WARM GAS IN THE VIRGO CLUSTER. I. DISTRIBUTION OF Lyα ABSORBERS

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ABSTRACT

The first systematic study of the warm gas ($T = 10^4$–$10^5$ K) distribution across a galaxy cluster is presented using multiple background QSOs in and around the Virgo Cluster. We detect 25 Lyα absorbers ($N_{\text{HI}} = 10^{13.1}$–$15.4$ cm$^{-2}$) in the Virgo velocity range toward 9 of 12 QSO sightlines observed with the Cosmic Origin Spectrograph, with a cluster impact parameter range of 0.36–1.65 Mpc (0.23–1.05 $R_{\text{vir}}$). Including 18 Lyα absorbers previously detected by STIS or GHRS toward 7 of 11 background QSOs in and around the Virgo Cluster, we establish a sample of 43 absorbers toward a total of 23 background probes for studying the incidence of Lyα absorbers in and around the Virgo Cluster. With these absorbers, we find (1) warm gas is predominantly in the outskirts of the cluster and avoids the X-ray-detected hot intracluster medium (ICM). Also, Lyα absorption strength increases with cluster impact parameter. (2) Lyα-absorbing warm gas traces cold H$_{\alpha}$-emitting gas in the substructures of the Virgo Cluster. (3) Including the absorbers associated with the surrounding substructures, the warm gas covering fraction (100% for $N_{\text{HI}} > 10^{13.1}$ cm$^{-2}$) is in agreement with cosmological simulations. We speculate that the observed warm gas is part of large-scale gas flows feeding the cluster both in the ICM and galaxies.

Key words: cosmology: observations – galaxies: clusters: general – intergalactic medium – quasars: absorption lines

Online-only material: color figures

1. INTRODUCTION

Most of the baryons in the universe exist in diffuse gas phases (Davé et al. 2010; Shull et al. 2011). Simulations predict that the diffuse gas that produces Lyα absorbers ($T < 10^5$ K) occupies most of the cosmic volume and accounts for 20%–40% of the baryonic mass budget at $z = 0$ (Cen & Ostriker 1999; Davé et al. 2001). Observations of low-redshift Lyα clouds find 20%–30% of the baryons in photoionized warm gas which is consistent with simulations (Penton et al. 2000, 2004; Lehner et al. 2007; Danforth & Shull 2008).

In a galaxy cluster, gas can exist in a variety of phases. Studies of the kinematics and thermal state of the intracluster medium (ICM) provide important clues about clusters, galaxies, and star formation mechanisms in cosmological simulations (Loken et al. 2002; Kravtsov et al. 2005; Roncarelli et al. 2006; Burns et al. 2010). Most of the gas falling into a cluster’s dark matter potential well is shock-heated to the virial temperature (White & Rees 1978; Cen & Ostriker 1999; Davé et al. 1999), and X-ray emission from this hot ICM is commonly observed. The hot gas contributes $\sim 80\%$ of the total baryonic content while the contribution of cold neutral gas (observed via 21 cm emission) is less than 1% in a galaxy cluster (Ettori et al. 2004).

The warm gas ($T = 10^4$–$10^5$ K) remains largely unprobed in a galaxy cluster despite its large mass fraction in the universe, and importance in understanding the multiphase nature of the ICM. It is too cold to be probed by X-ray emission, too hot to be traced by H$_{\alpha}$ emission, and usually too diffuse to be detected in optical emission. Observations of Lyα absorption lines are one of the most promising methods of studying warm gas in the intergalactic medium (IGM; Rauch 1998, and references therein).

Absorption line studies have been used to probe a variety of structures in the universe. The early work by Spitzer (1956) suggested the possible existence of a galactic corona surrounding a galaxy which could result in multiple UV absorption lines in a QSO spectrum (Bahcall & Spitzer 1969). While some Lyα absorbers are thought to be directly linked to halo gas in galaxies (Carilli & van Gorkom 1992; Lanzetta et al. 1995; van Gorkom et al. 1996; Chen et al. 1998, 2001; Penton et al. 2002), others seem to be unrelated to any galaxy systems (see the review of Rauch 1998). Rather, they seem to be associated with structures in the IGM, such as filaments or sheets (Dinshaw et al. 1997; Impey et al. 1999; Rosenberg et al. 2003; Côté et al. 2005). More specifically, weak absorbers ($W < 100–300$ mÅ) do not cluster strongly with known galaxies and the majority are speculated to originate in the cosmic web (Chen & Mulchaey 2009; Prochaska et al. 2011). Attempts to map warm gas in large-scale structures between galaxies and filaments (i.e., groups and clusters) are limited. IGM absorbers associated with a galaxy group or cluster toward a single QSO sightline were studied by several authors (Lanzetta et al. 1996; Koekemoer et al. 1998; Tripp et al. 1998; Ortiz Gil et al. 1999; Miller et al. 2002; Prochaska et al. 2006; Lopez et al. 2008), but no studies of the warm gas distribution throughout a cluster have been made.

The Virgo Cluster is the closest galaxy cluster to us (16.5 Mpc, Mei et al. 2007) and is therefore very extended spatially ($\sim 12^\circ$ diameter). It provides a unique location for studying the flow of gas in relation to both small and large dark matter structures. Observations of this irregular cluster have been obtained at various wavelengths to map the X-ray-emitting hot gas (e.g., Böhringer et al. 1994; Urban et al. 2011), atomic hydrogen (Gavazzi et al. 2005; Giovanelli et al. 2007; Popping & Braun 2011), dust (Davies et al. 2010), and stars (Côté et al. 2004; Mihos et al. 2005). The Virgo Cluster therefore provides a unique laboratory for studying the relationship between baryons in different phases.

