CLOUDS TOWARD THE VIRGO CLUSTER PERIPHERY: GAS-RICH OPTICALLY INERT GALAXIES

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ABSTRACT

Aperture synthesis observations of two H\textsc{i} cloud complexes located in the periphery of the Virgo galaxy cluster are presented. These low H\textsc{i}-mass clouds (M_{\text{H\textsc{i}}} < 10^9 M_\odot) are seen projected on the M region of the western Virgo cluster, where the galaxy population is thought to lie behind the main A cluster surrounding M87. The kinematic measurements of both unresolved Arecibo and resolved Very Large Array (VLA)-C observations are in good agreement. The H\textsc{i} detections cannot be identified with any optical, IR, or UV emission from available archival imaging. They are inert at these wavelengths. The H\textsc{i} masses of the individual VLA detections range from 7.28 \leq \log(M_{\text{H\textsc{i}}}/M_\odot) \leq 7.85. The total dynamical mass estimates are several times their H\textsc{i} content, ranging from 7.00 \leq \log(M_{\text{dyn}}/M_\odot) \leq 9.07, with the assumption that the clouds are self-gravitating and in dynamical equilibrium. We report the observed parameters derived from the VLA observations. One of these H\textsc{i} clouds appears to be the most isolated optically inert detection observed in the outer reaches of Virgo.

Key words: galaxies: clusters: individual (Virgo) – galaxies: clusters: intracluster medium – galaxies: halos – intergalactic medium – radio lines: galaxies

1. INTRODUCTION

Galaxies are characterized by their stellar content, morphology, environment, dust, and neutral and molecular gas content. The 21 cm line of neutral hydrogen (H\textsc{i}) continues to play an important role in diagnosing the star formation potential of a galaxy and any past dynamic interactions with a cluster environment or neighboring galaxies. Blind H\textsc{i} surveys can sample the gas-rich population of the local universe and search for low-mass, low-surface brightness systems.

The Arecibo Legacy Fast ALFA (ALFALFA; Giovanelli et al. 2005a) survey is providing such a sampling of gas-rich objects. The project utilizes the seven-element Arecibo L-band Feed Array (ALFA) receiver system to conduct a wide area extragalactic H\textsc{i} investigation with the 305 m Arecibo reflector. The survey improves over previous first-generation surveys (HIPASS: Barnes et al. 2001; Meyer et al. 2004; Wong et al. 2006; ADBS: Rosenberg & Schneider 2002) in spectral and spatial resolution, providing 5 km s\textsuperscript{-1} resolution with a 3′ beam. The 7000 deg\textsuperscript{2} of surveyed sky covers a velocity range out to cz \sim 18,000 km s\textsuperscript{-1}. This includes interesting areas of the local supercluster such as the Virgo cluster at cz \sim 1100 km s\textsuperscript{-1}. The first and second ALFALFA Virgo catalogs (Giovanelli et al. 2007; Kent et al. 2008) comprise a complete mass limited data set (M_{\text{H\textsc{i}}} \geq 2 \times 10^7 M_\odot at Virgo). Sources identified in Kent et al. (2007, 2009) comprise a sample of optically inert H\textsc{i} detections; these objects are important in understanding the fate of galaxies in a cluster environment and its surrounding periphery. Previous detections that cannot be correlated with optical counterparts have been associated with nearby galaxy groups or nearby spiral galaxies harassed by the cluster environment (Ryder et al. 2001; Minchin et al. 2005; Oosterloo & van Gorkom 2005; Haynes et al. 2007).

Nearby galaxy cluster environments are of great interest to H\textsc{i} studies as both the gravitational potential and intracluster medium (ICM) perturb the gas structure and morphology of galaxies. Ram pressure stripping and tidal encounters at different cluster radii result in spiral galaxy deficiencies in H\textsc{i} of varying degrees. While three-dimensional paths of galaxies through the cluster are often difficult to ascertain, the fingerprint of the cluster–galaxy interaction is well studied through aperture synthesis observations; high-resolution studies show that H\textsc{i} radii are smaller than their optical counterparts and match predictions of theoretical studies (Giovanelli & Haynes 1983).

Aperture synthesis observations have the ability to resolve higher sensitivity single-dish survey detections. Resolved H\textsc{i} observations reveal the truncation of disks, tidal tails, and the disturbed morphology of late-type spiral galaxies (Cayatte et al. 1990, 1994; Chung et al. 2007). All of these properties are indicators of galaxy–galaxy and galaxy–cluster interactions. It has been shown that H\textsc{i} deficiency in late-type galaxies decreases with increasing cluster radius (Giovanelli & Haynes 1985). An important question of galaxy and cluster evolution that remains is: what happens to the stripped gas in the cluster environment? Will it be destroyed by ablation and evaporate into the cluster halo? Is it possible that an isolated cloud can survive and re-initiate star formation?

Here we present H\textsc{i} aperture synthesis observations of two H\textsc{i} clouds in the Virgo Cluster periphery, initially reported in Kent et al. (2007). These clouds, unresolved by Arecibo, are resolved into separate clumps with Very Large Array (VLA)-C observations. In Section 2, we discuss the original Arecibo observations, data reduction, and detections. In Section 3, we describe the follow-up VLA observations, data reduction, and detections. In Section 4, we detail the environment and neighboring galaxies of the H\textsc{i} clouds. In Section 5, we discuss possible cloud origins and compare to other gas-rich optically inert phenomena. Section 6 summarizes the results of the study.

2. SINGLE DISH DETECTIONS

The H\textsc{i} clouds described here were detected by the ongoing ALFALFA survey. The meridian transit observing strategy uses a sky drift mode with a 100 MHz bandwidth and 4096 channels per polarization, centered at 1385 MHz. Each raw scan contains 14 spectra (7 beams × 2 linear polarizations per beam), with
a sampling rate of 1 Hz and spectral resolution of 24.4 kHz ($\delta V = 5.1 \text{ km s}^{-1}$ at the rest frequency of the 21 cm H I line). The system temperatures of the ALFA receivers during the observations were in the range 26 K < $T_{\text{sys}}$ < 30 K, yielding a root mean square (rms) noise of $\sigma_n = 2.5 \text{ mJy beam}^{-1}$ in channels with $\delta V = 5.1 \text{ km s}^{-1}$. The flagging, calibration, and gridding of the data into cubes are described in detail by Giovanelli et al. (2005a), Kent (2008), and Kent et al. (2009).

