THE EFFECT OF HALO MASS ON THE H I CONTENT OF GALAXIES IN GROUPS AND CLUSTERS

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ABSTRACT
We combine data from the Sloan Digital Sky Survey (SDSS) and the Arecibo Legacy Fast ALFA Survey (ALFALFA) to study the cold atomic gas content of galaxies in groups and clusters in the local universe. A careful cross-matching of galaxies in the SDSS, ALFALFA, and SDSS group catalogs provides a sample of group galaxies with stellar masses \(10^{8.4} M_\odot \leq M_* \leq 10^{10.6} M_\odot\) and group halo masses \(10^{12.5} h^{-1} M_\odot \leq M_h \leq 10^{15.0} h^{-1} M_\odot\). Controlling our sample in stellar mass and redshift, we find no significant radial variation in the galaxy H I gas-to-stellar mass ratio for the halo mass range in our sample. However, the fraction of galaxies detected in ALFALFA declines steadily toward the centers of groups, with the effect being most prominent in the most massive halos. In the outskirts of massive halos a hint of a depressed detection fraction for low-mass galaxies suggests pre-processing that decreases the H I in these galaxies before they fall into massive clusters. We interpret the decline in the ALFALFA detection of galaxies in the context of a threshold halo mass for ram pressure stripping for a given galaxy stellar mass. The lack of an observable decrease in the galaxy H I gas-to-stellar mass ratio with the position of galaxies within groups and clusters highlights the difficulty of detecting the impact of environment on the galaxy H I content in a shallow H I survey.

Key words: galaxies: clusters: general – galaxies: groups: general – ISM: general

1. INTRODUCTION
The amount of cold gas in group and cluster galaxies provides information on the impact of these environments on galaxy evolution. Previous studies have shown that the distribution of cold gas in galaxies, traced by neutral hydrogen (H I), is primarily affected by tidal interactions (Toomre & Toomre 1972) and ram pressure stripping (Gunn & Gott 1972; see Boselli & Gavazzi 2006 for a review of physical processes in galaxy environments).

Tidal interactions are expected to be important in galaxy groups and less so in clusters due to the large relative velocities of galaxies and short interaction timescales (Mihos 2004). Alternatively, ram pressure stripping is thought to be responsible for H I deficiency in cluster galaxies (Boselli & Gavazzi 2006; Roediger 2009; Gavazzi et al. 2013). Furthermore, ram pressure stripping can be felt by any galaxy that contains gas. Ram pressure can strip the cold gas in ellipticals (e.g., Lucero et al. 2005; McCarthy et al. 2008) and dwarfs (e.g., McConnachie et al. 2007; Freeland & Wilcots 2011), and the hot halo gas in galaxies (e.g., Jeltema et al. 2008) causing “starvation” ( Larson et al. 1980). For this work we select our sample to minimize the impact of tidal interactions so that we can focus on the effects of ram pressure stripping.

The impact of ram pressure stripping on galaxies has been well-studied in the Virgo and Coma clusters. Statistical analyses of the H I gas content of their member galaxies provides evidence for increasing gas depletion toward the cluster center for optically selected galaxies (e.g., Haynes et al. 1984; Haynes & Giovanelli 1986; Solanes et al. 2001) and for H I-selected late-type galaxies from Arecibo Legacy Fast ALFA (ALFALFA; Gavazzi et al. 2013). The disturbed H I morphologies of individual galaxies in Virgo and Coma cluster have provided additional evidence for ongoing ram pressure stripping (e.g., Bravo-Alfaro et al. 2000, 2001; Kenney et al. 2004; Crowl et al. 2005; Chung et al. 2007, 2009; Vollmer et al. 2008). Nevertheless, Taylor et al. (2012) and Cortese et al. (2008) find only marginal evidence for increasing H I deficiency toward the inner regions of the Virgo and Coma/ A1367 clusters, respectively, using H I-selected samples from the Arecibo Galaxy Environment Survey (AGES; Auld et al. 2006). This lack of H I depletion in these clusters is likely due to the limited dynamic range of this flux-limited H I survey.

While statistical and individual observations suggest that the interaction between galaxies and the intracluster medium (ICM) is important for the removal of gas from galaxies in the most massive groups, the situation is less clear in smaller groups (Rasmussen et al. 2012). In a small number of low-mass groups there is evidence for individual galaxies that have been ram-pressure stripped of their gas (e.g., Bureau & Carignan 2002; Rasmussen et al. 2006; McConnachie et al. 2007; Sengupta et al. 2007; Freeland & Wilcots 2011). Some of these groups also have X-ray detections of a hot intergalactic medium (IGM), consistent with the ram pressure stripping explanation.

A few recent studies have examined the impact of environment for a wide range of galaxy group halo masses using statistical samples. Catinella et al. (2013) used \(\approx 800\) galaxies from the GALEX Arecibo SDSS survey (GASS; Catinella et al. 2010, 2012) to show that the H I gas fraction (defined as \(M_{\text{HI}}/M_*\) in their work) of galaxies with stellar masses \(M_* > 10^{10.9} M_\odot\) residing in groups with halo masses \(M_h > 10^{13-14} M_\odot\), is at least 0.4 dex smaller than the galaxies with the same stellar masses but within the lower halo mass groups. Fabello et al. (2012) stacked ALFALFA spectra of galaxies meeting the GASS selection criteria in bins of stellar mass and local density and found a strong decline in the galaxy H I content in dark matter halos with masses \(M_h > 10^{13.5} M_\odot\). Hess & Wilcots (2013) used the Sloan Digital Sky Survey (SDSS) group catalog (Berlind et al. 2006) and the ALFALFA 40% catalog (Haynes et al. 2011) to show that as group membership increases, galaxy group centers become
increasingly deficient of H$_{\text{I}}$-rich galaxies. This work builds on these studies by using a control sample (i.e., isolated field galaxies with similar stellar masses and redshift) to compare the impact of the groups and clusters to the H$_{\text{I}}$ gas content of galaxies.

Hydrodynamic simulations show that ram pressure stripping can remove the outer H$_{\text{I}}$ gas from a galaxy falling into cluster (e.g., Abadi et al. 1999; Marcolini et al. 2003; Roediger & Brüggen 2007; Tonnesen & Bryan 2009, 2010) within 10–100 Myr (Abadi et al. 1999; Marcolini et al. 2003; Roediger 2009; Tecce et al. 2010), while the complete unbinding of the disk gas may take a few 100 Myr (Roediger 2009), less than the dynamical timescale in groups and clusters ($\approx$1 Gyr; Boselli & Gavazzi 2006). Theoretical models of ram pressure stripping based on the original formulation in Gunn & Gott (1972) find that the ratio of the mass of the infalling galaxy to that of the host group or cluster is an important parameter governing the efficiency of ram pressure stripping (Hester 2006) and the fraction of galaxies without cold gas increases toward the cluster center due to increasing ram pressure (Tecce et al. 2010). Therefore one can expect that gas depletion will increase toward the center of groups and clusters and that the depletion will be more significant in more massive clusters.

