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Published in:
Dwarf Galaxies

DOI:
10.1017/S174392131800710X

Dwarf Galaxies: From the Deep Universe to the Present
Proceedings IAU Symposium No. 344, 2019
K. B. W. McQuinn & S. Stierwalt, eds.

doi:10.1017/S174392131800710X

The dwarf galaxy population as revealed by ALFALFA

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Abstract. The combination of sensitivity and large sky coverage of the ALFALFA HI survey has enabled the detection of difficult to observe low mass galaxies in large numbers, including dwarf galaxies overlooked in optical surveys. Three different, but connected, studies of dwarf galaxies from the ALFALFA survey are of particular interest: SHIELD (Survey of HI in Extremely Low-mass Dwarfs), candidate gas-rich ultra-faint dwarf galaxies, and the (Almost) Dark population. SHIELD is a systematic multiwavelength study of all dwarf galaxies from ALFALFA with M_{HI} $< 10^{7.2}$ $M_{\odot}$ and clear optical counterparts. Candidate gas-rich ultra-faint dwarf galaxies extend the dwarf galaxy population to even lower masses. These galaxies are identified as isolated HI clouds with no discernible optical counterpart but subsequent observations reveal that some are extremely faint, gas-dominated galaxies. Leo P, discovered first as an HI detection, and then found to be an actively star-forming galaxy, bridges the gap between these candidate galaxies and the SHIELD sample. The (Almost) Dark sample consists of galaxies whose optical counterparts are overlooked in current optical surveys but which are clear detections in ALFALFA. This sample includes field gas-rich ultra-diffuse galaxies. Coma P, with a peak surface brightness of only $\sim$26.4 mag arcsec^{-2} in g', demonstrates the sort of extreme low surface brightness galaxy that can be discovered in an HI survey.

Keywords. galaxies: dwarf — galaxies: ISM — radio lines: galaxies — surveys

1. Introduction

The Arecibo Legacy Fast ALFA (ALFALFA) survey is an extragalactic survey of neutral hydrogen (H I) that covered nearly 7000 square degrees of sky over the redshift range $-2000 < cz < 18000$ km s^{-1}. The final ALFALFA source catalog has over 31000 high quality extragalactic H I detections, the vast majority (>98%) of which have a readily identifiable optical counterpart (Haynes *et al.* 2018).

The sensitivity of the ALFALFA survey allows the H I mass function (HIMF) to be robustly populated at low masses. There are ∼2500 galaxies with baryonic masses ($M_\star + M_{gas}$) below 10^9 $M_\odot$, and ∼400 galaxies with baryonic masses below 10^8 $M_\odot$. This large population of dwarf galaxies allows the identification of unique populations that hold vital clues for addressing galaxy formation models and tensions with cosmological simulations (e.g., Brooks, Navarro, this volume). In the following sections, we describe three key populations identified in the ALFALFA survey: the lowest-mass H I-bearing bona-fide dwarf galaxies (Section 2), candidate gas-bearing ultra-faint dwarf galaxies in the Local Group (Section 3), and extreme low surface-brightness galaxies (Section 4).

2. SHIELD

The Survey of H I in Extremely Low-mass Dwarfs (SHIELD) is a study of all dwarf galaxies detected in ALFALFA with $M_{HI} < 1.6 \times 10^7$ $M_\odot$ and clear optical counterparts. This sample consists of 82 dwarf galaxies with flow model distances at $D < 11.5$ Mpc. All galaxies have higher resolution H I from VLA/D observations, and roughly half the sample has secure distances and coarse star formation histories from *HST* imaging (McQuinn *et al.* 2014, McQuinn *et al.* 2015, Gordon *et al.* in prep.). Ongoing efforts include obtaining *HST* observations to measure secure distances for all sources, obtaining higher resolution VLA data, and more.

The first twelve SHIELD galaxies have a comprehensive multi-wavelength dataset and have been studied in detail. The star formation in these galaxies broadly breaks into three categories, separated by H I mass and column density (the highest mass systems also have the highest H I column densities). In the highest mass galaxies, star formation is well correlated with peaks of H I emission; in systems with moderate H I column densities, there is a moderate correlation; and in the lowest mass galaxies with the lowest peak H I column densities, the star formation is clearly offset from the H I peaks (Teich *et al.* 2016). The baryonic Tully-Fisher relation (BTFR) is an important scaling relation connecting the baryonic mass of a galaxy to its rotation velocity, or total dynamical mass. Examination of the kinematics of the SHIELD galaxies reveals that they extend the BTFR to the lowest rotation velocities (McNichols *et al.* 2016 see Figure 1).

Individual galaxies within the SHIELD sample have also proven to be intriguing objects in their own right. This includes AGC198691 (Leoncino) one of the most metal poor star-forming galaxies known (Hirschauer *et al.* 2016).