The ability to map warm gas in relation to dark matter structures has increased substantially with access to the Cosmic Origin Spectrograph (COS; Green et al. 2012) on board the...
follows. In Section 2, we describe the observational data used to a cosmological cluster simulation. The paper is organized as the hot ICM and cluster substructures. We also compute the probe the spatial distribution of the absorbers with respect to around a single galaxy cluster is studied systematically with spectroscopy. In this paper, the warm gas distribution in and density of background probes available for absorption line

| QSO          | Short Name | z_{QSO} | t_{exp} (s) |
|--------------|------------|---------|-------------|
| SDSSJ120556.08+104253.8 | J1205+1042 | 1.0884 | 4776        |
| SDSSJ120924.07+103612.0$^6$ | J1209+1036 | 0.3949 | 4839        |
| SDSSJ121430.55+082508.1 | J1214+0825 | 0.5854 | 4812        |
| SDSSJ121640.56+071224.3 | J1216+0712 | 0.5865 | 2048        |
| SDSSJ121716.08+080942.0 | J1217+0809 | 0.3428 | 2094        |
| SDSSJ121850.51+101554.2 | J1218+1015 | 0.5424 | 5116        |
| SDSSJ122018.43+064119.6 | J1220+0641 | 0.2864 | 2255        |
| SDSSJ122102.49+155447.0 | J1221+1554 | 0.2294 | 2263        |
| SDSSJ122312.16+095017.7 | J1223+0950 | 0.2771 | 2258        |
| SDSSJ122317.79+092306.9 | J1223+0923 | 0.6815 | 5108        |
| SDSSJ122512.93+121835.6 | J1225+1218 | 0.4118 | 2063        |
| SDSSJ122520.13+084450.7 | J1225+0844 | 0.5530 | 1942        |
| SDSSJ122642.80+072411.3 | J1226+0724 | 0.8439 | 2072        |
| SDSSJ122647.72+060048.4$^4$ | J1226+0600 | 1.2779 | 4743        |
| SDSSJ124035.51+094914.0$^6$ | J1240+0949 | 0.1049 | 5110        |

Note. $^6$ These sightlines were wiped out by an LLS.

**Hubble Space Telescope (HST).** It has a higher throughput than previous instruments, allowing us to obtain high signal-to-noise UV spectra of faint QSOs and increasing the surface density of background probes available for absorption line spectroscopy. In this paper, the warm gas distribution in and around a single galaxy cluster is studied systematically with multiple sightlines for the first time. The data enable us to probe the spatial distribution of the absorbers with respect to the hot ICM and cluster substructures. We also compute the covering fraction of warm gas, discuss the relative distribution of warm gas around gas-rich galaxies, and make comparisons to a cosmological cluster simulation. The paper is organized as follows. In Section 2, we describe the observational data used in this study as well as physical properties of the Virgo Cluster. The overall distribution of warm gas, its covering fraction, and the association of Lyα absorbers with Virgo substructures are discussed in Section 3. Finally, Section 4 discusses the results and the origin of warm gas, and Section 5 briefly summarizes our results. Throughout this paper, the cosmological parameters are assumed to be Ω_m = 0.3, Ω_Λ = 0.7, and H_0 = 70 km s^{-1} Mpc^{-1}.

### 2. DATA

We observed 15 QSOs in the background of the Virgo Cluster with COS, which are described in Section 2.1. We found 12 QSO spectra could be used to find absorption lines. We also searched the literature and found 11 QSO sightlines around the Virgo Cluster that were observed by STIS or GHRS (see Section 2.2). Forty-three Lyα absorbers are found along nine of the COS sightlines and seven of the STIS or GHRS sightlines and these are described in Section 2.3. The galaxy catalogs we use in this study and the known physical properties of the Virgo Cluster are noted in Section 2.4 and previous studies on the Virgo substructures are summarized in Section 2.5.

#### 2.1. COS Observations

We obtained UV spectra of 15 QSOs behind the Virgo Cluster with COS in HST Cycle 17 (PID 11698; PI: Putman). Table 1 shows a basic journal of the observations. The QSO sightlines were selected from the catalog of Véron-Cetty & Véron (2006) to lie within or slightly beyond the virial radius of Virgo and by their FUV brightness from the Galaxy Evolution Explorer (Martin et al. 2005) source catalog. As we are primarily interested in Lyα absorption lines in the Virgo Cluster, all targets were observed only with the G130M grating, using the 1300 Å central wavelength setting. Our targets were assigned either one or two orbits of time, based on their FUV brightness. For our eight single-orbit targets, we employed two FP-POS positions to dither the spectra in order to reduce the impact of fixed-pattern and grid-wire flat-field effects. The remaining seven targets were assigned two orbits, and for these we employed all four FP-POS positions.

The data were pipeline processed and extracted from the MAST archive using calcos v2.12. To combine the individual spectra, we employed the co-addition developed for several COS large programs. These routines are fully described in the literature (Meiring et al. 2011; Thom et al. 2011; Tumlinson et al. 2011). Briefly, each exposure in each of the two detector segments is aligned and co-added using a common Milky Way absorption line as a reference (e.g., Si iii 1206). Then the two detector segments are co-aligned and combined into a single one-dimensional spectrum. A primary advantage of these co-addition routines is that they operate in count space, and so correctly calculate the Poisson errors of the counts in each pixel (Gehrels 1986). This is beneficial since our data are in the low-count regime ($N < 30$).

#### 2.2. STIS and GHRS Observations from the Literature

From the previous STIS and GHRS observations of QSOs in the vicinity of the Virgo Cluster, 11 additional QSO sightlines are selected for this study (Impey et al. 1999; Rosenberg et al. 2003; Penton et al. 2004; Chen & Mulchaey 2009; Williger et al. 2010). We adopt line identifications and measurements from the references noted. For 3C273, four Lyα lines were consistently detected in the independent studies with GHRS and STIS data (Penton et al. 2000; Williger et al. 2010). We, therefore, adopt these four lines. The blended Lyα lines at $z = 0.005251$ and $z = 0.005295$ detected by Williger et al. (2010) are considered as one line since our COS data cannot resolve these two lines (COS velocity resolution $\sim 15$ km s$^{-1}$). The Lyα line list of PG1216+069 is adopted from Chen & Mulchaey (2009). For both sightlines, 3C273 and PG1216+069, equivalent widths of the Lyα absorption lines were not provided in the papers (Chen & Mulchaey 2009; Williger et al. 2010), hence, we re-measure the equivalent widths of these Lyα lines from the STIS data. Details of the spectral processing for the STIS data were described in Thom & Chen (2008).

#### 2.3. Lyα Absorbers

In the COS data, we identified a total of 25 Lyα absorption lines toward 9 sightlines in the Virgo velocity range ($700 < \text{cz} < 3000$ km s$^{-1}$, see Section 2.4) above a significance level $W/\sigma_W > 4.5$. Three sightlines had no detections over this significance level (see Table 2). We note that the lowest significance level of the absorbers detected is 4.9 which makes our absorber selections robust. The spectra of three sightlines, J1209+1036, J1236+0600, and J1240+0949, were wiped out by Lyman limit systems, and thus excluded. We do not attempt to detect absorption lines at velocities $< 700$ km s$^{-1}$ due to the contamination by the damping wing of the Milky Way Lyα absorption. Through close analysis of the data, we also find completeness is affected for a few sightlines between 700 and 1000 km s$^{-1}$ due to this damping wing. We therefore present the absorbers within this range in Table 2 (marked with d), but do...
not use them in the galaxy correlation and covering fraction analysis. The 4.5σ detection limits in Table 2, \( W_{\text{lim}} \), are estimated at 1228 Å for the typical width of a narrow line (0.3 Å). The column density, \( N_H \), is estimated from the linear part of the curve of growth assuming \( b = 30 \text{ km s}^{-1} \), and the column density is related to the velocity of each Ly\( \alpha \) absorber as presented in the color bar on the right side.