We use a statistical sample of galaxies with H$_{\text{I}}$ measurements from the ALFALFA survey to investigate the distribution of the galaxy H$_{\text{I}}$ gas-to-stellar mass ratio as a function of the projected distance from the center of galaxy group halos for a wide range of halo masses. We have combined the ALFALFA H$_{\text{I}}$ source catalog, the SDSS photometric and spectroscopic catalog, and the SDSS group catalog. In addition, we have created a control sample to remove the biases that arise from the correlation between the stellar mass and the H$_{\text{I}}$ gas-to-stellar mass ratio (Catinella et al. 2012; Huang et al. 2012).

In Section 2, we introduce the data sets used in this study and discuss our sample selection. In Section 3 we describe the procedure used to match SDSS galaxies, group catalog, and H$_{\text{I}}$ sources from ALFALFA. In Section 4, we examine the distribution of the galaxy H$_{\text{I}}$ gas-to-stellar mass ratio and the fraction of the H$_{\text{I}}$ detected galaxies as a function of the projected distance from the group center and derive a simple ram pressure stripping criterion depending on group halo mass, which provides a plausible explanation to our findings. In Section 5 we discuss the implications of our results and the relevant issues and summarize the results in Section 6. If not explicitly stated otherwise, we use a spatially flat LCDM cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 100h$ km s$^{-1}$ Mpc$^{-1}$, where $h = 0.73$.

2. DATA

The galaxies in this sample are selected from the NASA Sloan Atlas catalog$^3$ (Blanton et al. 2011) and have H$_{\text{I}}$ 21 cm measurements in the ALFALFA 40% catalog (Haynes et al. 2011) and a group identification in the SDSS group catalog (Yang et al. 2007). We restrict the sample to galaxies in halos with masses $10^{12.5} h^{-1} M_\odot \leq M_h \leq 10^{15} h^{-1} M_\odot$, more than four members, and redshifts of 0.01 < z < 0.055. A complementary sample of isolated galaxies is used to create a control sample for this study. The cross-matching of the three catalogs is discussed in detail in Section 3, but it is useful to note that the catalogs have very different selection functions and completeness. Requiring that the galaxies be in all three catalogs produces a sample that is mainly limited by the ALFALFA selection function.

2.1. The Optical Galaxy Sample

Our optical galaxy sample is selected from the NASA Sloan Atlas catalog (Blanton et al. 2011), which includes photometric and spectroscopic measurements for $\sim$150,000 galaxies within $\approx$220 Mpc ($z \approx 0.055$) selected from SDSS DR8 (Aihara et al. 2011). The size of the NASA Sloan Atlas catalog is much smaller than the full SDSS DR8 because of the redshift limit. However, the NASA Sloan Atlas catalog provides more reliable and accurate photometry than the SDSS DR8 catalog. In particular, the improved background subtraction removes the size-dependent flux bias for galaxies with half-light radii of $r_{50} \leq 10''$ (Blanton et al. 2011). The NASA Sloan Atlas catalog also provides an improved photometric center for galaxies in which the SDSS spectrum is not coincident with the photometric center and has eliminated objects where the SDSS spectroscopic object is a sub-clump of a larger galaxy. These improvements allow for a more reliable estimate of stellar mass and improved matching with the ALFALFA catalog.

The optical photometry from the NASA Sloan Atlas catalog is used to derive the stellar masses of the galaxies. Galaxy stellar mass is computed from galaxy color and luminosity following Bell et al. (2003):

$$\log \left( \frac{M_*}{h^{-2} M_\odot} \right) = -0.306 + 1.097 (g - r) - 0.1 - 0.4 (M_* - 5 \log h - 4.64),$$

where $M_*$ is the SDSS $r$-band absolute magnitude and $(g - r)$ is the $g - r$ color based on the Sérsic model magnitude. The color-based stellar mass measurement is used for consistency with the stellar mass definition in the SDSS group catalog (Yang et al. 2007). However, the results presented here do not change if stellar masses derived from spectral energy distribution fitting are used instead.

2.2. The H$_{\text{I}}$ Galaxy Sample

The ALFALFA survey is an extragalactic H$_{\text{I}}$ 21 cm line survey that provides information about the neutral atomic gas content of nearby galaxies ($z < 0.06$; Giovanelli et al. 2005). The survey covers $\sim$7000 square degrees of sky with 10 km s$^{-1}$ velocity resolution (after Hanning smoothing), an rms sensitivity of 1.8 mJy beam$^{-1}$ (Giovanelli et al. 2005), and a positional accuracy of $\sim$24$''$ for sources with a signal-to-noise ratio (S/N) > 6.5 (Giovanelli et al. 2007). The currently available source catalog, $\alpha_{40}$, contains $\approx$15,000 sources within 40% of the total survey area (Haynes et al. 2011) and includes measurements of redshift, H$_{\text{I}}$ flux, and H$_{\text{I}}$ line width that can be used to determine the H$_{\text{I}}$ mass of the source using the relation (Haynes et al. 2011):

$$M_{H_{\text{I}}} = 2.36 \times 10^{5} D^2 \int S \, d v \, M_{\odot},$$

where $D$ is the distance to the galaxy in Mpc, $S$ is the H$_{\text{I}}$ 21 cm flux density, and $\int S \, d v$ is the H$_{\text{I}}$ flux of the source integrated over the velocity.

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$^3$ http://www.nasatlas.org
Both “code 1” sources, which are highly reliable detections, with an S/N > 6.5, and “code 2” sources, which are lower signal-to-noise detections (4.5 < S/N < 6.5) that are likely to be real because there is a known optical counterpart at the redshift of the HI source (Haynes et al. 2011), are included in our sample. The majority (76%) of the sample consists of “code 1” sources and the fraction of “code 2” sources does not vary significantly with the projected distance from group center.

Figure 1 shows the relationship between the velocity integrated H I flux and the H I 21 cm line width measured at 50% of the peak flux, for the sample in this study. The 25%, 50%, and 90% completeness limits for the α.40 catalog (Haynes et al. 2011) are indicated by the red lines in the figure. The blue triangles are the group galaxies and the gray points are the isolated galaxies used as controls (see Section 3.1 for details on how this sample was selected from the cross-match of the three catalogs). The fraction of the sample below each completeness limit is nearly same for the isolated and group samples: 41% and 6% of them are below the 90% and 25% completeness limits, respectively.

The group halo masses are determined down to $M_h = 10^{13.5} h^{-1} M_\odot$ using two methods: ranking by luminosity and stellar mass of galaxies in groups. Although we used the luminosity-ranked group halo mass, the results do not change if the stellar mass ranked halo mass is used instead. The group finder has been shown to correctly select more than 90% of the true halos with $M_h > 10^{12} h^{-1} M_\odot$ (Yang et al. 2007), which allows us to reliably study our galaxy samples within groups and clusters with halo mass $10^{12} h^{-1} M_\odot \lesssim M_h \lesssim 10^{15} h^{-1} M_\odot$.