Table 1 describes the parameters of the Arecibo observations. The two H I clouds (henceforth Clouds 1 and 2) were detected in the ALFA data obtained in the spring 2005 campaign sampling the Virgo cluster and its surrounding periphery. The detections were reported in Kent et al. (2007) as part of an initial collection of gas-rich, optically inert extragalactic objects. A complex of H I clouds situated halfway between M87 and M49 and their VLA observations were examined in Kent et al. (2009). Here we continue this effort with two H I clouds located in the M cloud periphery west of the main A cluster. Upon detection in the ALFA survey, both objects were re-observed and confirmed with the single-pixel L-band Arecibo receiver. Integrated spectral profiles for each cloud are depicted in red in Figure 1. The Arecibo observations show both sources as narrow, single-peaked spectral profiles. Clouds 1 and 2 are unresolved by the Arecibo beam and are located 5′4 (1.5 Mpc in projection) and 4′2 (1.2 Mpc in projection) from M87, respectively, west toward the direction of the M cloud. The Arecibo detections are unresolved point sources and we cannot deduce any information about the morphology of the sources.

Table 2 describes the observed parameters and locations of these two H I detections as measured from the ALFA data cubes, derived in the manner described by Giovanelli et al. (2007). The spatial centroid of each cloud is in Column 2. Its accuracy depends on the source strength and is of order $\sim 30''$ for the reported sources. The heliocentric velocity $cz/\sigma$, width at 50% of the peak $W_{50}$, and total flux $F_c$ of the integrated spectral profiles in Figure 1 are in Columns 3–5. The signal-to-noise ratio (S/N) of the detections is in Column 6 and is given by

$$S/N = \left( \frac{1000}{W_{50}} \right) \frac{W_{\text{smo}}}{\sigma_{\text{rms}}},$$

(1)

where $F_c$ is in Jy km s$^{-1}$, $W_{50}$ is in km s$^{-1}$, $W_{\text{smo}}$ is a smoothing width equal to the number of 10 km s$^{-1}$ bins bridging half the signal, and $\sigma_{\text{rms}}$ is the rms noise (in mJy) across the integrated spectrum at 10 km s$^{-1}$ resolution. The H I mass $M_{\text{HI}}$ for each cloud is in Column 7 and is computed assuming that the clouds are optically thin:

$$M_{\text{HI}}/M_{\odot} = 2.356 \times 10^5 D^2 F_c,$$

(2)

where $D$ is in Mpc and $F_c$ is in Jy km s$^{-1}$ (Roberts 1975). The uncertainties on $M_{\text{HI}}$ in Table 2 and elsewhere do not include errors in the distance adopted, which is poorly constrained due to the large peculiar velocities of objects near or within the cluster. As described in Giovanelli et al. (2005b) and Springob et al. (2005a), this results in ambiguities for galaxies with $cz/\sigma < 3000 \text{ km s}^{-1}$. The peculiar flow model used for the ALFA distances published in the catalogs corrects only for large-scale perturbations in the velocity field. The model is not able to deal effectively with regions in the immediate vicinity of Virgo. We adopt the same distance values for consistency with Kent et al. (2007): 16.7 Mpc for Cloud 1 and 34.8 Mpc for Cloud 2. The model used to obtain the distances is based on the work of Tonry et al. (2000) and Masters et al. (2004), using a parametric model and spherical truncated power-law attractor to examine the peculiar motions that arise from a cluster like Virgo.

### Table 1

| Parameter | Value |
|-----------|-------|
| Spectral range | 25 MHz (−2000 to 3200 km s$^{-1}$) |
| Effective integration time | 48 s (beam solid angle)$^{-1}$ |
| Spectral resolution $\delta V$ | 24.4 kHz (5.1 km s$^{-1}$) |
| Half-power beam size | $3.3 \times 3.8$ |
| rms noise $\sigma_n$ for $\delta V = 5.1 \text{ km s}^{-1}$ | 2.5 mJy beam$^{-1}$ |

### Table 2

| Cloud | $\alpha, \delta$ (J2000) | $cz/\sigma$ (km s$^{-1}$) | $W_{50}$ (km s$^{-1}$) | $F_c$ (Jy km s$^{-1}$) | S/N | $\log(M_{\text{HI}}/M_{\odot})$ |
|-------|------------------------|--------------------------|----------------------|---------------------|-----|-------------------|
|       | (1)                    | (2)                      | (3)                  | (4)                 | (5) | (6)               |
| Cloud 1 | 120845.5, +115517      | 1230 ± 1                 | 29 ± 2               | 0.77 ± 0.04         | 11.6| 7.63              |
| Cloud 2 | 121341.8, +125351      | 2235 ± 2                 | 53 ± 3               | 1.21 ± 0.07         | 9.2 | 8.54              |

**Notes.** Column 1: cloud name; Column 2: R.A. and decl. of cloud centroid (J2000); Column 3: average heliocentric velocity of integrated spectral profile from Figure 1; Column 4: profile width, measured at 50% of the integrated spectra profile peak and corrected for instrumental broadening as described in Giovanelli et al. (2007); Column 5: total flux of integrated spectral profile; Column 6: S/N of the detection, computed using $W_{50}$ and $F_c$ via Equation (1); Column 7: base 10 logarithm of total H I mass, computed using $F_c$ via Equation (2).
Figure 1. Integrated spectral profiles of the Cloud 1 (left) and Cloud 2 (right) detections made with Arecibo and the ALFALFA survey (red), and total integrated profiles from the multiple cloud detections in the same fields made with the VLA in C configuration (blue). The channel resolution of the VLA spectrum is 12.2 kHz (2.6 km s\(^{-1}\)). The global profiles for the VLA were obtained by summing all emission for \(N'_{\text{H}\text{I}} \geq 1.5 \times 10^{20} \text{ cm}^{-2}\) in Figure 4 and for \(N'_{\text{H}\text{I}} \geq 0.7 \times 10^{20} \text{ cm}^{-2}\) in Figure 5.