### 2.4. Other Data and Known Properties of the Virgo Cluster

In this section, we describe other data we have collected from the literature in order to aid our analysis. We use the \textit{ROSAT} X-ray map from Böhringer et al. (1994), shown in Figure 1. Note that the X-ray data for the southern part, below decl. \( \sim 5^\circ \), is not available and the southeast edge around the virial radius is not reliable as explained in Böhringer et al. (1994). The approximate total mass of the Virgo Cluster, based on X-ray observations, is around \( M_{\text{tot}} \sim 10^{14.5} M_\odot \) (Böhringer et al. 1994; Schindler et al. 1999).

For the optical galaxy catalog, we use the spectroscopic Sloan Digital Sky Survey (SDSS) DR7 galaxies that have \( r_{\text{petro}} < 17.7 \) (York et al. 2000) in the same velocity range as the Ly\( \alpha \) absorbers (700–3000 km s\(^{-1}\)). The SDSS galaxies are shown in the right panel of Figure 1, color coded by their velocities. We make this choice because the traditional VCC (Binggeli et al. 1985) is not available and the southeast edge around the virial radius is not reliable as explained in Böhringer et al. (1994).

The H\( \text{I} \) galaxy catalog of the H\( \text{I} \) Parkes All Sky Survey (HIPASS; Meyer et al. 2004; Wong et al. 2006) and the Arecibo Legacy Fast ALFA survey (ALFALFA; Giovanelli et al. 2007; Haynes et al. 2011) are also used for comparisons to the absorbers. HIPASS covers the entire region around the Virgo Cluster, and the ALFALFA galaxy catalog covers the range...
Figure 1. Area of the Virgo Cluster and its surroundings with the virial radius of the cluster noted with the large gray dashed circle ($r_{100} = 1.65 h_{72}^{-1/3}$ Mpc (Mamon et al. 2004), equivalent to 1.57 Mpc in this study). The sightlines used are marked according to the instruments (cross: COS (this study); plus: STIS (literature); bar: GHRS (literature)) and the circle represents the detection of one or more Ly$\alpha$ absorber(s) with the color(s) within the circle representing the velocity(ies) of the absorber(s) (velocity color bar is to the right). Left: the QSO sightlines overlaid on the ROSAT X-ray contour map (Böhringer et al. 1994). The level of the contour corresponds to that of Böhringer et al. (1994) except that the lowest level here is 5$\sigma$. Gray crosses and bars with numbers indicate sightlines without Ly$\alpha$ detections and the detection limits in mÅ. Right: the same as the left panel but with the SDSS galaxies color-coded by their radial velocities. The substructures, A (Cluster A), B (Cluster B), M (M cloud), W (W cloud), and W$'$ (W$'$ cloud) are presented by circles as defined by Binggeli et al. (1987) and S (Southern Extension), marked with an ellipsoid, is defined by this study. The color of each substructure circle/ellipsoid corresponds to its mean velocity. The velocity ranges of each substructure are also noted by arrows on the right side of the color bar.

(A color version of this figure is available in the online journal.)

4° < decl. < 16°. The 5$\sigma$ detection limit is 0.72 Jy km s$^{-1}$ for ALFALFA and 5.6 Jy km s$^{-1}$ for HIPASS (Giovanelli et al. 2005). Adopting a distance to the Virgo Cluster of 16.5 Mpc (Mei et al. 2007), the H$\text{I}$ mass limits for ALFALFA and HIPASS are $4.6 \times 10^7 M_{\odot}$ and $3.6 \times 10^8 M_{\odot}$, respectively.

The mean velocity of the Virgo Cluster, $v_{\text{Virgo}}$, is taken to be at 1050 km s$^{-1}$ (Binggeli et al. 1993). Typically, 3000 km s$^{-1}$ is taken as the upper limit on the velocity of Virgo galaxies (Binggeli et al. 1993; Mei et al. 2007); therefore, we limit our analysis of the galaxies and Ly$\alpha$ absorbers in the Virgo Cluster to $cz < 3000$ km s$^{-1}$. The center of the Virgo Cluster is assumed to be at M87 (the coordinate from the NASA/IPAC Extragalactic Database$^4$) and the virial radius is adopted to be $1.65 h_{72}^{-1/3}$ Mpc (Mamon et al. 2004), equivalent to 1.57 Mpc in this study. However, the Virgo Cluster is an irregular cluster, so a fixed radius is not entirely appropriate (see the discussion in the next section).

2.5. Virgo Substructures

Since we will discuss the sightlines associated with substructures of the Virgo cluster in this paper, we summarize previous studies on the existence and kinematics of these substructures in this section. The Virgo cluster is known to have three main substructures which in order of total mass are: Cluster A containing M87, Cluster B which contains M49, and a subcluster of Cluster A containing M86. These are clearly seen as the three clumps in the X-ray map (the left panel of Figure 1). There are also the M, W, and W$'$ clouds and the Southern Extension, in order of coherence of substructures, behind the Virgo mean velocity (Shapley & Ames 1929; de Vaucouleurs 1961; Ftaclas et al. 1984; Binggeli et al. 1987). These substructures are labeled in the right panel of Figure 1. Note that the circles do not represent exact boundaries but are from estimates by Binggeli et al. (1985). The properties of these substructures are also listed in Table 4 and the velocity ranges are noted to the right of the color bar. Previous studies on these substructures include the following.

