ALFALFA DISCOVERY OF THE NEARBY GAS-RICH DWARF GALAXY LEO P. I. H1 OBSERVATIONS

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ABSTRACT

The discovery of a previously unknown 21 cm H1 line source identified as an ultra-compact high velocity cloud in the ALFALFA survey is reported. The H1 detection is barely resolved by the Arecibo 305 m telescope ∼4′ beam and has a narrow H1 linewidth (half-power full width of 24 km s⁻¹). Further H1 observations at Arecibo and with the Very Large Array corroborate the ALFALFA H1 detection, provide an estimate of the H1 radius, ∼1’ at the 5 × 10¹⁹ cm⁻² isophote, and show the cloud to exhibit a velocity field which, if interpreted as disk rotation, has an amplitude of ∼9.0 ± 1.5 km s⁻¹. In other papers, Rhode et al. show the H1 source to have a resolved stellar counterpart and ongoing star forming activity, while Skillman et al. reveal it as having extremely low metallicity: 12 + log(O/H) = 7.16 ± 0.04. The H1 mass to stellar mass ratio of the object is found to be 2.6. We use the Tully–Fisher template relation in its baryonic form to obtain a distance estimate D₉₅₆ = 1.3⁺⁰⁻⁰.₅. Additional constraints on the distance are also provided by the optical data of Rhode et al. and McQuinn et al., both indicating a distance in the range of 1.5 to 2.0 Mpc. The three estimates are compatible within their errors. The object appears to be located beyond the dynamical boundaries of, but still in close proximity to the Local Group. Its pristine properties are consistent with the sedate environment of its location. At a nominal distance of 1.75 Mpc, it would have an H1 mass of ∼1.0 × 10⁶ M⊙, a stellar mass of ∼3.6 × 10⁵ M⊙, and a dynamical mass within the H1 radius of ∼1.5 × 10⁵ M⊙. This discovery supports the idea that optically faint—or altogether dark—low mass halos may be detectable through their non-stellar baryons.

Key words: galaxies: distances and redshifts – galaxies: halos – galaxies: luminosity function, mass function – galaxies: photometry – galaxies: spiral – radio lines: galaxies

Online-only material: color figures

1. INTRODUCTION

The faint end of the luminosity function of galaxies is generally modeled by a power law which is significantly shallower than that prescribed by the ΛCDM scenario for the low end of the mass function of dark matter halos. When this mismatch between observations and theory is found in the vicinity of massive galaxies such as the Milky Way (MW), it is referred to as the “missing satellite problem” (Klypin et al. 1999); when encountered in regions of very low galaxy density, it is referred to as the “void phenomenon” ( Peebles 2001). Here, we shall refer to the issue generically as the “dwarf galaxy problem”: the observed abundance of low-mass galaxies relative to theoretical expectations. The conflict between observations and theory is also encountered in the behavior of the H1 high velocity clouds (HVCs) were invoked as baryonic but starless counterparts to low-mass dark matter halos in the Local Group (LG). In particular, the more compact of those HVCs (sizes < 2°) were proposed as representative of the relatively primordial, yet undisturbed population of LG low-mass halos. This interpretation was challenged by Sterling et al. (2002, hereafter SMW02), on the grounds that, if placed at typical LG distances (∼1 Mpc), (1) the sizes of even the more compact HVCs (CHVCs) known at the time were too large (sizes > 10 kpc) to match the mass–concentration relation of ΛCDM halos and (2) the CHVCs would be too massive (M_H1 > 10⁷ M⊙) to explain the lack of detection of similar populations in nearby groups of galaxies (Pisano et al. 2007). The existence of gas-bearing but starless (or nearly so) minihalos was recently revived by Giovanelli et al. (2010, hereafter G+10) who identified a category of even more compact HVCs (sizes < 10′, thus the ultra-compact HVCs: UCHVCs) in the ALFALFA extragalactic H1 survey (Giovanelli et al. 2005). The thermal models of SMW02 are given for a broad range of intergalactic medium (IGM) pressures. While we don’t know the specific environmental conditions at the location of any...
single cloud, plausible models can be fit to the UCHVC data. Placed to distances of a few Mpc, their H\textsc{i} masses would be smaller than detection limits of extant surveys of nearby groups. The one critical item preventing the validation of the idea that the UCHVCs can be counterparts of extragalactic minihalos is that their distances are not known. There are two main routes to advancing such validation—one would be the detection of stellar populations associated with the UCHVCs; the other would be the detection of a population of objects with comparable H\textsc{i} properties in a nearby group of galaxies, clearly associated by virtue of similarity in the distribution of radial velocities. Here we report on a finding that allows for progress along the former route. The object involved is a dwarf galaxy located in the immediate vicinity of the LG.