Figure 2. Naturally weighted channel maps for the Cloud 1 field from the VLA-C observations. The plotted channels are independent \((\delta V' = 7.8 \text{ km s}^{-1})\). Contours are at \((-3, -2, 2, 3, 4, 5, 6) \text{ mJy beam}^{-1}\); negative contours are represented with dashed lines. The cross indicates the centroid position of the original Cloud 1 Arecibo detection (Table 4). The heliocentric radial velocity is in the lower right corner of each panel, and the synthesized beam is in the lower left corner of the first panel.

Virgo distance). The data cubes created for the Cloud 1 field are not limited by dynamic range and do not gain image fidelity from self-calibration. For the field with Cloud 2, self-calibration was run using a strong continuum source (NVSS catalog position \(\alpha = 12^{h}13^{m}32^{.1}, \delta = +13^{\circ}07^{\prime}20^{.4}\); Condon et al. 1998) of flux density 1.3 Jy, greatly improving the fidelity and phase calibration of the images. As part of the reduction process, each image was smoothed to the resolution of the ALFALFA data cubes to identify emission in channels, as well as their extent in the frequency domain. A summary of the aperture synthesis observing and map parameters is given in Table 3. For clarity, all variables denoting parameters derived from the VLA observations are primed.

Channel maps of each field are shown in Figures 2 and 3, with solid and dashed contours in the primary beam-corrected maps depicting, respectively, positive and negative multiples of the median rms map noise. All maps are corrected for the attenuation of the primary beam and averaged over 3–4 spectral channels to yield a channel map resolution of \(\delta V' = 7.8 \text{ or } 10.4 \text{ km s}^{-1}\). The emission from detections in both fields is contiguous over multiple channels in different weighting and imaging deconvolution schemes.

Total intensity (zero moment) and intensity-weighted velocity (first moment) maps of each field are shown in Figures 4 and 5. The zero moment contours are overlaid on Sloan Digital Sky Survey (SDSS) g-band images. For each frequency channel, we
Figure 3. Naturally weighted channel maps for the Cloud 2 field from the VLA-C observations. The plotted channels are independent ($\delta V' = 10.4 \text{ km s}^{-1}$). Contours are at $(-3, -2, 2 (2 \sigma_m'), 3, 4, 5, 6) \text{ mJy beam}^{-1}$; negative contours are represented with dashed lines. The cross indicates the centroid position of the original Cloud 2 Arecibo detection (Table 4). The heliocentric radial velocity is in the upper right corner of each panel, and the synthesized beam is in the lower left corner of the first panel.

Table 3
Aperture Synthesis Observing and Data Cube Parameters

| Parameter                         | Cloud 1                  | Cloud 2                  |
|-----------------------------------|--------------------------|--------------------------|
| Pointing center (J2000)           | $12^h 08^m 45.5, +11^\circ 55' 17''$ | $12^h 13^m 41.8, +12^\circ 53' 51''$ |
| Total time on-source              | 547 minutes              | 532 minutes              |
| Net bandpass                      | 1.5 MHz (1132–1336 km s$^{-1}$) | 1.5 MHz (2137–2341 km s$^{-1}$) |
| Maximum spectral resolution $\delta V'$ | 12.2 kHz (2.6 km s$^{-1}$) | 12.2 kHz (2.6 km s$^{-1}$) |
| Synthesized beam/natural weighting| $25'2 \times 24'4$ at 56'7 | $25'3 \times 24'4$ at 57'2 |
| $\sigma_m'$ at pointing center, $\delta V'$ | 1.39 mJy beam$^{-1}$ | 1.37 mJy beam$^{-1}$ |

H$_1$ objects examined in Kent et al. (2009). No counterparts are observed in the field in any available optical, IR, or UV imaging databases. The combined kinematic properties of Clouds 1N and 1S agree well with the Arecibo data (Tables 2 and 4).

We recover 87% ± 5% of the flux (Tables 2 and 4) from the Cloud 1 field in the VLA observations. The VLA global profile of all the integrated emission (which consists of Clouds 1N and 1S) for $N_{\text{H_1}}' \geq 1.5 \times 10^{20} \text{ cm}^{-2}$ in Figure 4 is shown in comparison with the Arecibo spectra in Figure 1. The mean velocity of Clouds 1N and 1S is 1229.5 km s$^{-1}$ and agrees with the centroid velocity of the Arecibo data. Some lower surface brightness H$_1$ might escape detection below the $3\sigma_m'$ level if it is distributed uniformly over the 30$''$ region between the two detections. However, one would expect it to coincide kinematically with the mean velocity of the clouds.

3.1. H$_1$ Aperture Synthesis Detections

Field for Cloud 1. We observe two detections which we label Clouds 1N (North) and 1S (South), the two brightest in the field. Individual integrated spectral profiles of all detections in each field, representing the total emission for comparison with the original ALFALFA spectrum, are shown in Figure 1 in blue. The rms error on the computed total emission over the full width at half-maximum range in each individual channel for both spectra ranges from 0.67 to 1.03 mJy and also reflects a 5% uncertainty in calibration.
**Figure 4.** H\text$\text{I}$ distribution and kinematics of the Cloud 1 field, showing Clouds 1 North and 1 South as detected in the VLA-C data cube. The left panel shows total intensity map of the clouds (contours) superimposed on an SDSS $g$-band image (gray scale). Contours are at $N_{\text{HI}} = 10^{20} \times (1.5, 2, 2.5, 3) \text{ cm}^{-2}$, and the gray scale is plotted logarithmically. The cross indicates the centroid position of the original Cloud 1 Arecibo detection (Table 4). The synthesized beam is in the lower left corner of the panel. The right panel shows intensity-weighted velocity map of the clouds in regions where $N_{\text{HI}} \geq 1.5 \times 10^{20} \text{ cm}^{-2}$. The velocity spans 1222–1241 km s$^{-1}$ on a linear scale, as indicated by the color bar at the top of the plot.

