THE SURVEY OF H I IN EXTREMELY LOW-MASS DWARFS (SHIELD)

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ABSTRACT

We present first results from the Survey of H i in Extremely Low-mass Dwarfs (SHIELD), a multi-configuration Expanded Very Large Array (EVLA) study of the neutral gas contents and dynamics of galaxies with H i masses in the 10^6–10^7 M⊙ range detected by the Arecibo Legacy Fast ALFA (ALFALFA) survey. We describe the survey motivation and concept demonstration using Very Large Array imaging of six low-mass galaxies detected in early ALFALFA data products. We then describe the primary scientific goals of SHIELD and present preliminary EVLA and WIYN 3.5 m imaging of the 12 SHIELD galaxies. With only a few exceptions, the neutral gas distributions of these extremely low-mass galaxies are centrally concentrated. In only one system have we detected H i column densities higher than 10^{21} cm^{-2}. Despite this, the stellar populations of all of these systems are dominated by blue stars. Further, we find ongoing star formation as traced by Hα emission in 10 of the 11 galaxies with Hα imaging obtained to date. Taken together these results suggest that extremely low-mass galaxies are forming stars in conditions different from those found in more massive systems. While detailed dynamical analysis requires the completion of data acquisition, the most well-resolved system is amenable to meaningful position–velocity analysis. For AGC 749237, we find well-ordered rotation of 30 km s^{-1} at ~40′′ distance from the dynamical center. At the adopted distance of 3.2 Mpc, this implies the presence of a ≥1 × 10^8 M⊙ dark matter halo and a baryon fraction ≲0.1.

Key words: galaxies: dwarf – galaxies: evolution – galaxies: irregular

1. POPULATING THE COSMOLOGICALLY IMPORTANT FAINT END OF THE H I MASS FUNCTION: ALFALFA

One of the major accomplishments of the Arecibo Legacy Fast ALFA (ALFALFA) survey (Giovanelli et al. 2005) is the detection of hundreds of galaxies with H i masses <10^8 M⊙. As its design intended, ALFALFA provides the first statistically robust sampling of the faint end of the H i mass function (M_{H i} < 10^8 M⊙; Martin et al. 2010). The sensitivity and resolution of ALFALFA have now produced a collection of dozens of galaxies outside the Local Group with H i masses below 10^7 M⊙. Each of these objects has been cross-correlated with optical catalogs; these extremely low-mass dwarfs are among the lowest-mass, gas-bearing systems that harbor detectable stellar populations in the local universe.

Over the past few decades, the kinematics and stellar populations of dwarf galaxies have been explored in detail, both in targeted investigations and in dedicated surveys. These studies have focused largely (though not exclusively) on systems that populate the H i mass function above 10^8 M⊙. Three prominent surveys to this end are the FIGGS (Begum et al. 2008), LITTLE THINGS (Hunter et al. 2007), and VLA-ANGST (Ott et al. 2010) programs. While the selection and sample criteria vary from one program to the next (including some overlap), we note that the median H i masses are 8.5 × 10^7 M⊙, 2.7 × 10^7 M⊙, and 2.3 × 10^7 M⊙ for LITTLE THINGS, FIGGS, and VLA-ANGST, respectively. These surveys have revealed many new insights into low-mass galaxies, including the characteristics of 21 systems (4, 8, and 9 in LITTLE THINGS, FIGGS, and VLA-ANGST, respectively) with M_{H i} < 10^7 M⊙.