2. DISCOVERY OF HI102145.0+180501

Making use of the seven-horn Arecibo L-band Feed Array (ALFA), the Arecibo Legacy Fast ALFA Survey (ALFALFA; Giovanelli et al. 2005) is a blind survey in the H\textsc{i} 21 cm line covering 7000 deg\textsuperscript{2} of high Galactic latitude sky in two regions; a “Spring” northern Galactic circumpolar region between 7\textdegree.5 and 16\textdegree.5 in R.A. and a “Fall” southern Galactic region between 22\textdegree.5 and 0\textdegree.5 in R.A. Both footprints extend from 0\textdegree. to 36\textdegree. in Declination. The spectral coverage extends from −2000 to +18000 km s\textsuperscript{−1} with a channel separation of ∼5.5 km s\textsuperscript{−1}. Initiated in 2005 and completed in 2012, survey observations were carried out with the 305 m telescope at the Arecibo Observatory\textsuperscript{5} with an angular resolution of ∼4\arcmin. and an integration time of ∼40 s beam\textsuperscript{−1}, yielding an rms flux sensitivity of ∼2.5 mJy for a spectral feature smoothed to 11 km s\textsuperscript{−1}. A catalog containing sources over nearly 3000 deg\textsuperscript{2} (40% of the total ALFALFA sky) is in the public domain (Haynes et al. 2011).

As discussed in previous works (Haynes et al. 2011 and references therein), the ALFALFA survey observations consist of a series of drift scans which are combined to construct 3-D data cubes. Data processing is carried out sequentially on stripes 2\textdegree.4 wide in declination. Signal identification is performed by applying a matched filtering algorithm in the Fourier domain (Saintonge 2007). The process of catalog construction also includes the inclusion of optical databases and the assignment of the most probable optical counterpart to each H\textsc{i} signal.

During the course of construction of the ALFALFA catalog along the Spring stripe centered at decl. = +17\textdegree., an H\textsc{i} source with heliocentric velocity of 264 km s\textsuperscript{−1} was detected at 102145.0+180501 (epoch 2000.0). The source was designated as an UCHVC of the type reported by G+10. The H\textsc{i} emission appeared to be very weakly, if at all, resolved by the 4\footnote{The Arecibo Observatory is operated by SRI International under a cooperative agreement with the National Science Foundation (AST-1100968), and in alliance with Ana G. M\"{e}ndez-Universidad Metropolitana and the Universities Space Research Association.} ALFA beam. Although no cataloged optical galaxy is recorded near the H\textsc{i} position, a very faint blue object appears in both the SDSS and DSS2 blue images, ∼20\textdegree. NE of the ALFALFA centroid, but within the positional error box. The Sloan Digital Sky Survey (SDSS) image exhibits an irregular, lumpy light distribution that could be described as being marginally resolved into stars. In fact, what we now identify as a single galaxy is seen as a combination of several photometric objects in the SDSS database, some of which are classified as stars and some as galaxies. It is identified as a compact group of galaxies (SDSSCGB11269) by McConnachie et al. (2009) who used an automated search algorithm to identify such objects in the SDSS DR6 catalog. As those authors note, spurious identification of compact groups can be due to errors in the photometric catalog. In fact, this group candidate is included in their less reliable “catalog B.” Aided by the good position match with that of the H\textsc{i} source, however, the visual inspection of both the SDSS and the DSS2 blue images suggested an alternative interpretation: that of a very faint, nearby, star forming dwarf galaxy. Follow-up optical observations reported by Rhode et al. (2013): (1) confirmed that the H\textsc{i} source has a stellar counterpart, (2) provided an accurate optical flux, partly resolved into individual stars, (3) detected H\text{\small{\alpha}} emission indicative of current star formation activity, and (4) produced an independent estimate of the galaxy’s distance. Later optical spectroscopy of the H\textsc{i} region revealed the galaxy’s extremely low metallicity (Skillman et al. 2013). We shall hereafter refer to it as Leo P because of its apparently pristine nature. It is also identified as AGC208583 in the catalog maintained by M.P.H. and R.G. and reported in a number of online extragalactic data bases.