**Figure 5.** H\text$\text{I}$ distribution and kinematics of the Cloud 2 field. The left panel shows total intensity map of the clouds (contours) superimposed on an SDSS $g$-band image (gray scale). Contours are at $N_{\text{HI}} = 10^{20} \times (0.7, 0.8, 0.9, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5) \text{ cm}^{-2}$, and the gray scale is plotted logarithmically. The cross indicates the centroid position of the original Cloud 2 Arecibo detection (Table 4). The synthesized beam is in the lower left corner of the panel. The right panel shows intensity-weighted velocity map of the clouds in regions where $N_{\text{HI}} \geq 1.5 \times 10^{20} \text{ cm}^{-2}$. The velocity spans 2222–2248 km s$^{-1}$ on a linear scale, as indicated by the color bar at the top of the plot.

**Field for Cloud 2.** The emission detected in this field is, not unexpectedly, of lower S/N. The VLA global profile of all the integrated emission for $N_{\text{HI}} \geq 0.7 \times 10^{20} \text{ cm}^{-2}$ in Figure 5 is shown in comparison with the Arecibo spectra in Figure 1. We recover 41% ± 5% of the flux (Tables 2 and 4) compared to the Arecibo data. It is likely that lower column density emission is resolved out and we are only detecting the higher column density peaks of the source. We identify three of these peaks (Clouds 2 North, West, and South) fit for the same parameters as the Cloud 1 field. Clouds 2 North and West are elongated in an east–west direction, where the southern component is a marginal detection in the map with low S/N, albeit still a 5\text{$\sigma$} detection in the map. The velocity maps of all three Cloud 2 field detections show no ordered motion. The clutter in the field contains a number of bumps 1\text{$\sigma$} or 2\text{$\sigma$} above the rms noise.
3.2 Field Properties

The properties for the detections in both fields are summarized in Table 4 in the same manner as Kent et al. (2009). The global emission parameters, where measurable, are also listed. Each detected feature in the VLA data cubes was fitted with a centroid ellipse in the same fashion as the Arecibo data. The centroid de-tection parameters, where measurable, are also listed. Each detected feature in the VLA data cubes was fitted with a centroid ellipse in the same fashion as the Arecibo data.

Table 4

| Feature       | (α, δ) (J2000) | cz_Hi | W_{50} | F'_{i} | a''_{HI} | PA'_{HI} | log(M'_{HI}/M_⊙) | log(M'_{dyn}/M_⊙) |
|---------------|----------------|-------|--------|--------|-----------|-----------|-------------------|-------------------|
| Cloud 1 Global |                | 1229 ± 2 | 26 ± 4 | 0.67 ± 0.03 | ···       | ···       | 7.64              | ···               |
| Cloud 1 North | 12 08 47.6, +11 55.57 | 1234 ± 3 | 22 ± 6 | 0.29 ± 0.03 | 1.0 ± 0.3 | −268       | 7.28              | 7.83              |
| Cloud 1 South | 12 08 47.4, +11 54.48 | 1225 ± 3 | 20 ± 8 | 0.39 ± 0.03 | 1.4 ± 0.3 | 13         | 7.40              | 7.65              |
| Cloud 2 Global |                | 2231 ± 4 | 51 ± 6 | 0.50 ± 0.02 | ···       | ···       | 8.15              | ···               |
| Cloud 2 North | 12 13 42.5, +12 54.50 | 2237 ± 2 | 13 ± 4 | 0.14 ± 0.02 | 2.5 ± 0.04 | −7         | 7.60              | 8.09              |
| Cloud 2 West  | 12 13 33.1, +12 52.44 | 2205 ± 5 | 41 ± 9 | 0.25 ± 0.02 | 2.4 ± 0.03 | −4         | 7.85              | 9.07              |
| Cloud 2 South | 12 13 41.9, +12 51.16 | 2234 ± 3 | 6 ± 5 | 0.05 ± 0.01 | 0.8 ± 0.02 | 39         | 7.15              | 7.00              |

Notes. Column 1: cloud identifier; Column 2: centroid R.A. and decl. based on the fitting of ellipses to each detection; Column 3: average heliocentric velocity of integrated spectral profile from Figure 6; Column 4: profile width, measured at 50% of the integrated spectral profile peak and corrected for instrumental effects assuming that unbroadened profile is Gaussian; Column 5: total flux of integrated spectral profile; Column 6: maximum linear extent of region with N'_H_i ≥ 1.5 × 10^{20} cm^{-2} (Cloud 1 field) and N'_H_i ≥ 0.7 × 10^{20} cm^{-2} (Cloud 2 field) in the total intensity maps (Figures 4 and 5); Column 7: position angle at which a''_{HI} was measured; Column 8: base 10 logarithm of total H1 mass, computed using F'_{i} via Equation (2); Column 9: base 10 logarithm of the dynamical mass, computed using W_{50} and a''_{HI} via Equation (3).

where a''_{HI} is the object diameter in arcminutes, W_{50} is in km s^{-1}, and the distance D is in Mpc. We note that M'_{dyn} has physical meaning only if the clouds are self-gravitating and in dynamical equilibrium, which may or may not be a valid assumption.

4. THE ENVIRONMENT OF THE CLOUD COMPLEXES

Figure 7 shows the location of these two H1 clouds with respect to the Virgo Cluster, with the boundaries and areas of Binggeli et al. (1993) and plotted against the hot X-ray cluster background detected by ROSAT (Snowden et al. 1995). Both cloud regions are outside the projected virial radius of the dark matter halo around M87 determined by McLaughlin (1999). The detections lie in the vicinity of the M cloud (Ftachas et al. 1984) west of M87, where member galaxies are considered to lie behind the main A cluster. These M cloud galaxies have a larger mean velocity (cz_{⊙} ~ 2000 km s^{-1}) than the main cluster (cz_{⊙} ~ 1150 km s^{-1}). However, peculiar velocities due to the large central mass of the cluster yield a velocity dispersion of the projected M cloud region galaxies that ranges from −100 < cz_{⊙} < 2400 km s^{-1}. The assignment of these H1 features to the various areas of Virgo remains ambiguous.