In order to investigate galaxy H I properties as a function of the projected distance from the group center, we normalize each galaxy’s radial position by the virial radius of the group. For the virial radius of a group with halo mass $M_h$, we adopt the radius $R_{180}$ that encloses an overdensity of 180 relative to the critical density (Yang et al. 2007):

$$R_{180} = 1.26 h^{-1} \text{Mpc} \left( \frac{M_h}{10^{14} h^{-1} M_\odot} \right)^{1/3} \times \left( 1 + z_{\text{group}} \right)^{-1}$$

, which is based on the WMAP3 cosmological model parameters (Spergel et al. 2007), $\Omega_m = 0.238$, $\Omega_\Lambda = 0.762$, and $H_0 = 100 h \text{km s}^{-1} \text{Mpc}^{-1}$, where $h = 0.73$. While these parameters differ slightly from those used in this study, using this formulation does not make a significant difference given the low redshifts of our sample (0.01 < z < 0.055).

Figure 2 shows the normalized positions of the galaxies in the most massive and least massive group halos ($M_h < 10^{13.35} h^{-1} M_\odot$ and $M_h > 10^{13.85} h^{-1} M_\odot$) in this study. Complete details regarding the galaxy samples in groups are discussed in Section 3.2. Compared with the distribution of the optically selected galaxies (gray dots), the ALFALFA-detected galaxies (blue triangles) arerarer near the centers of the groups, with the effect significantly more pronounced for the more massive groups. This lack of H I detections near group centers matches the findings of Hess & Wilcots (2013). In Section 4.2 we investigate the H I detection fraction more carefully by using a control sample to avoid the effect of H I selection bias by the masses and distances of galaxies at different positions within group halos.

3. CROSS-MATCHING AND SAMPLE DEFINITION

3.1. Cross-matching SDSS, ALFALFA, and the Group Catalog

For each SDSS galaxy in the NASA Sloan Atlas catalog, the associated group halo was identified by locating the SDSS galaxy in the group catalog that is within 5″ in position. This produces 103,287 SDSS galaxy matches. Since galaxies in the SDSS group catalog and in the NASA Sloan Atlas catalog are the same sources, 5″ positional matching is very robust and the redshift difference is typically $\Delta z \approx 0.0001$ (i.e., 30 km s$^{-1}$ in velocity). Only 0.1% of matches have redshift differences of 0.0003 < $\Delta z$ < 0.0009 (none have $\Delta z > 0.0009$). The larger velocity differences occur for galaxies where the NASA Sloan Atlas Catalog uses a non-SDSS redshift measurement that is deemed more reliable. Generally this happens when SDSS does not have a spectrum near the photometric center of the galaxy. All 103,287 NASA Sloan Atlas galaxies that are associated with groups were then cross-matched with the α.40 catalog.

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Footnote:

3. All matching was done using the catalog manipulation software Topcat (Taylor 2005).

4. http://gax.shao.ac.cn/data/Group.html
Sources within 40′′ in position and 0.001 in redshift (300 km s⁻¹ in velocity) were considered potential matches. In total there were 6444 potential matches between SDSS group galaxies and ALFALFA sources. However, since the Arecibo beam is large (∼3′.5 diameter), there can be more than one galaxy in the beam that will influence the measurement of the H I mass. Figure 3 shows an extreme example in which there are four galaxies in the Hickson Compact Group 69 within the ALFALFA beam. In this case, the H I measurement is likely not that of a single galaxy. Cases of galaxy confusion will be more common in groups than in the field and thus the H I mass of the best matched galaxy among the multiple galaxies within the Arecibo beam will be biased (e.g., the best match indicated by the cross in Figure 3). To address this problem we exclude from the matched sample 520 galaxies that have additional SDSS sources within a 1′.75 radius. Removing these galaxies with close neighbors decreases our sample size to 5924 (a decrease of 8%) and removes systems that are likely to be experiencing strong and complex gravitational interactions, as is the case in compact groups (e.g., Rasmussen et al. 2012; Cluver et al. 2013), rather than purely galaxy–IGM interactions. This proximity limit excludes galaxies that are within 20 kpc at z = 0.01 and 105 kpc at z = 0.055.

The sample selected from matching the three different catalogs, excluding galaxies with close neighbors, includes 5924 galaxies. For these galaxies, the catalogs provide SDSS galaxy parameters, SDSS group parameters, and the ALFALFA H I 21 cm parameters. The lower limit on the redshift (z = 0.01) of the cross-matched sample is set by the SDSS group catalog and the upper limit (z = 0.055) is set by the NASA Sloan Atlas catalog. This is the matched sample catalog from which we construct the final group sample with controls as discussed in the following section.

3.2. Defining the Group and Control Samples

Our cross-matched galaxy sample is limited primarily by the ALFALFA detection limits, thus biasing the sample toward gas-rich systems. In particular, the detectability of an H I source depends on the galaxy redshift and the H I mass, which is at
least loosely correlated with the stellar mass (e.g., Catinella et al. 2010, 2012; Huang et al. 2012). To mitigate these biases, we constructed a control sample of isolated field galaxies. The control galaxies were selected to have similar stellar masses ($\Delta \log M_*=0.1$) and redshifts ($\Delta z<0.001$) as their group counterparts.

The catalog of 5924 galaxies provides the sample from which we drew both our isolated and group galaxies. Group galaxies were selected to have halo masses larger than $10^{12.5} h^{-1} M_\odot$, significantly larger than the 90% completeness limit ($10^{12.0} h^{-1} M_\odot$) in the group catalog (Yang et al. 2007), and group membership of more than four galaxies. Isolated galaxies were identified as galaxies residing in groups with one member. The numbers of galaxies with one group member (i.e., isolated field galaxies) and with group membership of more than four galaxies are 4372 and 618, respectively. The remaining 934 galaxies that are not included in this study reside in groups with 2–4 members.

The H I gas-to-stellar mass ratio is known to be correlated with galaxy stellar mass down to $M_* = 10^{10} M_\odot$, with a large scatter (0.43 dex, Catinella et al. 2012). This trend may continue to the lower masses but is harder to quantify because of sample incompleteness (Cortese et al. 2011; Huang et al. 2012; J. L. Rosenberg et al. 2015, in preparation). Because of the large scatter in this relationship, a small control sample will introduce a sampling bias and varying the numbers of controls will produce differences in the sample variance. Therefore, we use the same number of control galaxies, 8, for every group galaxy.