3. PROPERTIES OF THE GALAXY LEO P

The follow-up observations mentioned above include BVR broad-band imaging obtained in excellent seeing conditions (0\textdegree.6–0\textdegree.8) with the WITN 3.5 m telescope and more recently with the Large Binocular telescope (LBT); H\text{\small{\alpha}} imaging with the 2.1 m KPNO telescope; optical spectroscopy with the 4 m KPNO telescope and the LBT; and H\textsc{i} synthesis imaging with the Karl G. Jansky Very Large Array (VLA\textsuperscript{6}). Ongoing fitting of thermal structure models will yield insights into the phases of Leo P’s interstellar medium (Y. Faerman et al., in preparation).

Throughout this paper, properties of Leo P will be tabulated through their explicit dependence on the object’s distance $D_{\text{Mpc}}$ in Mpc. As we discuss in Sections 3.1 and 3.3, that distance is likely to be between 1.5 and 2 Mpc.

3.1. Summary of Optical Properties

Using the WITN telescope broad-band imaging data, Rhode et al. (2013) clearly detected the stellar population associated with Leo P, showed that it extends to a radius of $\simeq 225D_{\text{Mpc}}$ pc and has a stellar mass of $1.2 \times 10^5 D_{\text{Mpc}}^2 M_\odot$. They also obtained constraints to the distance $D_{\text{Mpc}}$ of Leo P. After extraction of a sample of $\simeq 10^5$ resolved stars, a color–magnitude diagram allowed an identification of the red giant stellar branch (RGB), to which isochrones could be fitted. However, the sparseness of the stellar population, coupled with the limited depth of their photometric data, makes the determination of the location of the branch tip (TRGB) difficult. Recently, deeper optical broad band images of the Leo P field have been obtained with the LBT by K. McQuinn et al. (2013, private communication). These data allow a clear identification of the RGB but, again, due to the sparseness of the resolved stellar population, the location of the TRGB cannot yet be sharply defined. Both groups do, however, agree that the analysis of their respective data sets indicate that the distance to Leo P lies somewhere between 1.5 and 2.0 Mpc. These estimates are complemented by, and in agreement with that of $D_{\text{Mpc}} = 1.3^{+0.9}_{-0.5}$ obtained using the baryonic Tully–Fisher relation, presented in Section 3.3.

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Figure 1. H\textsc{i} line spectra of Leo P from separate observations: the original ALFALFA spectrum (dashed blue line), the higher resolution spectrum from the targeted LBW observation (solid red line), and the spatially integrated spectrum extracted from the masked VLA cube used to create the moment map in Figure 2 (dotted black line). The LBW observation matches the ALFALFA spectrum very closely and, despite its substantially higher spectral resolution, it does not reveal any additional spectral detail. The VLA integrated spectrum, sampled at 3.3 km s$^{-1}$, shows missing flux relative to the single-dish observations. (A color version of this figure is available in the online journal.)

