cz ~8800 km/s
- Undersamples clusters but traces well the lower density regions
- Large overlapping areas with SDSS and GALEX
- Adds constraints on the gas to models of galaxy evolution

4° tile centered at +26°
The ALFALFA population

- Star-forming galaxies but not the red sequence

Shan Huang (Cornell) PhD thesis
Huang et al (2012b) submitted!
The ALFALFA population

- Although extinction is lower in HI selected galaxies, it is not negligible.

- HI selected galaxies are gas-rich, bluer, and have higher SFR and SSFRs but lower SFEs and metallicities than optically selected ones. Their gas depletion times (Roberts’ times) are longer.

- Nearly all star forming galaxies have HI

Shan Huang (Cornell) PhD thesis
Huang et al (2012a)
Huang et al (2012b) submitted
Ongoing deeper B,R band imaging of HI detections with no OC

Salzer, Adams
Dark galaxies

• In agreement with previous results, ALFALFA finds that fewer than 2% of (clearly extragalactic) HI sources cannot be identified with an optical counterpart.

• The majority of objects without OC’s are found near to galaxies with similar redshifts.

• There are few interesting cases to be confirmed (work in progress):
  • LSB or dark galaxies
  • OHMs with 0.16 < z < 0.25
  • Mystery lines?

The burden is always on us to prove that
(1) the signal is real and
(2) there is no OC
“Dark” object in a group

HI peak with no optical/marginal UV: almost dark?

Karen Waddell, KS, MH, RG (CU), Cannon (Macalester), Salzer (Indiana)
Left: $K_s$ (2.2 $\mu$m) image with 45” EVLA-D beam and centroid confidence intervals (red). The obvious IR/opt OC is a K or M star.
Right: Original ALFALFA spectrum. The HI source at 1378.2 MHz has been confirmed with AO/LBW, GBT and EVLA.
Lead: Jeremy Darling (Colorado)
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HIMF from ALFALFA: Good news for the SKA!

**Martin+ 2010 ApJ 723, 1359**
- Based on contiguous regions in Virgo vs anti-Virgo directions (35% of total)
- 10,119 Code 1 (“best”); cz < 15,000 km/s
- $\Omega_{HI} = 4.3 \pm 0.3 \times 10^{-4}$ (16% higher than HIPASS)

**HIPASS: Zwaan+ 2005**
- Did not sample low/high mass ends
- Issues of beam (15.5”) confusion
- Error bars are large!
  ⇒ Survey design must overcome cosmic variance and instrumental/selection bias

**ALFALFA is the first blind HI survey to cover adequate volume at both the low and high HI mass ends**

Ann Martin (Cornell) PhD thesis
The HI correlation function at z=0

The HI population is much less clustered on small scales, but follows the DM on large scales.


Important for interpretation of future evolution and intensity mapping experiments
Testing galaxy formation models

Manolis Papastergis
PhD thesis


ALFALFA

HIPASS also undercounted the massive (fast rotator) systems.
Testing galaxy formation models


• The ALFALFA Velocity Function VF maps nicely onto SDSS VF at moderate-high mass

• But, still a large discrepancy with theory at low W!

• Does HI trace halo $V_{\text{rot}}$?

Manolis Papastergis (Cornell) PhD thesis
ALFALFA & “missing satellites”?

• HIPASS result: no cosmologically significant population of HI-rich dark galaxies: ALFALFA agrees... but HIPASS $M_{HI} > 10^8 M_\odot$
  
• ALFALFA is specifically designed (wide area, high velocity resolution) to detect hundreds of objects with $M_{HI} < 10^{7.5} M_\odot$
  - Low HI mass
  - Narrow HI line width + exclude face-on objects
  - Will only be detected nearby

ALFALFA has already detected 50 objects with log $M_{HI} < 7.0$
and more than 15X as many with log $M_{HI} < 8.0$ as HIPASS

Next steps require:
  => Mapping the HI distribution and velocity field
  => Understand the stellar population => determining distances!
Baryon fractions as fn of halo mass

Hoeft et al 2006
Can small halos retain any baryons?

Ricotti (2009): Can gas accretion be reactivated at late z?

The cosmic baryon fraction is 0.16.
Transition dwarfs: Phoenix + Leo T

Young et al. 2006

Is Leo T a minihalo?