Imaging studies by Roberts et al. (2007) analyzed an area extending from the eastern part of the M cloud northward. They...

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M'_{dyn} = (3.39 \times 10^4) a''_{HI} D \left( \frac{W_{50}}{2} \right)^2, \tag{3}
\]
Figure 7. Location of the two Arecibo H\textsc{i} cloud detections in the context of the greater cluster environment. The centroid positions of Clouds 1 and 2 are indicated by star symbols. The peaks from the hard X-ray background image provided by ROSAT are labeled indicating Virgo cluster galaxies M49 and M87 (Snowden et al. 1995). The symbols are not indicative of source sizes and are shown only for positional indication. The dashed lines indicate the projected virial radius of the dark matter halo $r_{200}/2$ determined by McLaughlin (1999), for the A and B areas centered around cluster members M87 and M49, respectively. The two $2^\circ$ boxes surrounding the detections show the areas of sky examined in Figure 8.

Figure 8. Galaxies in the vicinity of the two cloud complexes. The plots show $2^\circ \times 2^\circ$ areas of sky surrounding each of the Arecibo detections. Each plot contains open circles from galaxies with published H\textsc{i} or optical redshifts within a given range of the measured Arecibo/H\textsc{i} velocity for the detection; $cz_{\odot} \leq 3000$ km s$^{-1}$ for the Cloud 1 area and $1400 < cz_{\odot} < 3000$ km s$^{-1}$ for the Cloud 2 area. Galaxies in those areas with no published redshifts at any wavelength are depicted as small crosses. We next examine a number of nearby galaxies of comparable redshift within the projected vicinity of Clouds 1 and 2.

4.1. The Projected Environment of Cloud 1

The galaxy environment below a redshift of $cz_{\odot} \leq 3000$ km s$^{-1}$ is rather sparse in the vicinity of Cloud 1. Galaxies that meet this criteria are listed in Table 5. Of particular note is the faint galaxy SDSS J120859.92+115631.2. This faint detection lies $3.8'$ northeast of the Arecibo centroid. It is the closest optical detection near Cloud 1; it remains ambiguous as to whether this object is a Virgo Cluster member or a more distance background galaxy. The SBb(r)II galaxy VCC 58 has a disturbed morphology and optical redshift of $cz_{\odot} = 2188$ km s$^{-1}$ (Rubin et al. 1999) and H\textsc{i} redshift of $cz_{\odot} = 2209$ km s$^{-1}$ (Giovanelli et al. 2007). This is the only spiral galaxy within $\sim 1^\circ$ though its velocity differs by $\sim 1000$ km s$^{-1}$. It is described as having a disturbed rotation curve (Rubin et al. 1999).

4.2. The Projected Environment of Cloud 2

Cloud 2 lies in a much higher galaxy density environment and includes, within $2^\circ$, nine galaxies with a cataloged late-type morphology for $1400 < cz_{\odot} < 3000$ km s$^{-1}$ (Table 6). Several galaxies have notable relevant properties. The aforementioned VCC 58 lies $49'$ southwest of Cloud 2 and is of comparable redshift. The closest published H\textsc{i} detection is VCC 85, detected by Gavazzi et al. (2006) with $cz_{\odot} = 1932$ km s$^{-1}$ and lies $\sim 8'$ from the Cloud 2 centroid. Also of note is VCC 97, an SAB galaxy that lies $17'$ north of Cloud 2. Chamaraux et al. (1980) showed this galaxy to be H\textsc{i} deficient (DEF$_{H\textsc{i}} = 0.21$; Helou arrived at a density of 20–60 low surface brightness (LSB) dwarf galaxies per square degree in the area $1^\circ.5$ west of M87. This may have some relation to possible parent galaxies of the Cloud 2 field. Figure 7 shows that the Cloud 1 field is more removed from the main cluster and galaxy density measurements.

No obvious optical features that resemble an extragalactic counterpart can be correlated with any of the cloud components in online imaging databases. The catalogs provided by the NASA/IPAC Extragalactic Database (NED), SDSS (York et al. 2000), Virgo Cluster Catalog (Binggeli et al. 1985), GOLD-Mine (Gavazzi et al. 2003), and published ALFALFA survey (Giovanelli et al. 2007; Kent et al. 2008) were examined for possible nearby associations to the Clouds 1 and 2 fields. Figure 8 shows $2^\circ \times 2^\circ$ areas of sky surrounding each of the Arecibo detections. Each plot contains open circles from galaxies with published H\textsc{i} or optical redshifts within a given range of the measured Arecibo/H\textsc{i} velocity for the detection; $cz_{\odot} \leq 3000$ km s$^{-1}$ for the Cloud 1 area and $1400 < cz_{\odot} < 3000$ km s$^{-1}$ for the Cloud 2 area. Galaxies in those areas with no published redshifts at any wavelength are depicted as small crosses. We next examine a number of nearby galaxies of comparable redshift within the projected vicinity of Clouds 1 and 2.
follow-up studies can be associated with galaxies in nearby clusters. Recently detected optically inert clouds and their respective identification of starless gas-rich halos. As one of the many important science goals, identifying such objects in blind surveys Yergalactic clouds in the field, isolated from other galaxies, have yet to be detected. Recent studies have focused on the search and envelopes, and clouds near groups or within clusters. Starless intergalactic clouds in the field, isolated from other galaxies, have yet to be detected. Recent studies have focused on the search and identification of starless gas-rich halos. As one of the many important science goals, identifying such objects in blind surveys like HIPASS and ALFALFA gives useful information on the formation and evolution of galaxies in a variety of environments. Recently detected optically inert clouds and their respective follow-up studies can be associated with galaxies in nearby clusters (Sancisi et al. 1987; Davies et al. 2004; Minchin et al. 2005; Haynes et al. 2007; Kent et al. 2007), in groups or disturbed galaxies (Schneider et al. 1983; Henning et al. 1993; Ryder et al. 2001), in tidal or harassed tails (Oosterloo & van Gorkom 2005; Giovanelli & Haynes 1989; Salzer et al. 1991), or as a high-velocity cloud or Milky Way Local Group companion (Kilborn et al. 2000; Giovanelli et al. 1989; Salzer et al. 1991). However, surveys have not revealed a large population of previously undetected dark matter halos predicted by large-scale simulations (Moore et al. 1999). In the nearby Virgo Cluster, the H1 detected in clouds or tidal streams does not make up a significant portion of the H1 deficiency in nearby parent spirals; the population of H1 clouds does not, by itself, offer a complete solution to the missing satellite or mass problem (Kent et al. 2009; Klypin et al. 1999).