Forcing each group galaxy to have the same number of controls means that for a larger number of controls, the number of group galaxies with enough controls that meet the selection criteria ($\Delta \log M_*=0.1$ and $\Delta z<0.001$) decreases. Alternatively, decreasing the number of control galaxies increases the number of group galaxies with a full complement of controls, but it also increases the variance in the control sample. To optimize the control sample size, we investigated how the standard deviation of the H I gas-to-stellar mass ratio changes as the size of the control sample changes. For 50 randomly selected pairs of values for stellar mass and redshift that lie within the survey range a control sample was assembled. The average log $(M_{HI}/M_*)$ for each group of controls was calculated, resulting in 50 values of this parameter. The mean and standard deviation of these 50 values was then computed. This procedure was repeated for control samples with $N = 3, 5, 7, 15, 25,$ and 30 and the values for the standard deviation were plotted as a function of the number of controls in Figure 4. The same computation was carried out 20 times and the results are shown by the 20 black lines. The red line is the average of the 20 trials. This figure shows that small control samples deviate significantly from the expected statistical behavior of variance with sample size (shown by the thin solid line), $n$, which is proportional to $1/\sqrt{n}$, because the controls are not representative of the H I gas-to-stellar mass ratio distribution. Alternatively, as the number of controls increases, the number of available group galaxies declines.

Figure 4 indicates that the optimal control sample size where the variance goes as $1/\sqrt{n}$ while maximizing the number of group galaxies is between 7 and 10. We use eight control galaxies for each group galaxy as a balance between maximizing the number of controls and maximizing the number of group galaxies. Group galaxies with fewer than eight controls meeting the selection criteria ($\Delta M_*=0.1$ dex and $\Delta z<0.001$) are not included in the final sample. The best controls were selected by ranking the isolated galaxies based on the normalized distance from the group galaxy in the stellar mass-redshift plane (i.e., $d_{\text{norm}} = \sqrt{(\Delta \log M_*/0.1)^2 + (\Delta z/0.001)^2}$). The eight closest isolated galaxies were selected as the control sample for each group galaxy. This technique is similar to that used by Ellison et al. (2008).

Figure 5 shows the distribution of stellar masses and redshifts for galaxies in the group and isolated samples. Small dots are the isolated galaxies used as controls and blue circles
are the group galaxies. The filled circles show the final galaxy sample (390 group galaxies that each have eight controls). Note that there are not many group galaxies with a full complement of controls above $M_\star = 10^{10.63} M_\odot$. For this reason, our final sample is limited by $M_\star < 10^{10.63} M_\odot$. The stellar mass and redshift distributions of the galaxy group sample and the sample of their associated controls are drawn from the same population with more than 99% and 95% confidence, respectively, based on the Kolmogorov–Smirnov test (Press et al. 1986).

Figures 6 and 7 show galaxy stellar mass and redshift for the group and control samples as a function of the projected distance from the group center normalized by the group virial radius ($R_{180}$). The three panels show different halo mass bins. The $\Delta \log M_\star$ values are the difference between the log of the stellar mass of the group galaxy and the log of the average stellar mass of its eight controls. The $\Delta z$ values are the difference between the redshift of the group galaxy and the average redshift of its eight controls. The error bars associated with each group galaxy correspond to the ranges of stellar mass and redshift spanned by the galaxy’s eight control samples. The black solid lines connect the average of $\Delta \log M_\star$ and $\Delta z$ in six radial bins up to $1.2 R_{180}$ with errors defined by standard deviations of $\Delta \log M_\star$ and $\Delta z$ in each radial bin. The dashed lines show the 5th and 95th quantiles of the range of radial variation of the average values of $\Delta \log M_\star$ and $\Delta z$. This range is obtained by randomly shuffling the galaxies’ projected distances within the full range of projected distances of the group sample while keeping the values of $\Delta \log M_\star$ and $\Delta z$ the same. These ranges provide a measure of the statistical significance of the observed radial variation. Note that the error bars for each galaxy are always smaller than 0.1 in $\Delta \log M_\star$ and 0.001 in $\Delta z$ since the control galaxies are selected to have smaller stellar mass and redshift difference than these values.

The radial variation of the average stellar mass compared to the control sample is within 0.01 dex, which corresponds to a less than 3% difference in stellar mass. The radial variation of redshift difference is within 0.0002. The stellar masses and redshifts of the group galaxies do not show any systematic radial variation with respect to the control sample, which ensures that any measured systematic trends as a function of projected group-centric distance are not driven by the radial variation of these properties.
Figure 8. Difference in the $\text{H} \iota$ gas-to-stellar mass ratio between galaxies in the group sample and the mean of the corresponding eight control galaxies, as a function of the projected group-centric distance for different halo mass bins. The symbols and lines are the same as those in Figure 6.

4. THE INFLUENCE OF THE GROUP ENVIRONMENT ON THE HI CONTENT IN GALAXIES

The goal of this work is to study the impact of environment on the $\text{H} \iota$ gas content of galaxies in groups and clusters. To examine the impact of environment, we compare the gas content of galaxies within groups and clusters to that in field galaxies (i.e., the control sample) as a function of projected distance from the group center.

4.1. Radial Distribution of $\text{H} \iota$ Gas-to-Stellar Mass Ratio as a Function of Halo Mass

Figure 8 shows $\Delta \log (M_{\text{HI}}/M_*)$ as a function of projected distance from the group center normalized by $R_{180}$. The value $\Delta \log (M_{\text{HI}}/M_*)$ is defined as:

$$\Delta \log (M_{\text{HI}}/M_*) \equiv \log (M_{\text{HI}}/M_*)_{\text{group}} - \log (M_{\text{HI}}/M_*)_{\text{control}},$$

where $(M_{\text{HI}}/M_*)_{\text{control}}$ is the average value of the $\text{H} \iota$ gas-to-stellar mass ratio of the control sample.

The three panels show the results for three different halo mass bins, $10^{12.5}h^{-1} \ M_<(M_\bullet < 10^{13.35}h^{-1} \ M_\bullet)$, $10^{13.35}h^{-1} \ M_<(M_\bullet < 10^{13.85}h^{-1} \ M_\bullet)$, and $10^{13.85}h^{-1} \ M_<(M_\bullet < 10^{15.0}h^{-1} \ M_\bullet)$. The halo mass bins are chosen so that there are a similar number of galaxies ($\approx 120–150$) in each bin and so that the variation in the number of galaxies across the radial bins is small (i.e., the standard deviation of the number of galaxies in the six radial bins is $\approx 50\%–58\%$ of the average number of galaxies). The results presented here do not change significantly as the boundaries between the bins are shifted from $10^{13.30}h^{-1} \ M_\bullet$ to $10^{13.40}h^{-1} \ M_\bullet$ and from $10^{13.80}h^{-1} \ M_\bullet$ to $10^{13.90}h^{-1} \ M_\bullet$. The error bars and symbols in this figure are the same as in Figure 6. The black points connected by a solid line show the average $\Delta \log (M_{\text{HI}}/M_*)$ in each bin of projected distance from the group center.