Optical spectroscopy data of Skillman et al. (2013) obtained with the LBT shows Leo P to have the extremely low metallicity of $(12 + \log(O/H) = 7.16 \pm 0.04$, and to exhibit essentially primordial Helium abundance.

3.2. H\textsc{i} Properties

Figure 1 displays the H\textsc{i} spectral profile of Leo P as extracted from the ALFALFA dataset, traced by the dashed blue line. In 2012 March, a single-pixel spectrum was obtained using the Arecibo telescope and the “L-band-wide” (LBW) receiver with a velocity resolution of 1.2 km s$^{-1}$ (after Hanning smoothing); the on-source integration time was 3 minutes. This spectrum is displayed as the solid red line in Figure 1; it matches and corroborates the ALFALFA spectrum. Since a single pointing recovers practically all the flux of the ALFALFA map, the source angular diameter must be significantly smaller than the FWHM = 4$^\prime$ Arecibo beam; however, close inspection of the ALFALFA map suggests that the Arecibo beam starts to resolve a weak extension of the source to the SE. It is unlikely to be due to telescope beam sidelobes. Thus, a rough estimate of the half-mass H\textsc{i} radius between 0.8 and 1.5 can be made. No indication of a narrow component of width less than 10 km s$^{-1}$ is evident in either line profile.

In 2012 April, 5 hr of VLA observations in the C configuration were obtained as part of the Observatory Director’s Discretionary Time. A resulting H\textsc{i} image, smoothed to an angular resolution of 30$^\prime\prime$, is shown in the form of contours of H\textsc{i} column density overlaid on the WIYN 3.5 m optical image in Figure 2. The peak column density is $\sim 2.3 \times 10^{20}$ cm$^{-2}$ and the H\textsc{i} major axis radius is 1’ at the column density level of $5 \times 10^{19}$ cm$^{-2}$. However, only half of the ALFALFA flux is recovered in the VLA image (including flux rescaling; see Jorsater

Figure 2. VLA-C integrated H\textsc{i} synthesis preliminary image of Leo P, smoothed to an angular resolution of 30$^\prime\prime$ (shown as the yellow circle in the lower right), superimposed on the WIYN optical image of Rhode et al. (2013). H\textsc{i} column density contours are shown at $0.5 \times 10^{20}$ cm$^{-2}$ intervals, starting at $0.5 \times 10^{19}$ cm$^{-2}$ for the outermost contour. (A color version of this figure is available in the online journal.)
& van Moorsel 1995) at 30′ resolution, indicating that much of the H\textsc{i} detected by ALFALFA is in a diffuse component more extended than that scale.

Figure 1 displays the VLA spectrum integrated over the whole source (dotted line), which is vaguely suggestive of having two spectral components: one as broad as indicated by the source (dotted line), which is vaguely suggestive of having two thermally stable phases of the atomic gas: a cold (T < 10 000 K) neutral medium (CNM) associated with the spectrally narrow component that could arise from a single dense, star-forming region, and a warm (T > 60 000 K), predominantly neutral medium (WNM), enveloping the former, associated with the spectrally broad component (Young & Lo 1996, Warren et al. 2012). The relative masses of the two components could be used to constrain thermal models of the ISM. The extant observations cannot reliably provide such a constraint yet. They do, however, provide evidence for a rotating disk.

Smoothed to an angular resolution of 30′ and a spectral resolution of 3.3 km s\(^{-1}\), the VLA-C data reveal a sustained velocity gradient along the major axis (with position angle of 34° clockwise from north) of the column density distribution shown in Figure 2. While the signal-to-noise ratio is poor, if the gradient is assumed to be due to disk rotation, a velocity gradient along the major axis (with position angle of 34° clockwise from north) of the column density distribution shown in Figure 2, uncorrected for disk inclination.