$^4$ http://ned.ipac.caltech.edu
Table 3

| Name | R.A. (J2000,◦) | Decl. (J2000,◦) | λ_{obs} (Å) | c_{z} (km s^{-1}) | W (mÅ) | σ_{W} (mÅ) | W_{limit} (mÅ) | log(N_{HI} (cm^{-2})) | SL | Inst. |
|------|----------------|----------------|-------------|----------------|--------|-----------|----------------|---------------------|----|-------|
| 3C273a | 187.2783 | 2.0522 | 1219.7643 | 1013 | 397 | 7 | 13 | 14.559 | 56.7 | STIS |
| 3C273b | 187.2783 | 2.0522 | 1222.1036 | 1582 | 405 | 6 | 13 | 14.607 | 67.5 | ... |
| 3C273c | 187.2783 | 2.0522 | 1224.4457 | 2149 | 27 | 3 | 13 | 12.713 | 6.8 | ... |
| 3C273d | 187.2783 | 2.0522 | 1224.9163 | 2276 | 24 | 3 | 13 | 12.654 | 8.0 | STIS |
| PG1216+069b | 184.8375 | 6.4349 | 1220.0860 | 1090 | 93 | 18 | 62 | 13.299 | 5.2 | STIS |
| RXJ1230.8+0115d | 187.7083 | 1.2560 | 1221.6800 | 1482 | 149 | 13 | 62 | 13.602 | 11.3 | STIS |
| RXJ1230.8+0115d | 187.7083 | 1.2560 | 1223.3287 | 1890 | 497 | 13 | 62 | 15.193 | 36.8 | ... |
| RXJ1230.8+0115d | 187.7083 | 1.2560 | 1224.4457 | 2149 | 27 | 4 | 13 | 12.713 | 6.8 | ... |
| RXJ1230.8+0115d | 187.7083 | 1.2560 | 1224.9163 | 2276 | 24 | 3 | 13 | 12.654 | 8.0 | STIS |
| PG1211+143e | 183.5737 | 14.0533 | 1224.3100 | 2130 | 186 | 19 | 45 | 13.416 | 8.2 | ... |
| Ton1542e | 188.0150 | 20.1581 | 1220.4800 | 1186 | 294 | 56 | 56 | 14.090 | 5.3 | STIS |
| Ton1542e | 188.0150 | 20.1581 | 1223.3600 | 1895 | 216 | 42 | 56 | 13.807 | 5.1 | ... |
| PKS1217+023f | 185.0492 | 2.0617 | 1223.9300 | 2038 | 451 | 88 | 210 | 13.758 | 9.8 | STIS |
| PKS1217+023f | 185.0492 | 2.0617 | 1224.8300 | 2260 | 648 | 132 | 210 | 14.881 | 5.1 | GHRS |
| Q1252+119f | 193.6592 | 11.6850 | 0 | 0 | 0 | 0 | 200 | 13.758 | 9.8 | GHRS |
| Q1214+1804f | 184.2046 | 17.8011 | 0 | 0 | 0 | 0 | 170 | 13.641 | 9.8 | GHRS |

Notes.

a Williger et al. (2010).
b Chen & Mulchaey (2009).
c Adopted from Tripp et al. (2005).
d Rosenberg et al. (2003).
e Penton et al. (2004).
f Impey et al. (1999).
g W_{limit} is converted to column density.

Table 4

| Description of the Virgo Substructures |
|----------------------------------------|
| Parameters | Cluster A | Cluster B | W Cloud | W_{Cloud} | M Cloud | Southern Extension |
| R.A., decl.(◦) | 187.71,12.39 | 187.44,8.00 | 184.88,5.85 | 186.00,6.90 | 183.10,2.50 | 187.50,2.50 |
| v_{mean}(km s^{-1}) | 1088a | 2198b | 1042a | 2179b | 1670 | 1670 |
| σ_{v}(km s^{-1}) | 222a | 121b | 433 | 433 | 433 | 433 |
| No. of absorbers | ... | 5d | ... | ... | ... | ... |
| Kinematics | Main Cluster | Possible infall to B | Infall to B | Infall to A | Local Supercluster |

Notes.

a Mei et al. (2007).
b Ftaclas et al. (1984).
c The number of Lyα absorbers in the spatial and kinematic vicinity of each substructure.
d Since there is no clear boundary between Cluster B and the W' cloud, the same five absorbers are listed in both places.
e The kinematics of each substructure from the literature (see the text).

1. Clusters A and B. Cluster A is the main structure as it is the most massive one and Cluster B is the second. Based on kinematics, it was suggested that Cluster B is falling onto Cluster A from the backside (Binggeli et al. 1987; Gavazzi et al. 1999); however, the latest results concluded that they are at nearly the same distance (Mei et al. 2007). The overabundance of spiral and irregular galaxies with velocities that deviate from a Gaussian distribution in Cluster A indicates that they may originate from an infalled population (Tully & Shaya 1984; Binggeli et al. 1987, 1993).

2. Cluster A subcluster. This subcluster, containing M86, is thought to be 1–2 Mpc behind the Virgo Cluster (Jerjen et al. 2004; Mei et al. 2007) and M86 has a negative radial velocity of −244 km s^{-1} (Smith et al. 2000). There are also a few other galaxies around M86 that show negative velocities, at cz ~ −700 km s^{-1} (Binggeli et al. 1993). This implies that the subcluster with M86 is infalling to Cluster A from the backside (Binggeli et al. 1987, 1993; Böhringer et al. 1994; Jerjen et al. 2004). Unfortunately, any Lyα absorbers associated with this subcluster, if they exist, cannot be studied in this paper due to the limitation of our data as described in Section 2.3.

3. M and W clouds. These substructures may be connected to each other (Paturel 1979; Ftaclas et al. 1984) and falling into the Virgo Cluster together (Yasuda et al. 1997). However,
another study partly disagrees with this suggestion and argues instead that the Virgo Cluster and the W cloud closely follow the Hubble flow while the M cloud is infalling onto Cluster A (Gavazzi et al. 1999).

4. **W cloud.** Binggeli et al. (1993) proposed that the W cloud is connected to the W cloud and both are falling into Cluster B, but the distance estimates of the W cloud make it appear to be more of a localized structure than a connecting bridge (Mei et al. 2007). The radial velocities of the W cloud galaxies are consistent with the Virgo inflow model (Mei et al. 2007). The W and W' clouds are spiral-rich (Binggeli et al. 1993), which supports the idea of both representing an infalling population of galaxies (Tully & Shaya 1984).

5. **Southern Extension.** There is an extended structure in the south of the Virgo Cluster called the Southern Extension which seems to be a filament in the Local Supercluster (de Vaucouleurs & de Vaucouleurs 1973; Tully 1982; Hoffman et al. 1995). This structure is also thought to be infalling to the Virgo Cluster (Binggeli et al. 1987). The Southern Extension seems to be connected to the W and M clouds (see Figure 5). This Southern Extension—W cloud–M cloud structure was also noted as a double sheet where galaxies concentrate around 1000 km s<sup>-1</sup> and 2000 km s<sup>-1</sup> in decl.–velocity space (see Figure 6 of Binggeli et al. 1993).

We estimate the velocity of the Southern Extension to be 1670 ± 433 km s<sup>-1</sup> with the biweight method (Beers et al. 1990) using the galaxies within the “S” ellipsoid in Figure 1. This was necessary as the definition of the Southern Extension is not clear in previous studies. Note that the velocity dispersion of the Southern Extension galaxies is relatively large because they are not as clustered as the other substructures (although it shows more clustering in the H<sub>1</sub> galaxy distribution shown in Figure 5).