Overall there is no statistically significant variation in the average $\Delta \log (M_{\text{HI}}/M_*)$ as a function of the projected group-centric distance. However, there is a hint of a decreasing $\Delta \log (M_{\text{HI}}/M_*)$ for galaxies in the central region ($d/R_{180} < 0.2$) of the group halos in the most massive halo bin. The average $\Delta \log (M_{\text{HI}}/M_*)$ in the smallest projected distance bin is beyond the range enclosed by the 5th and 95th percentiles of the variation but the deviation is small, so it can only hint at the impact of the most massive halos on the gas content of galaxies near their centers.

4.2. Radial Distribution of the Detection Fraction as a Function of Halo Mass

The lack of a statistically significant result in Figure 8 may be driven by the selection of only the most gas-rich galaxies by ALFALFA. Therefore, we investigate the fraction of galaxies detected by ALFALFA as a function of projected distance from the group center. For this analysis we compute the detection fraction for the group galaxies and compare it with the detection fraction of the associated controls. In practice, we define “detection ratio” as the ratio of the fraction of group galaxies detected at a given distance from the group center to the fraction of the associated control galaxies that are detected:

$$\text{Detection Ratio} = \frac{(N_{\text{det}}/N_{\text{tot}})_\text{group}}{(N_{\text{det}}/N_{\text{tot}})_\text{control}}.$$  

where $N_{\text{det}}$ is the number of galaxies detected by the ALFALFA survey and $N_{\text{tot}}$ is the total number of SDSS galaxies in the ALFALFA survey region.

For each bin of projected group-centric distance, we compute the numerator $(N_{\text{det}}/N_{\text{tot}})_\text{group}$ using all group galaxies that meet the selection criteria defined in Section 3.2. Then, for each SDSS group galaxy (both detected and not detected by ALFALFA) used for computing the numerator $(N_{\text{det}}/N_{\text{tot}})_\text{group}$, we identify a set of eight isolated control galaxies (the number of group members equals one in the group catalog) with similar stellar mass and redshift ($\Delta M_* < 0.1$ dex and $\Delta z < 0.001$). The denominator in Equation (5) is the fraction of the ALFALFA-detected control galaxies in the projected group-centric distance bin. The denominator provides a normalization of the detection fraction that is sensitive to the mass and distance of the group galaxies in each bin. For the control sample, $d/R_{180}$ and halo mass do not have a physical meaning. However, each control galaxy is associated with an individual galaxy that does have a projected separation from the group.

6 These massive halos were identified with some of the known galaxy clusters in the Abell catalog (Abell et al. 1989), including A160, A996, A1185, A1656 (in Coma), A1795, A1797, A2040, A2052, A2063, A2147 (in Hercules), and A2592.
Because there are different ways to select a control sample (e.g., the single best match like in Ellison et al. 2015 or allowing control galaxies to be selected only once), we performed this analysis using different selection criteria for the control sample and find no significant difference in the results. Therefore, we present the results for eight controls, consistent with the analysis from Section 4.1.

The upper left panel of Figure 9 shows the detection ratio for galaxies in group halos as a function of the group-centric distance for the same three halo mass bins as in Figure 8. The error bars are Poisson errors. The average detection fraction for the control galaxies is 27% and there is little variation among the three halo mass sub-samples (as expected since these are all isolated galaxies and are only associated with a halo mass bin because of the galaxies for which they serve as a control). When broken down further, there is a 7% variation in the detection fraction of the control samples across the radial bins with which they are associated (the higher variance is due to the smaller number of control galaxies associated with each radial bin).

For all halo masses there is a decrease in the detection ratio closer to the center of the groups. The decrease in detection ratio is significantly stronger for galaxies in the most massive halo bin, reaching only 6% of the detection fraction of the control sample in the smallest projected distance bin at $d/R_{180} = 0.1$.

We can only measure the projected distance of galaxies with respect to the group center and so in each projected radius bin there are foreground or background “interlopers,” group galaxies at significantly larger real separations from the group center than their projected separations. Therefore, the detection fraction in a given projected separation bin is an upper limit.
because these interlopers are further from the group center and thus more similar to the field galaxy population. To estimate the population of these interlopers in each bin, we use the projected mass profile from Lokas & Mamon (2001), which is based on an Navarro–Frenk–White (NFW) profile (Navarro et al. 1997) with a concentration parameter $c = 7$. At projected distances of $d/R_{200} = 0.1, 0.3, 0.5, 0.7, 0.9,$ and $1.1$, this model predicts interloper fractions of $0.33, 0.16, 0.11, 0.07, 0.06$, and $0.05$ respectively.

In the innermost radial bin $d/R_{200} = 0.1$, the numbers of group galaxies detected by ALFALFA are 16, 25, and 9 and the total numbers of group galaxies are 362, 366, and 486, for the lowest, middle, and highest halo mass bins, respectively, which corresponds to detection fractions of $4\%$, $7\%$, and $2\%$, respectively. If one-third of the galaxies in the innermost radial bin are interlopers (120, 120, and 161 for each halo mass bin), then even a modestly higher detection rate for these galaxies that only appear to be in the group because of projection effects would account for many of the detections. More relevant than the specific numbers, which are highly affected by small number statistics, is that these low detection rates in the centers of groups and clusters are likely to be upper limits because of these interlopers. In addition, the sample has been selected to avoid the densest groups (no more than one galaxy in the beam of the radio telescope) where some of these effects are likely to be even more severe.

### 4.2.1. Effect of Galaxy Stellar Mass

The differences in the depth of the gravitational potential mean that the impact of environment on the H\(_1\) gas in a galaxy may be correlated with galaxy mass. The three additional panels of Figure 9 show the detection ratio broken down by the galaxy stellar mass for each halo mass bin. The galaxies are divided into high (larger red symbol) and low (smaller blue symbol) stellar mass systems at a mass of $10^{9.6} M_\odot$, which roughly corresponds to the median of the galaxy stellar mass distribution in the group sample. The detection ratio for low stellar mass galaxies ($\sim0.25$) is significantly less than the ratio for high stellar mass galaxies ($\sim0.55$) inside the virial radius ($d/R_{200} < 0.8$) for the lowest halo mass bin (upper right panel of Figure 9). The impact of the stellar mass of the galaxy on the detection ratio becomes less significant with increasing halo mass. For the highest mass halos, the detection ratio for low-mass galaxies ($M_*= < 10^{9.6} M_\odot$) just beyond the virial radius is only $43\%$ of that in the field, corresponding to a $2\sigma$ deviation. Although the statistical significance is not large, this result may indicate that small galaxies in the outskirts of massive halos are already gas-poor compared to the field galaxies with similar stellar masses and redshifts.