3. V\(_{\text{gps}}\) = V\(_{\text{br}}\) + 225 sin \(i\) cos \(b\) is the radial velocity in the Galactic Standard of Rest frame and V\(_{\text{br}}\) is that in the Local Standard of Rest, with an assumed solar motion of 20 km s\(^{-1}\) toward l = 57°, b = 25°.

4. V\(_{\text{LG}}\) is the radial velocity in the LG dynamical rest frame, with respect to which the MW motion is of 316 km s\(^{-1}\) toward an apex of Galactic coordinates (l, b) = (93°, −4°) (Karachentsev & Makarov 1996).

5. W50 is the AO velocity width, measured at half power.

6. F\(_{\text{HI}}\) is the integrated flux density under the line of the AO feature.

7. R\(_{\text{HI}}\) is an (uncertain) estimate of the H\textsc{i} radius in kpc, corresponding to 1’ in angular size along the major axis of the isophote at 5 \times 10\(^{10}\) H\textsc{i} atoms cm\(^{-2}\) shown in Figure 2; the radius corresponding to the isophote at the level of half the peak H\textsc{i} column density is one-half the value of R\(_{\text{HI}}\) in Table 1.

8. M\(_{\text{HI}}\) is the H\textsc{i} mass, in solar units, as derived from F\(_{\text{HI}}\).

9. V\(_{\text{rot}}\) is the maximum observed rotational velocity, corrected for disk inclination, as extracted from Figure 3.

10. M\(_{\text{dyn}}(<R_{\text{HI}})\) is an estimate of the upper limit of the dynamical mass within the H\textsc{i} radius, on the assumption that the object is a self-gravitating system, computed via

\[
M_{\text{dyn}}(<R_{\text{HI}}) \simeq R_{\text{HI}} \sigma^2 / G
\]

with \(\sigma = \sqrt{W50 / 2 \ln 2}\). The same result is obtained if \(\sigma\) is replaced by V\(_{\text{rot}}\).

11. M\(_{\text{HI}}\)/M\(_{\odot}\) is the ratio of the H\textsc{i} mass to the stellar mass; the latter was estimated by Rhode et al. (2013). The assumed error is not driven by uncertainties in the photometry, but rather by the assumed protocol to convert optical flux and color into mass.

### 3.3. Preliminary Estimate of Distance

The Tully–Fisher relation (Tully & Fisher 1977) has been effective in the determination of cosmic distances. For galaxies with V\(_{\text{rot}}\) > 50 km s\(^{-1}\), that determination’s accuracy is 15%–20%. In its usual format, as the scaling law between optical or near infrared luminosity versus rotational velocity V\(_{\text{rot}}\), it is not useful in practice with galaxies with small V\(_{\text{rot}}\), both because the scatter grows with decreasing V\(_{\text{rot}}\) below 50 km s\(^{-1}\), and the power law behavior characterizing faster rotators fades.