In summary, these substructures are interconnected with each other and generally show kinematics characteristic of infall. It is important to note that the substructures are actually outside of the virial radius of the Virgo Cluster. The W cloud is ~6 Mpc further away from us than the Virgo Cluster (Mei et al. 2007). The W and M clouds are thought to be twice as distant as the main cluster (Binggeli et al. 1987; Gavazzi et al. 1999). If we relate Ly<sub>a</sub> absorbers to these substructures, this implies that many of the absorbers are located beyond the virial radius of the main cluster. Thus, this paper presents a study of gas both in the Virgo Cluster and in the cosmic filaments feeding into the cluster.

3. RESULTS

With our 25 Ly<sub>a</sub> absorbers toward COS sightlines and 18 absorbers toward STIS/GHRS sightlines in the range of 700 < cz < 3000 km s<sup>-1</sup>, we examine the overall distribution of warm gas in the cluster in Section 3.1, the covering fraction of warm gas in Section 3.2, the absorbers associated with the Virgo substructures in Section 3.3, the absorbers’ relation to the H<sub>1</sub> galaxy distribution in Section 3.4, and the absorbers in the Virgo background in Section 3.5.

3.1. **Large-scale Distribution of Ly<sub>a</sub> Absorbers**

All QSO sightlines from our COS observations and the literature discussed in Section 2 are shown in Figure 1. We immediately note two visually striking trends: first, the Ly<sub>a</sub> absorbers are more predominant in the outskirts of the cluster, and second, the majority of them have radial velocities larger than the mean velocity of the Virgo Cluster (although still lower than 3000 km s<sup>-1</sup>, our outer cutoff). The last point needs to be interpreted with some care, as the velocities of the Ly<sub>a</sub> absorbers in this study are constrained to be larger than 700 km s<sup>-1</sup> due to the observational limitation (see Section 2.3).

The Ly<sub>a</sub> absorbers also seem to avoid the X-ray gas region in position–velocity space. Only two absorbers overlap with the contour of the X-ray map. Even for these two, their velocities are actually more than twice the Virgo mean velocity (2272/2483 km s<sup>-1</sup> versus 1050 km s<sup>-1</sup>). This velocity offset, together with the fact that the X-ray gas usually follows a cluster’s potential well, implies that these absorbers are likely to be behind the hot ICM. Three out of the four sightlines within the X-ray contours do not have any Ly<sub>a</sub> absorbers (one COS sightline and two from GHRS). This is particularly significant for the COS sightline given its sensitivity (W<sub>lim</sub> = 76 mÅ). The two GHRS sightlines, although they have poorer sensitivity (W<sub>lim</sub> = 250 mÅ, 540 mÅ), do at least support the lack of strong absorbers in the X-ray-emitting region. Thus, we conclude that the Ly<sub>a</sub> absorbers avoid the hot ICM in position–velocity space.

Next, we address the relation between the absorbers and the galaxy catalogs. To do this, we compute the velocity distributions of the SDSS and ALFALFA galaxies within a radius of 200, 300, 400, 500, and 600 kpc around each sightline with the Ly<sub>a</sub> absorbers within 4<sup>°</sup> < decl. < 16<sup>°</sup>. To test if the velocity distributions of each of these populations are consistent with being drawn from the same parent distribution, in Table 5, we present the result of the Kolmogorov–Smirnov (K-S) test in the velocity range 1000–3000 km s<sup>-1</sup>. The cumulative distributions of the velocities of the galaxies in the 200 and 600 kpc cases are illustrated in Figure 2.

Based on the computed K-S probability, we cannot differentiate the ALFALFA (H<sub>1</sub>) galaxies from the Ly<sub>a</sub> absorbers with a high significance level. Hence, we conclude that cold gas (H<sub>1</sub>)

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5 Although it is, of course, not possible to determine a three-dimensional location based on the radial velocity as it cannot be directly translated into distance. For example, although the radial velocity of M86 is negative, the distance to M86 is 1–2 Mpc larger than the mean Virgo distance.
coexists with warm gas (Ly$\alpha$ absorbers) on all scales. This is consistent with the finding of a positive association between Ly$\alpha$ absorbers and gas-rich galaxies by Ryan-Weber (2006) and Pierleoni et al. (2008). However, for the case of the SDSS (optical) galaxies and Ly$\alpha$ absorbers (warm gas), as the search radius of galaxies around each sightline increases, we can reject the hypothesis that they are drawn from the same parent population with a significance level $>94\%$ except the case for 200 and 300 kpc. This is mostly because as the search radius grows, the optical galaxies in the cluster center are included which do not typically have warm or cold components due to environmental effects. As the search radius decreases, we approach a more localized scale (e.g., a galaxy halo) and the distributions of SDSS, ALFALFA, and Ly$\alpha$ absorbers become more indistinguishable.

We investigate the distribution of Ly$\alpha$ absorbers as a function of a projected radius from the cluster center in Figure 3. We divide the Ly$\alpha$ absorbers into two classes, depending on whether their position and velocity can be associated with the Virgo substructures (red and blue symbols) or not (black symbols). We consider an absorber to be associated with a substructure if it is spatially consistent with being within it and within 500 km s$^{-1}$ of the substructure’s velocity (see Table 4 and Figure 1). As described further in Section 3.3, the following sightlines in Figure 1 have substructure-related absorbers: J1214+0825, J1216+0712, J1217+0809, J1220+0641, and PG1216+069 with the W/W$'$ cloud, J1223+0923 and J1225+0844 with the Cluster B$'$ Cloud, PG1211+143 in the M cloud, and 3C273, RXJ1230.8+0115, and PKS1217+023 in the Southern Extension (“S” ellipsoid). All other absorbers (black symbols) are within the velocity range of the Virgo and do not have nearby clearly related substructures. We note that all the strong absorbers (>160 mÅ) within the virial radius in projection coincide with the Virgo substructures in position–velocity space (bottom panel of Figure 3). When we exclude the Ly$\alpha$ absorbers associated with the substructures, there are only weak absorption lines within the virial radius in projection (top panel of Figure 3). Regardless of whether these weak absorbers actually reside in the virial radius or are due to a projection effect, strong absorbers are not found in the virial radius and upper limits on line strengths for the nondetection sightlines also support this argument. It is also notable that in the top panel of Figure 3 without the substructure absorbers, there appears to be a gradual trend of increasing line strengths with a projected radius. The thick gray line in the top panel illustrates a weighted linear regression of the maximum line strength of each sightline in four bins. Overall, we find a suppression of the Ly$\alpha$ absorbers within the virial radius in projection and the presence of the strong absorbers with the substructures and outside the virial radius.