The existence of such gas-rich galaxies with very shallow potential wells poses interesting puzzles for the Λ CDM paradigm. Ram pressure should easily strip their interstellar medium (ISM) via encounters with coronal gas if they venture within the virial radius of nearby giant galaxies or clusters (e.g., Lewis et al. 2002; Grebel et al. 2003). Star formation (SF) activates feedback mechanisms that result in gas loss via superwinds; simulations have predicted that galaxies with gas masses M_{H i} < 10^7 M⊙ are highly susceptible to mass loss via starburst-driven superwinds (e.g., Mac Low & Ferrara 1999; Ferrara & Tolstoy 2000), and observational results support this scenario (e.g., Martin et al. 2002; Ott et al. 2005). The metagalactic UV radiation field inhibits gas accretion and cooling most severely in low-mass halos (Rees 1986; Bulbul & Rees 1992; Benson et al. 2002; Hoef et al. 2006). A hot intergalactic medium should vaporize a small, unshielded cold gas mass within less than a Hubble time (Benson 2008), which would otherwise give rise to these low-mass systems without an external source of gas.

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et al. 2002). And yet, despite these myriad destruction mechanisms, objects such as Leo T ($M_{\text{HI}} \lesssim 10^5 M_{\odot}$, SF within the last few hundred Myr; Irwin et al. 2007) exist. The survival of such systems seems to depend on both the protection provided by a shielding envelope of warm, ionized gas (Sternberg et al. 2002), and on environment, i.e., they are found in locations removed from the immediate vicinity of dense coronal gas. For halo masses below $\sim 10^9 M_{\odot}$, the baryon fraction ($f_b$) of dwarf systems is predicted to fall below the cosmic value of $f_b \sim 0.16$ (Hoeft et al. 2006; McGaugh et al. 2010). Most of the remaining baryons within a given system are in the form of a warm, ionized phase that is difficult to detect. In the central regions of these halos, a small fraction of the gas is predicted to be neutral and thus capable of condensing into stars.

The extremely low-mass galaxies observed in the local universe by ALFALFA have not been detected in large enough numbers to solve the “missing satellite problem” (Klypin et al. 1999). However, these systems are nonetheless critical for models of cosmological structure formation for two primary reasons. First, an understanding of their characteristics as the survivors of the structure formation process provides constraints on the aforementioned destruction mechanisms acting on low-mass halos. Second, these systems bridge the observational gap between the well-studied and comparatively high-mass ($10^4 M_{\odot} < M_{\text{HI}} < 10^8 M_{\odot}$) dwarfs of the local universe and the extremely low-mass ultra-faint dwarf companions of the Milky Way (e.g., Willman 1, with $M_{\text{HI}} \simeq 5 \times 10^5 M_{\odot}$; Willman et al. 2005; Martin et al. 2007). To probe this transition, we have thus undertaken a multiwavelength study of very low mass ($M_{\text{HI}} \lesssim 10^4 M_{\odot}$) dwarfs across the range of halo masses over which the transition from $f_b \simeq 0.16$ to $< 0.01$ takes place (see Hoeft et al. 2006; McGaugh et al. 2010). This Letter presents first results from optical and radio imaging of extremely low-mass galaxies that form part of this observing campaign.

### 2. Exploring the Faint End of the H I Mass Function: SHIELD

The measurement of the total halo masses of the extremely low-mass galaxies detected by ALFALFA requires deep, high spatial and spectral resolution H I observations in order to characterize the systems’ rotation curves. This measurement is the primary motivation for The Survey of H I in Extremely Low-Mass Dwarfs (SHIELD). We now describe the strategy, goals, and present status of SHIELD.

Our investigation began with a series of concept demonstration observations of six low-mass systems detected in early ALFALFA observations (see “Concept Demonstration Targets” in Table 1). These systems were observed with the Very Large Array (VLA)\(^{10}\) for programs AC963 (PI: Cannon) and AS883 (PI: Saintonge) during the VLA → EVLA transition. The data reduction and imaging were performed with the Astronomical