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**Table 1**

| Property                  | Value          |
|---------------------------|----------------|
| Right Ascension (J2000) AO| 10:21:45.0     |
| Declination (J2000) AO    | 18:05:01       |
| Right Ascension (J2000) VLA| 10:21:44.8    |
| Declination (J2000) VLA   | 18:05:20       |
| Galactic longitude        | 210:654        |
| Galactic latitude         | 54:430         |
| V\(_{\odot}\) (km s\(^{-1}\)) AO | 264 ± 2     |
| V\(_{\text{gps}}\) (km s\(^{-1}\)) | 177          |
| V\(_{\text{br}}\) (km s\(^{-1}\)) | 137         |
| W50 (km s\(^{-1}\)) AO    | 24 ± 2         |
| F\(_{\text{HI}}\) (Jy km s\(^{-1}\)) | 1.31 ± 0.04   |
| R\(_{\text{HI}}\) (kpc) VLA | 0.29 ± 0.07 D\(_{\text{Mpc}}\) |
| M\(_{\text{HI}}\)/M\(_{\odot}\) AO | 3.1 \times 10\(^{5}\) D\(_{\text{Mpc}}\) |
| V\(_{\text{rot}}\) (km s\(^{-1}\)) VLA | 10.6 ± 2.2    |
| M\(_{\text{dyn}}(<R_{\text{HI}})/M_{\odot}\) | 8 \times 10\(^{6}\) D\(_{\text{Mpc}}\) |
| M\(_{\text{HI}}\)/M\(_{\star}\) | 2.6 ± 0.5      |
However, in the form of a relation between observed baryonic mass and rotational width (hereafter referred to as the baryonic Tully–Fisher relation, or "BTFR"), its power law behavior holds over more than five orders of magnitude in baryonic mass, with only moderate increase in scatter to the lowest over more than five orders of magnitude in baryonic mass, with the Tully–Fisher relation, or "BTFR"), its power law behavior holds with a mean scatter in log $M_{\text{bar}}$ of 0.24 dex. The scatter is however clearly increasing with decreasing $M_{\text{bar}}$. For a value more appropriate to the low mass end of the BTFR we assume 0.36 dex, 50% higher than the mean value. The intersection of Leo P’s log $V_{\text{rot}}$ and the BTFR template relation yields a determination of the galaxy’s distance: 1.3 Mpc. We coarsely estimate that the combination of errors in the estimate of the galaxy’s disk inclination and rotational velocity is 20%. Combining this with an assumed scatter about the BTFR of 0.36 dex results in an estimated error for the distance of 72%, i.e., $D_{\text{Mpc}} = 1.3^{+0.9}_{-0.5}$. This is statistically in agreement with the optical estimates of Rhode et al. (2013) and K. McQuinn (2013, private communication), discussed in Section 3.1. We thus adopt a distance of $D_{\text{Mpc}} = 1.75$ for the remainder of this paper, for consistency in derived parameters with the papers by Rhode et al. (2013) and Skillman et al. (2013).

4. DISCUSSION

In a very useful recent compilation of galaxy properties in the LG and nearby groups, McConnachie (2012) separates LG members into three subgroups: MW satellites, M31 satellites and satellites of the LG as a whole. Galaxies that fall within the caustic curves of constant escape velocity in the $R–V$ plane of each subgroup—where $R$ is the distance of an object from the barycenter of the subgroup and $V$ that object’s velocity in the subgroup’s rest frame—are assigned membership to the subgroup. At a distance of 1.75 Mpc, the location of Leo P in the $R–V$ planes of each subgroup is incompatible with membership in any of them. At that distance, its H I mass, as derived from the ALFALFA data, is $1.0 \times 10^6 M_\odot$, its stellar mass $3.6 \times 10^5 M_\odot$, its H I radius 0.5 kpc and its dynamical mass within that radius $1.4 \times 10^7 M_\odot$.