![Figure 3. Cluster impact parameter (clustocentric radius in projection from M87) and equivalent widths (W) of the Ly$\alpha$ absorbers for the sightlines from COS (×), STIS (+), and GHRS (–). The top panel only includes the sightlines not related to the substructures and the bottom shows all the sightlines. The gray solid line in the top panel illustrates the weighted least-square regression of the maximum W of each sightline alongside its mean error in four radii bins with a bin size 3.1. Red indicates the sightlines in the region of the W, W$'$ M clouds, and Cluster B, and blue represents sightlines in the Southern Extension. Gray symbols with downward arrows present the detection limits of each sightline without any Ly$\alpha$ absorbers. The vertical dotted line presents the virial radius as presented in Figure 1. The mean error bars of the absorbers from each instrument are illustrated in the top left with the legend. The red plus with an upward arrow actually has a W of 1953 mÅ (sub-DLA system, see the text). (A color version of this figure is available in the online journal.)]

### Table 5

| $R_{\text{clustocentric}}$ [Mpc] | $\alpha_{\text{SDSS}}$ | $\alpha_{\text{ALFALFA}}$ | $\alpha_{\text{LY} \alpha}$ |
|-----------------|-----------------|-----------------|-----------------|
| 0.0             | 0.1             | 0.2             | 0.3             |
| 0.5             | 0.6             | 0.7             | 0.8             |
| 1.0             | 1.1             | 1.2             | 1.3             |
| 1.5             | 1.6             | 1.7             | 1.8             |
| 2.0             | 2.1             | 2.2             | 2.3             |
| 2.5             | 2.6             | 2.7             | 2.8             |
| 3.0             | 3.1             | 3.2             | 3.3             |

**Note.** See the text for the details of the ALFALFA and SDSS galaxy selections.

3.2. The Covering Fraction of Warm Gas

We examine the covering fraction of warm gas by counting the number of the sightlines with and without Ly$\alpha$ absorbers within $2 R_{\text{vir}}$ and in the velocity range 1000–3000 km s$^{-1}$. The estimated total volume of this region is about $\pi (2 R_{\text{vir}})^2 \times 33 \text{Mpc}^3$, using the Virgo distance of 16.5 Mpc for the x- and y-axes and the distances to known Virgo substructures and Hubble flow considerations for the z-axis (see Section 2.5). A covering fraction can be estimated with the ratio of the number of sightlines with a detected absorber to the total number of
The ratio of the sum of the area of the polygons with Voronoi tessellation and compute the area of a polygon around
In order to alleviate any possible spatial bias, we also use the cluster are more clustered than those in other regions.
higher velocities, as detailed in Table 6) in order to compare the background (i.e., for a part of the spectra with significantly
thresholds (\(N_{\text{H}1} > 10^{13.123}\) cm\(^{-2}\)) in the Virgo Cluster with the velocity range noted.

As previously noted, the sightlines in the southwest of the cluster are more clustered than those in other regions. In order to alleviate any possible spatial bias, we also use Voronoi tessellation and compute the area of a polygon around each sightline as an independent way to estimate the covering fraction. The ratio of the sum of the area of the polygons with detections to the total area in 1 \(R_{\text{vir}}\) and 2 \(R_{\text{vir}}\) is defined to be the covering fraction. Hence, the Voronoi tessellation method assumes that the correlation length of a Ly\(\alpha\) absorbing cloud is larger than the minimum transverse distance between the sightlines. The estimates from this Voronoi tessellation method are also listed in Table 6 in brackets following the results for the counting method. We see that the results from both counting sightlines and Voronoi tessellation do not differ from each other significantly and show the same trend.

The distributions of the Ly\(\alpha\) absorbers’ equivalent widths and column densities are shown in Figure 4 and compared to a cosmological simulation of a cluster carried out with the adaptive mesh refinement code ENZO (Bryan 1999; Norman & Bryan 1999; O’Shea et al. 2004). The cluster simulation has the same physics but has a higher resolution than the run of Tonnesen et al. (2007). The simulation has a particle mass of \(\sim 2 \times 10^8 M_\odot\), a spatial resolution of 2 kpc, and includes a prescription for radiative cooling, star formation, and feedback, as well as an ionizing background from Haardt & Madau (2001). The simulated cluster has \(M_{200} = 8 \times 10^{14} M_\odot\) and a gas temperature of \(\sim 5\) keV. H\(\text{I}\) fractions are computed by post-processing with CLOUDY (Ferland et al. 1998). To do the comparison, we projected the H\(\text{I}\) column density along one sightline. When doing this calculation, we use five different thresholds (\(W > 65, 100, 150, 200, 300\) mÅ), and ignore the sightlines for which the detection limit is larger than the specified threshold (since we cannot determine if that sightline has a detection at the specified threshold or not). Note that the estimated covering fraction is limited by the nonuniform sightline distribution.

In Table 6, we present the covering fractions in different radius bins 0–1 \(R_{\text{vir}}\), 0–2 \(R_{\text{vir}}\), and 1–2 \(R_{\text{vir}}\). The gas covering fraction, \(N_{\text{H}1} > 10^{13.123}\) cm\(^{-2}\) (\(=65\) mÅ), is unity within 2 \(R_{\text{vir}}\) of the Virgo Cluster. The covering fraction of gas with higher column density is less than unity, but becomes higher outside of the virial radius (1–2 \(R_{\text{vir}}\)). The covering fraction is computed for the background (i.e., for a part of the spectra with significantly higher velocities, as detailed in Table 6) in order to compare with noncluster environments. We find that the covering fraction of warm gas in the background is less than half that in the environment of the Virgo Cluster.