None of the detections discussed here appear to be tidal tails that clearly extend to an obvious parent galaxy. The largest tail extending from a Virgo galaxy is near NGC 4532 at a length of 500 kpc (Koopmann et al. 2008). While late-type spirals and dwarfs are within a projected 500 kpc range of both Clouds 1 and 2, neither has a tail or streamlike morphology leading to another nearby galaxy. The clouds do not belong to a compact group of galaxies, nor are they part of the main A or B clusters surrounding M87 or M49.

5. DISCUSSION

Roberts (1988; see references therein) outlined various categories of intergalactic H1 clouds: tidal tails, extended H1 envelopes, and clouds near groups or within clusters. Starless intergalactic clouds in the field, isolated from other galaxies, have yet to be detected. Recent studies have focused on the search and identification of starless gas-rich halos. As one of the many important science goals, identifying such objects in blind surveys like HIPASS and ALFALFA gives useful information on the formation and evolution of galaxies in a variety of environments. Recently detected optically inert clouds and their respective follow-up studies can be associated with galaxies in nearby clusters (Sancisi et al. 1987; Davies et al. 2004; Minchin et al. 2005; Haynes et al. 2007; Kent et al. 2007), in groups or disturbed galaxies (Schneider et al. 1983; Henning et al. 1993; Ryder et al. 2001), in tidal or harassed tails (Oosterloo & van Gorkom 2005; Giovanelli & Haynes 1989; Salzer et al. 1991), or as a high-velocity cloud or Milky Way Local Group companion (Kilborn et al. 2000; Giovanelli et al. 1989; Salzer et al. 1991). However, surveys have not revealed a large population of previously undetected dark matter halos predicted by large-scale simulations (Moore et al. 1999). In the nearby Virgo Cluster, the H1 detected in clouds or tidal streams does not make up a significant portion of the H1 deficiency in nearby parent spirals; the population of H1 clouds does not, by itself, offer a complete solution to the missing satellite or mass problem (Kent et al. 2009; Klypin et al. 1999).

None of the detections discussed here appear to be tidal tails that clearly extend to an obvious parent galaxy. The largest tail extending from a Virgo galaxy is near NGC 4532 at a length of 500 kpc (Koopmann et al. 2008). While late-type spirals and dwarfs are within a projected 500 kpc range of both Clouds 1 and 2, neither has a tail or streamlike morphology leading to another nearby galaxy. The clouds do not belong to a compact group of galaxies, nor are they part of the main A or B clusters surrounding M87 or M49.

Although the region surrounding the Cloud 1 detection lies at a projected distance of 1.5 Mpc from M87, it has been shown that the spiral galaxy population in the M cloud area is H1 deficient. The Cloud 1 detection lies on the boundary of higher H1 deficiency (Solanes et al. 2001), whereas the Cloud 2 field lies within it. The intracluster X-ray density in the vicinity of the Virgo M cloud is estimated to be n_{X cm} \sim 3 \times 10^{-6} cm^{-3} (computed from Vollmer et al. 2001). The Virgo Cluster ICM temperature maps computed by Shibata et al. (2001) do not cover the region of sky containing the H1 clouds. If we entertain the assumption that these clouds came from a spiral disk, then the presence of this gas deficiency means that a ram pressure stripping hypothesis cannot be completely discarded.

We can place upper limits on the optical surface brightness based on models of Bell et al. (2003). As in Kent et al. (2009) we assume a g-band imaging surface brightness limit similar to other SDSS LSB galaxy studies ($\mu_g \sim 26$ mag arcsec$^{-2}$; Kniazev et al. 2004). A feature of source size $\sim 10''$ would have a g-band luminosity of $L_g \sim 10^3 L_\odot$ and model stellar M/L ratio of $M^*/L^* \sim 1.6$. The theoretical upper limits for the stellar to H1 mass ratio would range from $\sim 0.02$ to 0.11 for the clouds extracted from the VLA data cubes. Upper limits for the H1 mass to stellar luminosity would range from $\sim 15$ to 70. It remains an open issue as to whether or not any optical emission can be positively correlated with these H1 detections.

As indicated in Section 4, nine late-type galaxies lie in the vicinity and near redshift range of Cloud 2; only one lies $\sim 1^\circ$ northeast of Cloud 1. This makes it difficult to identify a parent galaxy. However, we can hypothetically consider the movement of these clouds through the cluster environment. As both clouds are at higher velocities than the systemic heliocentric cluster velocity ($cz_{\odot, Virgo} \sim 1150$ km s$^{-1}$ Huchra 1988), their line-of-sight velocity with respect to the cluster reference frame is
Table 6
Galaxy Environment of Cloud 2 (cz⊙ = 2235 km s$^{-1}$)