### 4.2.2. Effect of Galaxy Type: Sérsic Index

The morphology–density relation (Dressler 1980) implies that there are more early-type galaxies toward the centers of galaxy clusters (e.g., Blanton et al. 2005). To examine whether the decreasing detection ratio in Figure 9 is due to decreasing amounts of gas in the galaxies or to different galaxy morphologies as a function of position in the group, the three additional panels of Figure 10 show the detection ratio broken down by the galaxy Sérsic index for each halo mass bin. The galaxies are divided into high (larger red symbol) and low (smaller blue symbol) Sérsic index systems at $n = 2.0$ and then a control sample for each galaxy with $n > 2.0$ (and $n < 2.0$) is drawn from the pool of isolated galaxies with $n > 2.0$ (and $n < 2.0$), using the same stellar mass and redshift criteria that we used. This cut in the Sérsic index provides a very clean sample of late-type galaxies (Maller et al. 2009) that can be examined for gas depletion. However, the $n > 2$ sample is more mixed and thus more difficult to interpret. We also controlled the Sérsic index when making the control sample by restricting the Sérsic index difference between group galaxy and controls (i.e., $\Delta n = 2$); however, we found that the result has not been changed qualitatively. The detection ratio for both low and high Sérsic index galaxies decreases toward the group center, indicating that even in the disk galaxies gas is being depleted toward the center of the groups.

### 4.3. Halo Mass Dependent Ram Pressure Stripping

The strongly decreasing detection ratio of galaxies toward the center of the most massive halos compared with that of the lower-mass halos suggests a gas depletion process that is dependent on halo mass. The H\(_1\) gas depletions seen in galaxies that reside in massive clusters is best explained by ram pressure stripping (e.g., Vollmer et al. 2001; Boselli & Gavazzi 2006; Roediger 2009; Cortese et al. 2011). Some galaxies in groups also represent strong candidates for ram pressure stripping (e.g., Bureau & Carignan 2002; Rasmussen et al. 2006; McGonnachie et al. 2007; Sengupta et al. 2007), although it is harder to distinguish the impact of ram pressure stripping from that of tidal interactions in these lower-mass halos (e.g., Rasmussen et al. 2008; Kilborn et al. 2009). The decrease in the detection fraction for galaxies with small ($n < 2$) Sérsic indices implies that gas is being removed from the system regardless of the galaxy type and that mergers that can transform galaxies from late- to early-types are not the dominant reason for this result. This gas removal can take two forms in these environments: ram pressure stripping (removal of cold gas from the disk of the galaxy) and starvation (removal of hot gas from the galaxy halo). Since starvation cannot be probed directly with these H\(_1\) observations, we focus our discussion on ram pressure stripping. The simple criterion for ram pressure stripping first proposed by Gunn & Gott (1972) is

$$\rho_{\text{ICM}} v^2 > 2\pi G \Sigma_e \Sigma_{\text{ISM}},$$

where $\rho_{\text{ICM}}$ is the density of the hot ICM, $v$ is the speed of infalling galaxy, $\Sigma_e$ is the galaxy stellar surface density, and $\Sigma_{\text{ISM}}$ is the galaxy interstellar medium (ISM) surface density. This criterion implies that gas stripping occurs if the ram pressure (i.e., force per unit area) is greater than the gravitational binding force per unit area in the ISM.

We provide a simple analytic calculation based on the Gunn and Gott (GG) criterion to examine the effect of halo mass on ram pressure stripping. The GG criteria has previously been modified to be expressed in terms of specific observables: for example, IGM electron density, a component of the galaxy velocity relative to the group, central stellar velocity dispersion of the galaxy, and H\(_1\) gas density of the galaxy (e.g., Grebel et al. 2003; Greveich & Putman 2009; Freeland & Wilcots 2011). To study the impact of halo mass on ram pressure stripping for a range of galaxy stellar masses we use the virial theorem and galaxy scaling relations to rewrite the left side of the GG criterion to have explicit dependence on group halo
mass and ICM density and the right side to depend only on galaxy stellar mass (see Appendix for details). With these changes the GG criterion depends on the mean electron number density in groups or clusters, the halo mass and the galaxy stellar mass:

\[
\left( \frac{n}{10^{-3} \text{ cm}^{-3}} \right) \left( \frac{M_h}{10^{14} h^{-1} M_\odot} \right)^{2/3} \geq 1.24 \left( \frac{M_*}{10^{10} M_\odot} \right)^{0.58} \left( 1 + 0.25 \times \frac{M_h}{10^{10} M_\odot} \right)^{-1}.
\] (7)

Massive halos have high ICM densities (e.g., Cavagnolo et al. 2009) due to their strong gravitational potentials, while small mass halos tend to have low ICM densities. The halo mass is also related to the X-ray luminosity through an observational scaling relation (e.g., Arnaud et al. 2007).

Therefore, the virial theorem and X-ray scaling relation imply that the mean electron number density of the ICM, the halo mass, and the kinetic temperature of the ICM are related by (see the Appendix for details):

\[
\left( \frac{n}{10^{-3} \text{ cm}^{-3}} \right) \approx 0.68h^3 \left( \frac{T}{\text{keV}} \right)^{-1} \left( \frac{M_h}{10^{14} h^{-1} M_\odot} \right)^{0.824}.
\] (8)

By combining these two relations and neglecting the redshift dependence, one can determine where the GG criterion is valid in the group halo mass and galaxy stellar mass plane for a given ICM temperature. Figure 11 shows the distribution of the group sample (black points) in the halo mass and galaxy stellar mass plane for galaxies within the virial radius of their group halo (where ram pressure is expected to play a role), with black lines representing Equation (7) using \( n \) determined by Equation (8) for ICM temperatures ranging from 1 to 8 keV. The colored regions show the average \( \Delta \log (M_{11}/M_*) \) of galaxies in each
Figure 11. Halo-mass galaxy stellar mass plane that determines the conditions for efficient ram pressure stripping. The black lines represent the different ICM temperatures based on Equation (7) and divide the halo mass galaxy stellar mass parameter space into the regions where ram pressure dominates and where galaxy gravity dominates. Ram pressure stripping is efficient in the region above the black lines for a given ICM temperature. The distribution of the group galaxy sample used in this study is shown by black points; the colored squares represent the weighted average of \( \Delta \log (M_{\text{HI}}/M_*) \) in each bin.

5. DISCUSSION

5.1. Gas Removal in Group and Cluster Halos

Using the SDSS and ALFALFA surveys, we have examined the evidence for ram pressure stripping of H\textsc{i} gas in groups and clusters. We find no statistically significant evidence for a change in the galaxy H\textsc{i} gas-to-stellar mass ratio as a function of projected distance from the group center in this sample despite the existing evidence for gas depletion in clusters (Haynes et al. 1984; Haynes & Giovanelli 1986; Solanes et al. 2001). This result is, however, consistent with the previous H\textsc{i} studies of gas depletion in Virgo Cluster galaxies (Taylor et al. 2012) and Coma Supercluster galaxies (Abell 1367, Cortese et al. 2008). The distribution of the H\textsc{i} gas-to-stellar mass ratio in galaxies shows a large scatter (e.g., 0.43 dex in Catinella et al. 2012), even at fixed stellar mass, which drives a large standard deviation (approximately 0.4 dex or a factor of 2.5 as seen in Figure 4) in \( \Delta \log (M_{\text{HI}}/M_*) \).