Ryan-Weber et al. 2007

$M_{HI} \sim 2.8 \times 10^5 \, M_\odot$

$M/L > 50$

$D = 420 \, \text{kpc}$
HVCs: an Intergalactic Population?

• Blitz et al (1999): “HVCs are large clouds, with typical diameters of 25 kpc, containing $3 \times 10^7$ solar of neutral gas and $3 \times 10^8$ solar of dark matter, falling towards [the barycenter of] the Local Group; altogether the HVCs contain $10^{10}$ solar of neutral gas.”

• Braun & Burton (1999): The “undisturbed” minihalos appear as Compact HVCs (CHVCs), which have typical sizes of 0.5 deg and FWHM linewidths 20-40 km/s

Problems:
• If HVCs (or CHVCs) are bona fide LG members, they should also exist in galaxy groups other than the LG: NOT SEEN

• Sternberg et al (2002) show that, in order to fit DM halo models to the CHVCs, their HI fluxes and angular sizes objects constrain them to be no farther than 150 kpc, else they famously violate the LCDM mass-concentration relation: CHVCs ARE TOO LARGE
We have found a subset of the HVC phenomenon that appears to be compatible with the LG minihalo hypothesis (Giovanelli+ 2010)

⇒ **much** smaller than the Blitz et al. and Braun&Burton CHVCs

\[ M_{\text{HI}} \sim 3 \times 10^5 \, M_\odot; \text{ size } \sim 0.7 \text{ kpc} \]

⇒ Do not violate astrophysical constraints (Sternberg+ 2002)

⇒ But, other interpretations possible but minihalo possibility still in play need distances!

On-going work (Adams, MH, RG et al.)

• Optimize signal extraction algorithm => ALFALFA CHVC catalog

  • HI mapping: HI distribution, dynamics
  • Look for the neutral core

• Distances:

  • TRGB (resolved CMDs)
  • \( H_\alpha \): ionized by galactic RF places lower limit
  • HST/COS abundances

Betsey Adams (Cornell) PhD thesis
Adams et al. (2012) in prep.
Leo P: A new LG galaxy

Left: EVLA-C HI contours superposed on WIYN image

Right: Original ALFALFA HI spectrum, LBW spectrum and EVLA-C spectrum

Giovanelli+ 2012 ApJL submitted
Rhode+ 2012 ApJL submitted

HI mass $4.7 \times 10^4 M_\odot$

$M_v$ -6.1

Stellar mass $1.9 \times 10^4 M_\odot$

$R_{HI}$ 120 pc

$M_{dy}(<R_{HI})$ $3.2 \times 10^6 M_\odot$
Perhaps the most surprising result is the richness of the high HI mass population.

At highest HI mass, we predict 10X more than HIPASS

Ann Martin
PhD thesis
**HIghMass:**
High HI mass, gas-rich galaxies at z~0

ALFALFA detects a rich population with log $M_{HI} > 10$.

- Candidates to migrate from BC to RS but not yet reached phase of significant SF?
- Alternative mode of (late) accretion?
- => higher than average spin parameter?

Preliminary; Chengalur+

Huang (PhD: GALEX, Herschel, Hα, SED-fitting)
Adams (PhD: GMRT/WSRT)
Hallenbeck (PhD: EVLA, CARMA)
High gas fraction => High spin

$$\lambda = \frac{\sqrt{2} V_{rot}^2 R_d}{GM_{halo}}.$$ 

$$\lambda = 21.8 \frac{R_d [\text{kpc}]}{(V_{rot} [\text{km s}^{-1}])^{3/2}}.$$
• ALFALFA is the first blind HI survey to sample a cosmologically significant volume at z=0
  • Robust determination of HIMF and VF at z=0
  • HI-selected galaxies are weakly clustered on small scales but trace the large scale structure
  • Work environmental variations on-going

• There are **no** “dark” HI galaxies with HI masses > 10^9 M_☉

• ALFALFA sources provide the means to determine the baryon fraction as fn. of halo mass and test models of dropoff at M_{halo} ~ 10^9 M_☉

• ALFALFA identifies a set of gas-rich Local Group “minihalo” candidates; evidence which will refute or confirm that hypothesis is being sought.

• ALFALFA detects a previously-unrecognized population of very high HI mass galaxies with HI masses > 10^{10} M_☉; in some, cool gas contributes the dominant form of baryons. => Good news for SKA!

• There is more ALFALFA to be harvested!