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#### Table 1

| AGC\(^a\) | $\alpha$ (J2000) | $\delta$ (J2000) | Distance (Mpc) | $M_1$ (mag) | $(a-r)$ (mag) | $M_{\text{HI}}$ (mag) | $(B-V)$ (mag) | $\% Z_\odot$\(^b\) | $V_{21}$ (km s$^{-1}$) | $W_{21}$ (km s$^{-1}$) | $\log (M_{\text{HI}})$ (M$\odot$) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 100062 | 00:09:52.8 | 15:43:58 | 12.7\(^\ddagger\) | $-15.02$ | $1.02 \pm 0.02$ | N/A | N/A | N/A | 869 | 45 | 7.82 |
| 101772 | 00:11:08.2 | 14:44:08 | 11.7\(^\ddagger\) | $-13.64$ | $0.98 \pm 0.06$ | N/A | N/A | N/A | 802 | 37 | 7.54 |
| 111945 | 01:44:42.7 | 27:17:18 | 6.3\(^d\) | $-11.88$ | $3.35 \pm 1.26$ | N/A | N/A | N/A | 420 | 38 | 7.28 |
| 321203 | 22:13:03.3 | 28:04:28 | 16.4\(^d\) | $-14.20$ | $0.98 \pm 0.04$ | N/A | N/A | N/A | 14% | 983 | 62 | 7.83 |
| 321307 | 22:14:04.4 | 25:41:08 | 18.7\(^d\) | $-13.88$ | $1.24 \pm 0.07$ | N/A | N/A | N/A | 1152 | 60 | 7.96 |
| 332939 | 23:08:16.0 | 31:53:57 | 11.4\(^d\) | $-13.67$ | $0.69 \pm 0.05$ | N/A | N/A | N/A | 692 | 41 | 7.74 |

#### Notes:

\(^a\) Arecibo General Catalog.

\(^b\) Assuming the solar oxygen abundance from Asplund et al. (2009).

\(^d\) Derived using the parametric multiaffector flow model developed by Masters (2005); see further discussion in Martin et al. (2010).

\(^\ddagger\) Magnitudes and colors uncertain due to SDSS shredding issues.

\(^\text{WVY}\) WIYN 3.5 m imaging acquired in Fall 2010.

\(^\text{WVY}\) WIYN 3.5 m imaging acquired in Spring 2011.

\(^\text{WVY}\) WIYN 3.5 m imaging acquired in Fall 2010.

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\(^{1}\) AGC 174585 is outside the SDSS footprint; an absolute calibration of the WIYN 3.5 m observations awaits subsequent re-imaging.
The Astronomical Image Processing System (AIPS\textsuperscript{11}); reductions proceeded normally, with modifications as necessary for aliased baselines. The calibrated data sets were imaged to the rms level using both natural (ROBUST = 5) and robust (ROBUST = 0.5) weighting, and then smoothed to a common circular beam size of 20′. The two approaches resulted in flux integrals that differed by $\lesssim 10\%$ for most systems, and we thus show only the robust weighted images in this work.

Figure 1 shows Sloan Digital Sky Survey (SDSS) three-color images of the six precursor galaxies. It is immediately obvious that the high surface brightness stellar populations are dominated by blue stars. This is confirmed by the SDSS photometry presented in Table 1. The weighted mean ($u-r$) color for the six precursor systems is $(u-r) = 0.99 \pm 0.02$. This can be compared with $(u-r) \approx 1.3$, the mean SDSS color for all ALFALFA galaxies with $\log(M_{\text{HI}}) < 7.7$ (S. Huang et al. 2011, in preparation).

Figure 1 compares the stellar and neutral gas distributions; overlaid on each panel are H$\text{I}$ column density contours at the (0.5, 1, 2, 4) $\times 10^{20}$ cm$^{-2}$ levels. The neutral gas distributions are centrally concentrated and spatially coincident with the blue stellar populations. All systems show peak column densities below the canonical SF surface density threshold of $n_{\text{HII}} = 10^{21}$ cm$^{-2}$ (Skillman 1987; Kennicutt 1998). While the spectral resolution of these images are sufficient to resolve the H$\text{I}$ profiles derived from ALFALFA, the H$\text{I}$ distributions are only slightly larger than the synthesized beam size (20′). Although these six systems have H$\text{I}$ masses above $10^7 M_{\odot}$ (see Table 1), these precursor observations nonetheless demonstrate the scientific potential of a coordinated observing campaign using the EVLA (see Perley et al. 2011 for a description of the EVLA project) to explore the low-mass galaxies detected by ALFALFA.