![Figure 4. Distribution of equivalent widths W, column densities, and covering fraction. The top panel shows the distribution of observed equivalent widths (W) where black shows the absorbers from COS and STIS sightlines and the light gray dotted line shows the GHRs data. The middle and bottom panels show the column densities and covering fraction for the observations (same line coding) and the cosmological simulation (dashed gray line). Vertical dotted-dashed lines indicate the completeness cut at 95 mÅ (\(N_{\text{H}1} = 10^{13.3}\) cm\(^{-2}\)) for the COS and STIS data completeness in the K-S test. In the bottom panel, the covering fraction of the observed data is normalized to 0.81 which is estimated by counting sightlines with/without Ly\(\alpha\) detections stronger than 95 mÅ. The left side of the vertical dot-dashed line for the observed covering fraction is incomplete due to sensitivity issues (see the text). On the top right of the bottom panel, the K-S probability between the observation and simulation is noted.](image-url)
each observational sightline, but we draw a line at 95 mÅ ($N_{\text{HI}} = 10^{13.3} \text{ cm}^{-2}$) as a completeness limit, which is the maximum detection limit of the COS and STIS sightlines with Lyα detections. In the top and middle panel of Figure 4, at the cut, shown by a vertical dot-dashed line, there is a clear drop in the number of absorbers. In the bottom panel, we also show the result of applying the K-S test, finding that $P_{\text{K-S}} = 0.24$ at $N_{\text{HI}} > 10^{13.3} \text{ cm}^{-2}$ ($W = 95$ mÅ, the completeness limit of our data). This indicates that the gas covering fraction from the observation and simulation does not significantly differ from each other. Note that the simulated covering fraction is broken up into multiples. A more careful comparison will be performed in a future paper.

### 3.3. Absorbers Related to the Virgo Substructures

In this section, we discuss the likely associations of the absorbers noted with the color symbols in Figure 3 to the infalling substructures described in Section 2.5. The Lyα absorbers are considered associated with the substructures if close in position–velocity space as noted in the last paragraph of Section 3.1 and shown in Figure 1. As mentioned previously, all the strong absorbers ($>160$ mÅ) in the virial radius are found toward the sightlines penetrating through the substructures.

There are many Lyα absorbers concentrated in the southwest region where the W cloud, W′ cloud, and Cluster B are connected to each other. We also see an overdensity of SDSS galaxies with similar velocity ranges to the substructures in that region (see the right panel of Figure 1). The sightline J1225+0844 is near Cluster B and the W′ cloud and has five Lyα absorbers in the velocity range of the galaxies in these substructures. The sightlines J1214+0825, J1216+0712, J1217+0809, J1220+0641, and PG1216+069 are near the W and W′ clouds, and have many Lyα absorbers that mostly coincide with the W cloud in position–velocity space.

There are also several Lyα absorbers which seem to concur with the M cloud and the Southern Extension. The sightline PG1211+143 in the M cloud, in Figure 1, has only one Lyα absorption line and this is also near the presence of an H I filament in its velocity range (as discussed in Section 3.4). The three sightlines in the Southern Extension, 3C273, RXJ1230.8+0115, and PKS1217+023 (in the “S” ellipsoid of the right panel of Figure 1), also show Lyα absorbers coinciding with the filamentary structure of galaxies in position–velocity space. This was also noted by previous studies (Bahcall et al. 1991; Morris et al. 1991, 1993; Salpeter & Hoffman 1995).

The remaining absorbers are not considered part of known substructures. The sightline J1225+1218, near the subcluster containing M86, has two Lyα absorbers at $cz = 2272$ and 2483 km s$^{-1}$. However, this subcluster is infalling to Cluster A from the back side and the galaxies in it exhibit negative velocities as discussed in Section 2.5. Thus, these absorbers are not likely to be associated with this substructure, but more likely in the background of the hot ICM as discussed in Section 3.1.

The remaining sightlines with Lyα absorbers show various environments. Although there are only a handful of galaxies around the sightline J1205+1042 (rightmost symbol in Figure 1) and Ton1542 (top symbol in Figure 1), they have five and three absorbers, respectively. The sightline J1234+0723 (gray X labeled 76) is in Cluster B and has no absorbers, while J1218+1015 has two low column density absorbers ($10^{13.1}$ and $10^{13.3} \text{ cm}^{-2}$) at high velocities (2782 and 2924 km s$^{-1}$, colored with orange and red) with no galaxies around it in position and velocity space.

### 3.4. Lyα Absorbers and H I Galaxies

H I observations of the galaxies in the Virgo Cluster are presented in several pointed studies (i.e., Hoffman et al. 1989; Gavazzi et al. 2005; Chung et al. 2009), as well as in H I surveys which cover a large fraction of the sky (Wong et al. 2006; Haynes et al. 2011). The HIPASS survey covers the entire region around the Virgo Cluster and the ALFALFA survey observed most of our region of interest. We plot the HIPASS and ALFALFA galaxies in different velocity bins with the Lyα absorbers to...
investigate the cold and warm gas distributions in Figure 5. The ALFALFA survey region is illustrated between the horizontal dotted lines and is also evident with the larger abundance of H\textsubscript{i} galaxies due to the survey depth differences (see Section 2.4).

In the leftmost panel of Figure 5, around the sightline J1225+0844 (with five Ly\textalpha\, absorbers near M49 in Figure 1), the overdensity of H\textsubscript{i} detections is clearly visible and highlighted by the large gray ellipsoid. This is where Cluster B and the W\textsuperscript{'} cloud meet. The H\textsubscript{i} overdensity near J1225+0844 seems to be parallel to the edge of the X-ray contour of Figure 1. As discussed in Tully & Shaya (1984), this overdensity of gas-rich galaxies could originate from an infalling population. The smaller gray ellipse to the southeast of this panel contains an overabundance of H\textsubscript{i} galaxies that is also seen in the SDSS galaxy distribution (see the right panel of Figure 1). Though not discussed in their study, this structure can also be partially seen in the H\textsubscript{i} maps of Popping & Braun (2011). There are no Ly\textalpha\, absorbers detected here, but the GHRS sightline from the literature has poor sensitivity ($W_{\text{limit}} = 270$ mÅ). Future work may detect Ly\textalpha\, absorbers in this region.

In the second and third panels, we see abundant H\textsubscript{i} detections that link the Southern Extension to the W and M clouds. The majority of the Ly\textalpha\, absorbers in this filamentary structure lie at a similar velocity to the H\textsubscript{i} filament. The connecting structure of the Southern Extension, and W and M clouds was noted in previous studies (as mentioned in Section 2.5), but is seen

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**Figure 6.** Ly\textalpha\, absorbers in the background of the Virgo Cluster with the SDSS (left) and ALFALFA/HIPASS (right) galaxies. Symbols for the sightlines are the same as in Figures 1 and 5. The ALFALFA galaxies are only available between the two dotted lines in the right panel. All galaxies and absorbers are color-coded by their velocities as noted in the bar on the right side.