| Galaxy Name       | (α, δ) (J2000) | cz⊙ (H$\text{i}$) (km s$^{-1}$) | cz⊙ (optical) (km s$^{-1}$) | NED Type | d$_{C2}$ (kpc) | H$\text{I}$ Ref. | Optical Ref. |
|-------------------|----------------|---------------------------------|----------------------------|----------|---------------|----------------|--------------|
| VCC 13            | 120946.3,+133301 | 2535                           | 2505                       | Sm       | 337           | G07           | F99          |
| VCC 15            | 120954.5,+130258 | 292                            |                            |          |               |                |              |
| VCC 20            | 120198.8,+121949 | 1726                           |                            | BCD      | 247           | G07           | AM06         |
| VCC 22            | 120134.2,+131014 | 269                            |                            |          |               |                |              |
| AGC 224966        | 12038.0,+130119 | 2418                           |                            |          |               |                |              |
| VCC 32            | 121102.7,+120615 | 1894                           |                            | E        | 298           | G07           | B85          |
| VCC 35            | 121119.9,+115437 | 333                            |                            |          |               |                |              |
| VCC 36            | 121128.2,+133501 | 255                            |                            |          |               |                |              |
| SDSS J121140.32+125824.6 | 121140.3,+125825 | 2221                           |                            |          | 145           |                | AM06         |
| SDSS J121141.87+131146.7 | 121141.9,+131147 | 1496                           |                            |          | 166           |                | AM06         |
| SDSS J121145.94+131707.9 | 121145.9,+131708 | 2468                           |                            |          | 178           |                | AM06         |
| AGC 224807        | 121309.4,+133504 | 2100                           |                            |          | 204           |                | AM06         |
| SDSS J121131.69+133122.0 | 121313.7,+133122 | 2158                           |                            |          | 185           |                | AM06         |
| SDSS J121137.79+130935.6 | 12137.8,+130936 | 1915                           |                            |          | 82            |                | AM06         |
| VCC 84            | 121335.3,+132413 | 148                            |                            |          |               |                |              |
| VCC 85            | 121336.4,+130201 | 1932                           |                            |          | 40            | Ga06          |              |
| VCC 89            | 121347.3,+132528 | 2114                           |                            | SAB(rs)cd| 154           | G07           | AM06         |
| VCC 97            | 121353.6,+131021 | 2470                           |                            | SAB(s)c  | 81            | G07           | F95          |
| VCC 100           | 121404.0,+133908 | 228                           |                            |          | 24           |                |              |
| VCC 106           | 121409.0,+115619 | 281                            |                            |          |               |                |              |
| VCC 107           | 121410.7,+131407 | 104                            |                            |          |               |                |              |
| SDSS J121419.86+132706.4 | 121419.9,+132706 | 2467                           |                            |          | 168           |                | AM06         |
| VCC 113           | 121432.8,+120611 | 2115                           |                            |          | 239           | G07           | AM06         |
| VCC 122           | 121444.2,+121048 | 2348                           |                            | S0       | 222           |                | AM06         |
| AGC 224705        | 121444.6,+124723 | 229                           |                            |          | 81            | G07           | AM06         |
| VCC 132           | 121503.8,+130155 | 2085                           |                            | SB       | 105           | G07           |              |
| VCC 133           | 121505.2,+130644 | 284                            |                            |          |               |                |              |
| VCC 135           | 121506.8,+120058 | 2402                           |                            | Sa       | 276           | S05           | AM06         |
| VCC 146           | 121520.8,+123656 | 2115                           |                            |          | 143           |                |              |
| VCC 150           | 121528.6,+123856 | 2115                           |                            |          | 146           |                |              |
| VCC 155           | 121535.7,+133711 | 2470                           |                            |          | 250           |                |              |
| VCC 163           | 121546.0,+123344 | 177                            |                            |          |               |                |              |
| VCC 164           | 121552.6,+120150 | 296                            |                            |          |               |                |              |
| VCC 175           | 121602.8,+123544 | 189                            |                            |          |               |                |              |
| VCC 185           | 121620.1,+130814 | 200                            |                            |          |               |                |              |
| VCC 197           | 121632.7,+130944 | 216                            |                            |          |               |                |              |
| VCC 204           | 121639.2,+125220 | 210                            |                            |          |               |                |              |
| VCC 215           | 121658.3,+121549 | 2074                           |                            | dE4      | 297           |                | AM06         |
| VCC 224           | 121709.2,+122712 | 2131                           |                            | Sbc      | 278           | G07           | AM06         |
| VCC 230           | 121719.5,+115632 | 1429                           |                            | dE4      | 380           |                | AM06         |
| VCC 232           | 121723.6,+133020 | 316                            |                            |          |               |                |              |
| AGC 224489        | 121728.1,+125556 | 2056                           |                            |          | 268           | G07           | AM06         |
| SDSS J121731.31+115715.9 | 121731.3,+115716 | 387                            |                            |          |               |                |              |

Notes. Column 1: galaxy name; Column 2: R.A. and decl. reported in NED; Column 3: heliocentric velocity based on H$\text{i}$ measurements; Column 4: heliocentric velocity based on optical spectroscopy; Column 5: NED morphological type; Column 6: projected linear displacement from Cloud 2 at the Virgo distance of 16.7 Mpc; Column 7: H$\text{I}$ measurement reference; Column 8: optical measurement reference. References are abbreviated as: G07: Giovanelli et al. 2007; K08: Kent et al. 2008; Ga06: Gavazzi et al. 2006; B85: Binggeli et al. 1985; B93: Binggeli et al. 1993; AM06: Adelman-McCarthy et al. 2006; F99: Falco et al. 1999; R99: Rubin et al. 1999; T08: Tully et al. 2008; S05: Springob et al. 2005b; F95: Fisher et al. 1995.
directed away from us. If the clouds were torn from a spiral disk that is in a similar reference frame, with the clouds decelerating, then the parent galaxy would be at a higher systemic velocity than the cluster. The only nearby spiral galaxy of comparable velocity is the aforementioned VCC 58 (IC 769), located one degree northeast of the Cloud 1 detection at a redshift $cz_{\odot} = 2209$ km s$^{-1}$. VCC 58 also lies one degree southwest of Cloud 2 and stands as a remote, yet possible candidate parent of either cloud.

6. SUMMARY

We have presented new follow-up observations obtained with the VLA that resolve original Arecibo H$\text{I}$ detections of extragalactic H$\text{I}$ clouds in the Virgo Cluster periphery. The results of these observations are summarized as follows.