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We thus initiated SHIELD (OSRO Program 10B-187, PI: Cannon; time allocation of 180 hr), a multi-configuration study of the neutral ISM of 12 extremely low-mass systems. The sample members were selected from the $>11,000$ ALFALFA-detected galaxies to date on the basis of H$\text{I}$ mass ($M_{\text{HI}} \leq 1.6 \times 10^9 M_{\odot}$) and line width (full width at 50% of peak $< 65$ km s$^{-1}$ from ALFALFA); the latter discriminates against massive but H$\text{I}$-poor galaxies and identifies the truly low mass galaxies. The median distance, H$\text{I}$ mass, and H$\text{I}$ line width are 5.7 Mpc, $4.7 \times 10^9 M_{\odot}$, and 25 km s$^{-1}$, respectively. Our observational strategy (9, 4, and 2 hr per source in the B, C, and D arrays, respectively, with typical calibration overheads of 25%) achieves high spatial ($\sim 6′$ synthesized beam at full resolution) and spectral resolution ($\sim 0.82$ km s$^{-1}$ ch$^{-1}$), while retaining sensitivity to extended structure. When data acquisition is complete, the 5σ (per channel) column density sensitivity will be $n_{\text{HI}} > 10^{19}$ cm$^{-2}$ and $>2.3 \times 10^{20}$ cm$^{-2}$ at low and high spatial resolutions, respectively; the realized column density sensitivities will be higher because the line widths are larger than the channel spacing (see Table 1). The WIDAR correlator is used to provide a single 1 MHz sub-band with 2 polarization products and 256 channels each, covering 211 km s$^{-1}$ of frequency space at 3.906 kHz ch$^{-1}$. Data acquisition for SHIELD began in 2010 October. The images presented here use only the data acquired in the C configuration; the reduction techniques are standard, and the same imaging techniques are used for the SHIELD galaxies as described above for the precursor galaxies. The rms

\textsuperscript{11} The Astronomical Image Processing System (AIPS) has been developed by the NRAO.
noise values in the robust weighted cubes range from 0.8 to 1.0 mJy Bm$^{-1}$.

Figures 2–4 present comparisons of the optical and HI properties of all 12 galaxies using the C-configuration data sets only. The optical images were acquired with the WIYN$^{12}$ 3.5 m telescope and the Mini-Mosaic camera during two observing runs (2010 October and 2011 March). The Fall images (see Table 1) were obtained during superior observing conditions ($\sim 0.4$ FWHM seeing); the Spring images (see Table 1) were obtained during average observing conditions ($\gtrsim 1''$ FWHM seeing). Broadband Johnson–Cousins ($B, V, R$) filters, and a narrowband H$\alpha$ filter, were used. Standard reduction strategies were applied. The images are first cosmic ray rejected, aligned and combined. The broad- and narrowband images are then smoothed to a common point-spread function size and flux scaled to remove the continuum from the narrowband image.

$^{12}$The WIYN Observatory is a joint facility of the University of Wisconsin–Madison, Indiana University, Yale University, and the National Optical Astronomy Observatories.

Figure 2. WIYN 3.5 m three-color (BVR) and continuum-subtracted H$\alpha$ images of five SHIELD galaxies; AGC 748778 is an H$\alpha$ non-detection, while cloud cover compromised the H$\alpha$ image of AGC 749241 and the $B$ and $V$ images of AGC 174585 (hence only the $R$-band image is shown). EVLA HI column density contours are overlaid at the (0.5, 1, 2, 4, 8) $\times 10^{21}$ cm$^{-2}$ levels. The beam size is 20'' in each panel; note that the fields of view are tailored to each galaxy to display the most detail in the stellar populations, and thus the beam sizes are best assessed using the coordinate axes. Note the remarkably blue stellar populations, low surface density neutral gas, and ongoing SF in each of these systems.