3. Ultra-compact high velocity clouds

Recent years have seen the discovery of 45 new dwarf galaxies around the Milky Way (e.g., Newton *et al.* 2018), giving new urgency to the drive to connect the smallest dwarf galaxies to small scale structure predicted in ΛCDM. The discovery of Leo P highlighted that low luminosity dwarf galaxies may be best identified by H I, especially if they lack the ongoing star formation to stand out in existing optical data (Giovanelli *et al.* 2013).

Ultra-compact high velocity clouds (UCHVCs) identified within the ALFALFA survey are good candidates to represent low-luminosity galaxies in and around the Local Group (Adams *et al.* 2013). Subsequent higher resolution H I imaging with WSRT reveals that some of the UCHVCs appear to have gas distributed in a rotating disk, making them excellent galaxy candidates (e.g., Adams *et al.* 2016). Deep ground-based optical imaging

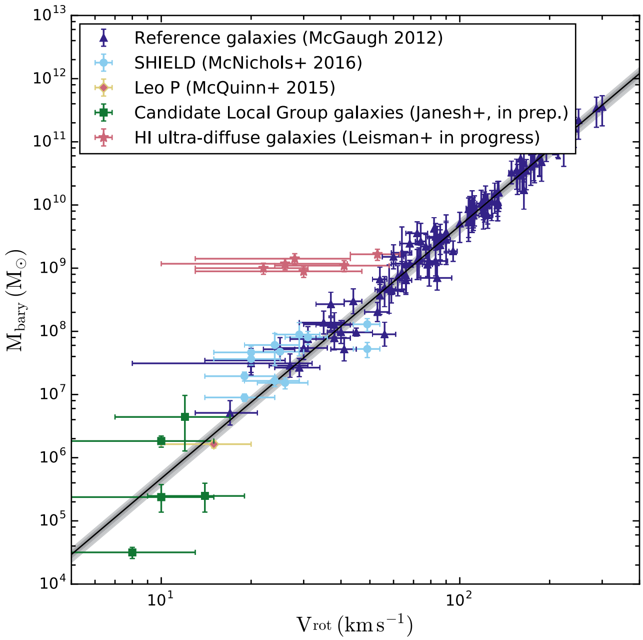

Figure 1. Dwarf galaxy populations identified by ALFALFA on the baryonic Tully-Fisher relation (BTFR) defined by McGaugh (2012). The SHIELD galaxies extend the BTFR to lower rotational velocities. The candidate galaxies (UCHVCs) appear to lie on the relation at the lowest rotational velocities. The H I-bearing ultra-diffuse galaxies appear to lie off the relation.

with WIYN/pODI reveals that several UCHVCs have potential stellar counterparts (e.g., Janesh *et al.* 2017, Janesh *et al.*, in prep.). These objects are similar to the known dwarf galaxies around the Milky Way but are extremely gas-rich. Intriguingly, the UCHVCs with stellar counterparts (and hence distances) appear to lie on the BTFR, extending it to a mass regime below that of the SHIELD galaxies (see Figure 1).

4. (Almost) Dark galaxies

The identification in clusters of large numbers of extended, low surface brightness (LSB) galaxies that have been overlooked in previous surveys has reinvigorated interest in the (optical) low surface brightness universe (e.g., van Dokkum *et al.* 2015). Termed ultra-diffuse galaxies for their large sizes and LSB nature, the large numbers of these galaxies may impact our understanding of galaxy formation. The large population of this galaxy class was originally recognized in the cluster environment, but in order to understand the formation and evolution of this galaxy population, it is vital to connect the cluster population to a field progenitor population. A well-known method for finding LSB galaxies in the field is to search for their H I component. Within the ALFALFA survey, extreme LSB galaxies are termed (Almost) Dark galaxies as their optical counterparts are not immediately apparent in the best optical imaging available (typically SDSS) when they were identified. Leisman *et al.* (2017) identified a sample of 115 H I bearing galaxies within the 70% complete ALFALFA survey that meet the optical definition (size and surface brightness) of ultra-diffuse galaxies. In contrast to the cluster population, these field galaxies are bluer and have patchier morphologies. They also appear to have narrower velocity widths than the general ALFALFA population, which implies higher spin parameters, in line with the formation model of Amorisco & Loeb (2016). Higher resolution H I imaging, where the inclination can be measured, seems to uphold this finding that the H I-bearing UDGs have low rotation velocities for their baryonic mass (Leisman *et al.*, in prep.; see Figure 1), but further work is needed to conclusively show this.

The (Almost) Dark population includes LSB galaxies that do not meet the definition of an UDG but still challenge our understanding of galaxy formation. One intriguing example is Coma P. This galaxy is extremely low surface brightness – it was not visible at all in SDSS imaging but does have a FUV GALEX counterpart. Subsequent deep optical imaging with WIYN/pODI revealed a stellar counterpart with a peak of 26.4 mag arcsec^{-2} in g' (Janowiecki *et al.* 2015). This galaxy is extremely gas dominated, with an H I-to-stellar mass ratio of 81, an order of magnitude larger than values typically considered to be extremely gas-rich (Ball *et al.* 2018).

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