Although in principle it is possible to detect a difference in the average H\textsc{i} gas-to-stellar mass ratio between groups and the field with enough statistics, our sample of groups with eight controls (390) is not enough to detect the difference. A robust detection of gas depletion in groups will require deeper H\textsc{i} surveys that increase the dynamic range of detected gas fractions for a large number of galaxies in groups and clusters.

While the direct measurement of gas removal in groups and clusters using ALFALFA-detected galaxies alone is not possible without relying on a deeper H\textsc{i} survey for a sample with a stellar mass threshold (GASS; Catinella et al. 2010, 2012) or a stacking of ALFALFA spectra (Fabello et al. 2012), we confirm the results of Hess & Willcocks (2013) using a sample with matched controls and measure this removal indirectly through the decreasing detection ratio, which is a ratio of the detection fraction for group galaxies to that for isolated galaxies. By controlling our sample for stellar mass and redshift we show that this is a real effect and not a function of selection effects and sampling. We find that the most significant decrease in detection ratio occurs in the most massive halos, as expected from the ram pressure stripping discussed in Section 4.3. This result is consistent with previous studies by Catinella et al. (2013) and Fabello et al. (2012). Nevertheless, the detection ratio does decrease significantly in the innermost regions of even the lowest-mass groups, which is consistent with the detection of X-rays in some halos of these masses (e.g., Zabludoff & Mulchaey 1998; Henslon & Ponman 2000; Mulchaey 2000).

Assuming the IGM temperature to be 1 keV for the lowest-mass groups (\( M_h < 10^{13.5} h^{-1} M_\odot \)) in this study, our calculation indicates that ram pressure should only be effective for galaxies with stellar masses below \( 10^8 M_\odot \), yet all of the galaxies in this sample are more massive than this limit and still show a decreasing detection ratio toward the group center. Either the IGM temperature in these low-mass groups is lower than assumed (<1 keV, e.g., Henslon & Ponman 2000; Trinchieri et al. 2012), implying a larger mean IGM density than 8 \( \times 10^{-3} \text{ cm}^{-3} \) from Equation (8) which is similar to the value for poor groups (8.9 \( \times 10^{-3} \text{ cm}^{-3} \), Zabludoff & Mulchaey 1998), enough for ram pressure stripping of dwarf galaxies (e.g., Bureau & Carignan 2002), or a process other than ram pressure stripping is responsible for removing the gas in these low-mass halos (e.g., Rasmussen et al. 2012).

Using a large sample (N \( \approx 23,000 \)) of galaxies with H\textsc{i} mass inferred from photometry, Zhang et al. (2013) investigate the effect of galaxy stellar mass on the H\textsc{i} content of galaxies in groups and clusters and find that lower stellar mass galaxies show a stronger radial decrease in H\textsc{i} gas content toward the brightest cluster galaxy and that this trend becomes
more significant for galaxies with lower stellar surface density. While we cannot probe the effect of stellar surface density for a given galaxy stellar mass due to a small sample size, Figure 9 shows that for the lowest-mass halos it is only the low-mass galaxies that are significantly stripped, while in the high-mass halos all of the galaxies are likely to be impacted. Our result that the halo mass impacts the degree of gas depletion contrasts with those of Zhang et al. (2013), who find no difference as a function of group velocity dispersion as a proxy for halo mass. This difference may be related to the large dispersion in the velocity dispersion–halo mass relation (e.g., Weinmann et al. 2010) and/or the additional impact of tidal stripping on the gas in their sample galaxies (Zhang et al. 2013). For this study galaxies with neighbors within 1.75 (which means no pair galaxies within 20 kpc at z = 0.01 and 105 kpc at z = 0.055) have been excluded. Many of the excluded galaxies with small velocity separations are likely to be undergoing tidal interactions, as suggested by Scudder et al. (2012). Therefore, this sample should be significantly less strongly impacted by tidal interactions than Zhang et al. (2013) and should more clearly show the impact of ram pressure stripping on these galaxies.

5.2. Effect of Pre-processing

In hierarchical models, the gas content in galaxies decreases during interactions within small groups before they enter a large halo (e.g., Fujita 2004). Observing this pre-processing of small groups is challenging because the current merger rate is considerably lower than in the past (Gottlöber et al. 2001). However, there is supporting evidence for pre-processing revealed, for example, by the star formation quenching as a function of galaxy environment in and around the Coma Supercluster (Cybulski et al. 2014); the distribution of post-starburst galaxies in sub-structures of galaxy clusters (Mahajan 2013); and the ionized gas distribution in compact groups of galaxies (Cortese et al. 2006).

The detection ratio of galaxies at the largest group-centric distances (i.e., beyond the virial radius) may provide a measurement of how environment has affected the systems prior to their falling into the group. The upper left panel of Figure 9 shows with marginal (1.5σ) statistical significance that the H I detection fraction in massive halos (M h > 10^3.85h^{-1}M_\odot) is 68% of the detection fraction for the control sample even beyond the virial radius (i.e., d/R_{vir} ≈ 1). The effect is even more strongly pronounced for the lowest-mass galaxies, as shown in the lower right panel of Figure 9, where the detection fraction of the lowest-mass galaxies is less than that of the control sample by 43%, corresponding to a 2σ difference.

While not definitive because of the low statistical significance, this depression in the detection fraction for small galaxies in massive halos provides a tantalizing indication that these small galaxies are already H I deficient when they fall into the massive halos, as also suggested by Jaffé et al. (2012) based on the H I measurement of compact group. This trend of gas deficiency at the outskirts of massive halos supporting a pre-processing scenario is predicted by a semi-analytic model of mass accretion (e.g., McGee et al. 2009) and hydrodynamic simulation of H I gas content (e.g., Rafieferantsoa et al. 2014), and also implied by recent observational studies using a statistical sample (e.g., Hess & Wilcots 2013; Hou et al. 2014).

In considering the significance of this depression at large group-centric distances and the other results presented here, it is important to consider whether the sample selection criteria (excluding groups with fewer than five members, excluding galaxies with close neighbors, and excluding galaxies with fewer than eight controls) might bias these results. While bias cannot be ruled out, these selection criteria should not influence these results within the bounds of the sample (i.e., we cannot evaluate the impact of the group environment on the smallest and most compact groups) with the exceptions of the close neighbors. The removal of galaxies with close neighbors will preferentially eliminate interacting pairs. Interacting pairs, however, have not shown any significant decrease or increase in their detection fraction (Fertig et al. 2015, submitted) implying that the impact of removing galaxies with close neighbors will not introduce a significant bias to the detection ratio estimate.

6. CONCLUSIONS

We have investigated the H I gas content in groups and clusters over a wide range of halo masses and the results of this study are as follows.

1. There is no statistically significant variation in the H I gas-to-stellar mass ratio with the projected distance from the group center in the sample studied here.