It is interesting to note that the galaxy Leo I, which in terms of its sky location (6.6 angular separation) and heliocentric radial velocity (282 km s$^{-1}$ versus 264 for Leo P) would appear to be a close companion of Leo P, has a measured distance of 0.25 Mpc; that places Leo I within the 300 kpc virial radius of the MW, assumed to have a mass of $10^{12} M_\odot$. Correcting its velocity for MW rotation, Leo I is traveling through the MW corona at 174 km s$^{-1}$. The ALFALFA survey yields an upper limit to its H I mass of $6.0 \times 10^3 M_\odot$. The nearest neighbors of Leo P appear to be the galaxies in the sparse NGC 3109 group, including Sextans B, located at 1.4 Mpc from us and ~350 kpc from Leo P. The largest galaxy in that group, NGC 3109, has a V-band absolute magnitude of $-14.9$ and is located 44° away from Leo P. The nearest giant galaxy to Leo P is the MW itself. Leo P is a bona fide gas bearing, star forming galaxy inhabiting a very low-mass halo, located in a low density environment lacking any massive companions, in the immediate vicinity of the LG. Its measured oxygen abundance is lower than that of any galaxy in the Local Volume and is similar to those of I Zw 18 and DDO 68. Leo P is however closer to us than the latter two by 11 and 7 times respectively. We use a distance to DDO 68 of 12.1 ± 0.7 Mpc based on recent TRGB data (A. Aloisi 2013, private communication). With a reported metallicity of 7.25 ± 0.1 (Grossi et al. 2007), HIPASS J1337-39 could belong to this extreme group. Unlike I Zw 18 and DDO 68, Leo P shows no evidence for tidal disturbances, although the asymmetry shown by the SE extension of the H I isophotes in Figure 2 could be the remnant of a past mild encounter. Forthcoming H I synthesis observations should help clarify this matter. There is, however, no evidence, either in optical or H I surveys, of any massive system in the vicinity of Leo P. In this object, the evolutionary history and extreme metallicity of a very...
The “dwarf galaxy problem,” the observed underabundance of dwarf galaxies with respect to theoretical expectations, appears to be tightly related to their baryon deficiency (Papastergis et al. 2012). For low mass halos, the baryon deficiency is attributable to the shallow potential well of those systems, which makes them unable to retain their gas, which is lost due to either heating by the metagalactic UV field or to galactic winds, after episodic star formation events. This is shown effectively by the simulations of Hoeft et al. (2006), Hoeft & Gottloeber (2010) and others. Heating of the IGM raises the Jeans mass, making IGM gas infall onto low mass systems ineffectual, yet these circumstances may change at later epochs, then gas accretion and star formation in a dwarf system may resume (Ricotti 2009). The transition from halos capable of retaining most of their baryons to those losing most of them takes place over a narrow range of halo masses. The mid-point for that transition is referred to as the “characteristic halo mass” $M_*$. This would be the halo mass marking the onset of the dwarf galaxy problem. One should thus expect that the baryon-to-dark matter fraction of halos with mass $M_h < M_*$ would be measurable—if at all—at levels much lower than the cosmic fraction of $\sim 1/6$. Within this scenario, the thermal models of SMW02 are most useful in estimating the detectability of these objects. They indicate that halos with $M_h < 10^9 M_\odot$ can retain a small fraction of their baryons, albeit far below the cosmic baryon fraction as $N$-body simulations suggest. Most of those baryons would be present in the form of a warm, ionized, thermal gas phase (WIM) with a temperature near 7000 K or higher, depending on the gas metallicity. An even smaller fraction of the baryon mass could be present within the inner region of the WIM, in the form of a warm neutral gas phase (WNM) or even in the form of a cold neutral phase (CNM), eventually capable of converting some of its gas into stars. According to those models, the neutral gas content of a $10^9 M_\odot$ dark matter halo would thus not be around $10^8 M_\odot$, but rather a few orders of magnitude lower, even below $10^6 M_\odot$. Detection of such weak H I emitters would have been impossible by past or current wide field surveys beyond a few Mpc from us. Given their shallow potential wells, their gas content would be of marginal stability and their detection may require that they be located in environments shielded from interaction with threatening neighbors and able to provide a measure of confining IGM pressure.

G+10 reported the discovery of a category of ultra-compact H I HVCs which are plausible minihalo candidates, as shown by the SMW02 models. Leo P belongs to that category of objects. Leo P and Leo T—the LG transition galaxy which is located 417 kpc from the MW, just outside the MW virial radius (Ryan-Weber et al. 2008) may be the most extreme confirmed examples of gas-bearing minihalos. Others may exist with even fainter stellar counterparts, and some with no detectable starlight (or H I) at all. The catalog of UCHVCs as minihalo candidates of Adams et al. (2013), extracted from the ALFALFA data base, provides us with the targets that may help to shed further light on this category of dim galaxies.

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