Figure 3. Same as Figure 2, for four more SHIELD galaxies.
Figure 4. Same as Figure 2, for three more SHIELD galaxies. The bottom panels show the H\textsubscript{i} distribution and kinematics of the most highly resolved system, AGC 749237. (a) Color-coded isovelocity contours between 325 and 370 km s\textsuperscript{-1} in intervals of 3 km s\textsuperscript{-1} per contour. The position of the H\textsubscript{i} major-axis position–velocity cut (position angle 246\textdegree 7, measured east of north) is indicated by the white arrow. The 20\arcsec beam size is shown at the lower right. (b) The resulting position–velocity diagram; the rotation is almost perfectly solid body over the inner 40\arcsec (620 pc at the adopted distance of 3.2 Mpc).
Finally, standard photometry routines are applied, using observations of photometric standard stars acquired during the same observing session. We estimate the photometric accuracies of the Fall and Spring images to be better than 2% and 4%, respectively.

Table 1 compiles the absolute $B$ magnitudes and $(B - V)$ colors of 11 of the 12 SHIELD galaxies; an absolute calibration of the images of AGC 174585 (which is outside the SDSS footprint) was not attained. Similar to the precursor systems shown in Figure 1, the optical appearances of the 12 galaxies shown in Figures 2–4 are each dominated by blue stars (note that only the $R$-band image of AGC 174585 is shown, due to two of the images being affected by cloud cover). The weighted mean $(B - V)$ color is $0.43 \pm 0.01$; this compares well with the typical $(B - V) = 0.42 \pm 0.05$ found for local star-forming dIrr galaxies (van Zee et al. 1997; van Zee 2000). Similarly, the weighted mean $(u - r)$ color for the SHIELD galaxies is $1.25 \pm 0.02$; these systems are on average slightly redder than the precursor objects, though still consistent with the results of S. Huang et al. (2011, in preparation).

SHIELD is a systematic investigation of a sample of galaxies with $H_\alpha$ masses below $10^7 M_\odot$ outside the Local Group. Using our EVLA data sets, we are focusing on three primary goals. First, what properties change between mini-halos ($H_\alpha$ clouds without optical counterparts; see Giovanelli et al. 2010), very outermost regions of the disks. Extended structure, which we will exploit to study gas in the baryonic fraction throughout the disks. Equally important is the inner regions of these galaxies and to infer the dark-to-luminous mass ratio of the precursor objects, though still consistent with the results of S. Huang et al. (2011, in preparation).

Second, what fraction of the mass in these low-mass dwarfs is baryonic? When data acquisition is complete, our EVLA observing campaign will allow us to study the ISM kinematics on spatial scales of order 200 pc in the galaxies in our sample (assuming a 6" beam and a maximum distance of ∼8 Mpc). These data will allow us to extract detailed rotation curves in the inner regions of these galaxies and to infer the dark-to-baryonic fraction throughout the disks. Equally important is the sensitivity of the combined EVLA + Arecibo data sets to extended structure, which we will exploit to study gas in the outermost regions of the disks.

Third, is the character of the SF process different in very low-mass galaxies? These systems have retained $H_\alpha$ mass reservoirs of $10^6$–$10^7 M_\odot$ over a Hubble time; they are apparently evolving in relative quiescence and are exceedingly inefficient at converting their interstellar gas into stars. These clues suggest that the SF law may in fact deviate significantly from the canonical Schmidt–Kennicutt prescription derived for more massive systems (Skillman 1987; Kennicutt 1998).