1. Two H$\text{I}$ clouds detected and unresolved with Arecibo using ALFALFA survey data. The H$\text{I}$ detections have heliocentric radial velocities of $cz_{\odot} = 1230$ and 2235 km s$^{-1}$. The velocity widths are narrow at 29 and 53 km s$^{-1}$. The H$\text{I}$ masses of Clouds 1 and 2 are, respectively, $4.3 \times 10^7$ and $3.5 \times 10^8 M_{\odot}$.

2. Detections have been made with the VLA in both the Clouds 1 and 2 fields at the same velocities as the Arecibo detections. The data show two and three separated regions of H$\text{I}$ emission for the Clouds 1 and 2 fields, respectively. The individual H$\text{I}$ masses range from $\log(M_{\text{HI}}/M_{\odot}) = 7.1$ to 7.8 $M_{\odot}$. We recover 87% of the flux for the Cloud 1 field and 41% of the flux for the Cloud 2 field. No optical, IR, or UV counterpart can be identified with these H$\text{I}$ features using available online imaging databases.

3. The galaxy environment is relatively sparse around Cloud 1—one faint object with no redshift information, SDSS J120859.92+115631.2, lies 3.8 degrees northeast of the Arecibo centroid. The nearest late-type galaxy of comparable Virgo redshift within a one degree radius. The closest H$\text{I}$ detection is VCC 58, located one degree to the northeast.

4. The Cloud 2 detection lies in a dense galaxy environment showing higher H$\text{I}$ deficiency with nine late-type spiral systems of comparable Virgo redshift within a one degree radius. The closest H$\text{I}$ detection is VCC 85 at 8$^\circ$.

5. The H$\text{I}$ deficient spirals in the M cloud region show that dynamic processes are prevalent even at large distances from the Virgo Cluster center. While there are no larger spirals immediately in the vicinity or at comparable velocity of the H$\text{I}$ Clouds, we cannot dismiss a cloud origin hypothesis of ram pressure stripping. Much like previous detections reported in Kent et al. (2007, 2009), it is unlikely that the H$\text{I}$ clouds described here are primordial gas structures in dark matter halos. These two clouds are located in the outer parts of the cluster and are in a lower density environment than other H$\text{I}$ clouds and tidal tails further toward M87 or M49. Cloud 1 remains unique in its isolation. To date, there are no other gas structures that are both definitively extragalactic and unambiguously not associated with another galaxy outside the Local Group.

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REFERENCES

Adelman-McCarthy, J. K., et al. 2006, ApJS, 162, 38
Barnes, D. G., et al. 2001, MNRAS, 322, 486
Bell, E. F., McIntosh, D. H., Katz, N., & Weinberg, M. D. 2003, ApJS, 149, 289
Binggeli, B., Popescu, C. C., & Tammann, G. A. 1993, A&AS, 98, 275
Binggeli, B., Sandage, A., & Tammann, G. A. 1980, AJ, 90, 1681
Cayatte, V., Kotanyi, C., Balkowski, C., & van Gorkom, J. H. 1994, AJ, 107, 1003
Cayatte, V., van Gorkom, J. H., Balkowski, C., & Kotanyi, C. 1990, AJ, 100, 604
Chamaraux, P., Balkowski, C., & Gerard, E. 1980, A&A, 83, 38
Chung, A., van Gorkom, J. H., Kenney, J. D. P., & Vollmer, B. 2007, ApJ, 659, L115
Condon, J. J., Cotton, W. D., Greisen, E. W., Yin, Q. F., Perley, R. A., Taylor, G. B., & Broderick, J. J. 1998, AJ, 115, 1693
Davies, J., et al. 2004, MNRAS, 349, 922
Doyon, R., & Joseph, R. D. 1989, MNRAS, 239, 347
Falco, E. F., et al. 1999, PASP, 111, 438
Fisher, K. B., Huchra, J. P., Strauss, M. A., Davis, M., Yahil, A., & Schlegel, D. 1995, ApJS, 100, 69
Ftaclas, C., Struble, M. F., & Fanelli, M. N. 1984, ApJ, 282, 19
Gavazzi, G., Boselli, A., Donati, A., Franzetti, P., & Scodeggio, M. 2003, A&A, 400, 451
Gavazzi, G., O’Neil, K., Boselli, A., & van Driel, W. 2006, A&A, 449, 929
Giovanelli, R., & Haynes, M. P. 1985, ApJ, 292, 404
Giovanelli, R., & Haynes, M. P. 1983, AJ, 88, 881
Giovanelli, R., & Haynes, M. P. 1989, ApJ, 346, L5
Giovanelli, R., Haynes, M. P., Kent, B. R., & Adams, E. A. K. 2010, ApJ, 708, L22
Giovanelli, R., et al. 2005a, AJ, 130, 2613
Giovanelli, R., et al. 2005b, AJ, 130, 2598
Giovanelli, R., et al. 2007, AJ, 133, 2569
Greisen, E. W. 2003, Astrophys. Space Sci. Lett., 285, 109
Haynes, M. P., Giovanelli, R., & Kent, B. R. 2007, ApJ, 665, L19
Helou, G., Hoffman, G. L., & Salpeter, E. E. 1984, ApJS, 55, 433
Henning, P. A., Sancisi, R., & McMamara, B. R. 1993, A&A, 268, 536
Huchra, J. P. 1988, The Minnesota Lectures on Clusters of Galaxies and Large-Scale Structure, 5, 41
Kent, B. R. 2008, Ph.D. thesis, Cornell Univ.
Kent, B. R., Spekkens, K., Giovanelli, R., Haynes, M. P., Momjian, E., Cortés, J. R., Hardy, E., & West, A. A. 2009, ApJ, 691, 1595
Kent, B. R., et al. 2007, ApJ, 665, L15
Kent, B. R., et al. 2008, ApJ, 136, 713
Kilborn, V. A., et al. 2000, AJ, 120, 1342
Klypin, A., Kravtsov, A. V., Valenzuela, O., & Prada, F. 1999, ApJ, 522, 82