2. The detection ratio of galaxies decreases toward the center of groups spanning the range of masses studied here, with the most significant decrease occurring toward the centers of the most massive halos.

3. We frame the GG criteria in terms of halo mass and stellar mass and find that the change in the radial distribution of the detection ratio with respect to halo mass is qualitatively consistent with ram pressure stripping, while the decrease in the detection ratio for galaxies with M_h < 10^{9.6} M_\odot in the lowest-mass halos is not consistent with ram pressure stripping unless the temperature of the IGM is lower than assumed (i.e., <1 keV).

4. The detection ratio for low (M_h < 10^{0.6}M_\odot) stellar mass galaxies just beyond the virial radius of the most massive groups is 2σ below unity, which could be due to the pre-processing of these galaxies before they fall into the larger groups.

The lack of a significant detection of H I depletion in groups and clusters indicates that ALFALFA is not sufficiently deep to measure this effect because of the large galaxy-to-galaxy dispersion in gas content. Even deeper H I surveys like the AGES do not find strong evidence for H I deficiency increasing toward the center of the Virgo (Taylor et al. 2012) and Coma/A1367 (Cortese et al. 2008) clusters. Explicitly measuring the amount of environment dependent gas depletion will require significantly deeper large statistical samples, which might have to wait for the full SKA (Catinella et al. 2013).

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APPENDIX

A SIMPLE FORM OF THE GG CRITERION DEPENDING ON HALO MASS

A simple criterion for ram pressure stripping first proposed by Gunn & Gott (1972) is

$$\rho_{\text{ICM}} v^2 \geq 2\pi G \Sigma_* \Sigma_{\text{ISM}},$$

where $\rho_{\text{ICM}}$ is the density of hot ICM, $v$ is the speed of infalling galaxy, and $\Sigma_*$ and $\Sigma_{\text{ISM}}$ are the density of galaxy stellar mass and the ISM, respectively. Using a simple assumption that the galaxy stellar mass ($M_*$) and ISM mass ($M_{\text{ISM}}$) are distributed along the same characteristic radius $r_g$, we can rewrite this criterion as

$$\left( \frac{n}{10^{-3} \text{cm}^{-3}} \right) \left( \frac{\sigma}{1000 \text{ km s}^{-1}} \right)^2 \geq 0.37 \left( \frac{M_*}{10^{10} M_\odot} \right)^2 \left( \frac{M_{\text{ISM}}}{10^8 M_\odot} \right) \left( \frac{r_g}{10 \text{ kpc}} \right)^{-4},$$

where $n$ is the mean electron number density in a galaxy cluster such that $\rho_{\text{ICM}} = nm_p$ and $\sigma$ is the line-of-sight velocity dispersion of galaxies in groups and clusters (i.e., $v^2 \approx 3\sigma^2$).

If one defines the halo mass $M_h = M_{180}$ and the halo virial radius $R_{\text{vir}} = R_{500}$ using the quantities at an overdensity of 180 and combines the virial theorem $\sigma^2 = \frac{2GM_h}{R_{\text{vir}}}$ and Equation (3), one can modify Equation (10), and the ram pressure criterion, including halo, mass is written as

$$\left( \frac{n}{10^{-3} \text{cm}^{-3}} \right) \left( \frac{M_*}{10^{14} h^{-1} M_\odot} \right)^{2/3} \geq 4.23 \left( \frac{M_*}{10^{10} M_\odot} \right)^2 \left( \frac{M_{\text{ISM}}}{M_*} \right) \left( \frac{r_g}{10 \text{ kpc}} \right)^{-4},$$

where we replace $M_{\text{ISM}}$ with cold atomic gas mass $M_{\text{HI}}$.

Furthermore, if we adopt the scaling relations between $M_*$ and $r_g$ and between $M_*$ and $M_{\text{HI}}$, the physics on the right side of the above criterion can be described by galaxy stellar mass $M_*$ only. Among galaxy scaling relations, we use the relation $M_{180}/M_* \approx 0.72 \left( \frac{M_*}{10^{10} M_\odot} \right)^{-0.86}$ from Masters et al. (2012), which finds the similar relation to other studies (Catinella et al. 2010; Fabello et al. 2011; Toribio et al. 2011) and the relation between $M_*$ and $r_g$ derived from the relation between galaxy stellar mass and half-light radius for late-type galaxies with a Sérsic index $n < 2.5$, $r_{500} \approx 0.1 \left( \frac{M_*}{M_\odot} \right)^{0.14} \left( \frac{1 + M_*}{3.98 \times 10^{10} M_\odot} \right)^{0.25}$ in Shen et al. (2003). We define $r_g$ as $5 \times r_{500}$ which encloses nearly 100% and 90% of the total luminosity from the Sérsic profile for $n = 1$ and $n = 4$, respectively (e.g., Yoon et al. 2011). Then we can simplify the Equation (11) as follows

$$\left( \frac{n}{10^{-3} \text{cm}^{-3}} \right) \left( \frac{M_*}{10^{10} h^{-1} M_\odot} \right)^{2/3} \geq 1.24 \left( \frac{M_*}{10^{10} M_\odot} \right)^{0.58} \left( 1 + 0.25 \times \frac{M_*}{10^{10} M_\odot} \right).$$

(12)

On the other hand, soft X-ray emission from a galaxy cluster can be used to infer the mean electron number density $n$ of the cluster. One of the robust scaling relations is the $I_X$-$M_{500}$ relation (Arnaud et al. 2007):

$$h^2/(z)M_{500} \approx 10^{14.40} \times \left( \frac{M_{\text{ISO}} T_X}{2 \times 10^{14} M_\odot \text{keV}} \right)^{0.548} h^{-1} M_\odot,$$

(13)

where $h^2/(z) = \Omega_\text{M}(1 + z)^3 + \Omega_\Lambda$, $T_X$ is the kinetic temperature of the ICM, $M_{500}$ is the total mass of a cluster enclosed by the radius $R_{500}$, and $M_{\text{ISO}}$ is the mass of hot gas enclosed by $R_{500}$. By substituting $M_{\text{ISO}}$ with $\frac{4\pi}{3}R_{500}^3n_m$, we express the $n$-given halo mass and temperature at $z = 0$ (i.e., $h(z) = 1$) as follows:

$$\left( \frac{n}{10^{-3} \text{cm}^{-3}} \right) \approx 0.68h^3 \times \left( \frac{T}{\text{keV}} \right)^{-1} \left( \frac{M_{180}}{10^{14} h^{-1} M_\odot} \right)^{0.824},$$

(14)

where $M_{180}$ is converted from $M_{500}$ (Reiprich et al. 2013) by assuming an NFW profile (Navarro et al. 1997). By combining Equations (12) and (14) and using $M_* \approx M_{180}$, one can find a region where ram pressure stripping becomes efficient for a given galaxy stellar mass, halo mass, and kinetic temperature of the ICM in the halo, as shown in Figure 11.

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