3. PRELIMINARY RESULTS

While data acquisition for SHIELD is ongoing, we are able to draw conclusions about various intriguing properties of these extremely low-mass galaxies using the C configuration images alone. We discuss three results in turn below. First, with only one exception (AGC 111977), the $H_\alpha$ distributions of the SHIELD galaxies are centrally concentrated at 20′ resolution. In only one case (AGC 110482) does the observed $H_\alpha$ column density reach the $10^{21}$ cm$^{-2}$ level; however, we expect that higher-resolution imaging will localize regions of larger column densities (see, e.g., the discussion of beam smearing effects in Begum et al. 2008). The SHIELD galaxies appear to have gas surface densities comparable to those in other nearby galaxies with similar $H_\alpha$ masses (e.g., all of the galaxies with $M_{H_\alpha} < 10^6 M_\odot$ in Begum et al. 2008 have peak $n_{H_\alpha} < 10^{21}$ cm$^{-2}$).

Second, as discussed in detail by Begum et al. (2006) and Roychowdhury et al. (2009, Roychowdhury et al. 2011), the relationship between $H_\alpha$ column density and ongoing SF in low-mass galaxies is complex. Stochastic effects play an important role, and the overall process appears to be less efficient than in more massive galaxies. When taken at face value, the low integrated column densities of the SHIELD galaxies are not conducive to ongoing SF. And yet, the stellar populations of these systems are dominated by blue stars (as evidenced by the blue integrated colors in Table 1), and the majority of the galaxies show active SF as traced by $H\alpha$ emission (see Figures 2–4). Our WIYN 3.5 m imaging produced usable $H\alpha$ images of 11 systems (images of AGC 749241 were acquired but were compromised by cloud cover). Ten of these systems show high surface brightness $H\alpha$ emission; the only conclusive $H\alpha$ non-detection is AGC 748778. In most cases, $H\alpha$ emission is located in close proximity to the highest $H_\alpha$ column densities (but see the diffuse $H\alpha$ emission in the southern region of AGC 111977); however, as noted above, none of these columns exceeds the canonical SF surface density threshold of $10^{21}$ cm$^{-2}$. We note with interest that two of the six precursor systems (AGC 100062 and AGC 101772) have strong $H\alpha$ emission lines in their SDSS spectra.

Finally, the full SHIELD data sets will allow us to test our understanding of the dark matter contents of these low-mass galaxies and of $f_b$ within them. While detailed rotation curve analysis requires higher resolution B-configuration EVLA images, a few systems are already amenable to meaningful position–velocity analysis using the 20′ datacubes alone. Using AGC 749237 as an example (see the velocity field and position–velocity slice in Figure 4), we find solid-body rotation of 30 km s$^{-1}$ at a distance of ∼40′ from the dynamical center. We apply no inclination correction to this velocity; we note, however, that the optical inclination $i \geq 56°$, and thus the true rotational velocity may be higher by ∼20% or more. At the adopted (but uncertain) distance of 3.2 Mpc, this implies a dynamical mass $M_{dyn} \geq 1 \times 10^8 M_\odot$. Correcting for helium and molecular gas ($35\%$ of $M_{H_\alpha}$) and assuming equal masses of stars and gas, this implies $f_b \lesssim 0.1$. As expected, this low-mass galaxy follows the trends of $f_b$ at low dynamical masses in the models of Hoeflt et al. (2006) and McGaugh et al. (2010).

4. CONCLUSION

We have introduced SHIELD, a systematic investigation of a sample of galaxies with $H_\alpha$ masses below $10^7 M_\odot$ outside the Local Group. A primary goal of SHIELD and of ALFALFA is to characterize changes in fundamental galaxy properties as functions of total halo mass. The EVLA imaging described in this Letter is the centerpiece of a multiwavelength observing campaign designed to place these low-mass systems in an evolutionary context. When completed, the SHIELD data suite will offer a unique opportunity to study the fundamental properties of galaxies in a newly opened region of parameter space.
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