(A color version of this figure is available in the online journal.)

| Name          | R.A. (J2000,°) | Decl. (J2000,°) | $\lambda_{\text{obs}}$ (Å) | $cz$ (km s$^{-1}$) | $W$ (mÅ) | $\sigma_W$ (mÅ) | $W_{\text{limit}}$ (mÅ) | log$N_{\text{H}_1}$ (cm$^{-2}$) | SL | Inst. |
|---------------|----------------|----------------|-----------------------------|-----------------|--------|---------------|--------------------------|-------------------|-----|-------|
| J1205+1042    | 181.4837       | 10.7150        | 1235.3704                   | 4862            | 388    | 20            | 91                       | 14.510            | 19.4| COS   |
| J1214+0825    | 184.6273       | 8.4189         | 1231.7817                   | 3976            | 297    | 20            | 60                       | 14.100            | 14.9| COS   |
| J1216+0712    | 184.1690       | 7.2068         | 1230.8713                   | 3776            | 61     | 9             | 58                       | 13.094            | 6.8 | COS   |
| J1216+0712    | 184.1690       | 7.2068         | 1231.0527                   | 3796            | 70     | 9             | 58                       | 13.162            | 7.8 | COS   |
| J1217+0809    | 184.3170       | 8.1617         | 1231.9110                   | 4008            | 211    | 14            | 55                       | 13.797            | 15.1| COS   |
| J1217+0809    | 184.3170       | 8.1617         | 1238.8798                   | 5720            | 148    | 16            | 55                       | 13.562            | 9.3 | ...   |
| J1218+1015    | 184.7105       | 10.2651        | 1239.6635                   | 5921            | 145    | 11            | 55                       | 13.543            | 13.2| ...   |
| J1220+0641    | 185.0768       | 6.6888         | 1232.3699                   | 4121            | 163    | 22            | 95                       | 13.621            | 7.4 | COS   |
| PG1216+0693   | 184.8375       | 6.6439         | 1231.0341                   | 3792            | 296    | 17            | 62                       | 14.100            | 17.4| STIS  |
| J1218+1015    | 184.8375       | 6.6439         | 1233.8179                   | 4478            | 44     | 9             | 62                       | 12.938            | 4.9 | ...   |

**Table 7.** The Ly\textalpha\, Absorbers in the Virgo Background

Note. a References from Table 3.
here for the first time in both cold and warm gas. In the last panel, although there are not many detections, the majority of the H\textsc{i} sources and the Ly\textalpha{} absorbers are found around the W cloud.

3.5. Gaseous Structures behind The Virgo Cluster

Our multiple sightlines in the Virgo Cluster allow us to probe structures beyond the Virgo environment as well. The Ly\textalpha{} absorbers in the velocity range of 3700–6000 km s\(^{-1}\) are listed in Table 7 and they are presented with the SDSS, ALFALFA, and HIPASS galaxies in Figure 6. There are 10 Ly\textalpha{} absorbers toward the COS sightlines and 2 absorbers toward the STIS sightlines. A filamentary structure from the southeast to the northwest is evident in Figure 6 and the Ly\textalpha{} absorbers coexist with this filament in position–velocity space. Another filament of warm gas and galaxies seems to be evident in a branch from the galaxy cluster MKW 04 to the three Ly\textalpha{} absorbers at \(\sim 5800 \text{ km s}^{-1}\) (orange and red). There are no Ly\textalpha{} absorbers in the range 3000–3700 km s\(^{-1}\). This absorber gap is in agreement with the existence of the gap in the galaxy distribution (Binggeli et al. 1993).

The covering fraction of the Ly\textalpha{} absorbers in this background region is 0.33\(^{+0.19}_{-0.14}\), as determined by counting the sightlines and 0.08 by Voronoi tessellation (\(W > 65 \text{ m} \text{A}\), 3700 < \(c_z\) < 5700 km s\(^{-1}\) to have the same velocity range). This is lower than in (and around) the Virgo Cluster and the same as the other two comparison samples in the velocity ranges 10,000–12,000 km s\(^{-1}\) and 15,000–17,000 km s\(^{-1}\) (Table 6). These ranges are arbitrarily chosen to compare absorber statistics over a similar velocity interval in noncluster environments.

4. DISCUSSION

Warm gas in the environment of a galaxy cluster can be interpreted in the context of predictions from cosmological simulations of cluster formation and its relation to the other observed phases of a cluster. In this section, we discuss the distribution and origin of the Ly\textalpha{} absorbers. We also discuss the comparison of our results to simulation results and the relation of the absorbers to hot X-ray gas, galaxies (all and only the gas-rich), and Virgo substructures.

4.1. Diffuse Warm Gas and the Virgo Cluster

We detect warm gas surrounding the Virgo Cluster, but few absorbers are apparently within the virial radius of the cluster. This is inferred because most of the absorbers are at velocities higher than the mean velocity of the Virgo Cluster and/or can be associated with the infalling substructures. They are also largely detected beyond the X-ray contours, and those within the X-ray contours in projection have higher velocities than the Virgo mean velocity. In contrast to within the cluster, the outskirts of the cluster show an abundance of the absorbers relative to the background indicating warm circumcluster gas is abundant. This can be interpreted in the context of warm gas coming into a cluster and being shock heated, as predicted for gas coming into a massive dark matter halo such as Virgo (White & Rees 1978). It is also consistent with the hot ICM stripping any cold/warm gas from galaxies and that material rapidly being integrated in the hot ICM (Chung et al. 2007; Tonnesen et al. 2007). Indeed, the majority of warm gas in simulations is not found in virialized structures, consistent with our finding of abundant warm circumcluster gas beyond the virial radius (Davé et al. 2001, 2010; Shull et al. 2011).

The high covering fraction found for warm gas also points toward abundant circumcluster gas (see Table 6). The covering fraction of warm gas with \(N_{\text{HI}} > 10^{13.1} \text{ cm}^{-2}\) (\(W > 65 \text{ m} \text{A}\)) within 2 \(R_{\text{vir}}\) in projection is unity. As mentioned above, this is thought to largely represent surrounding gas, and not gas within the virial radius, as our velocity cut at 3000 km s\(^{-1}\) includes not only Virgo, but also the substructures that are twice as distant as the Virgo Cluster (see Section 2.5). This projection effect is partially evident when examining the trend toward lowering the covering fraction from 0–1 \(R_{\text{vir}}\) to 1–2 \(R_{\text{vir}}\) for the higher column density absorbers. This clearly shows that the higher column density absorbers are preferentially found in the outskirts of the galaxy cluster, and may be partially due to blending of multiple absorbers along the line of sight. Using background velocities as discussed in Section 3.5, the covering fraction is lower, showing again the prevalence of warm circumcluster gas relative to noncluster environments. Figure 3 also shows that the high column density absorbers within the virial radius in projection coexist with the substructures.

We find agreement between a simulation of a galaxy cluster and our absorber statistics within our completeness limit (Figure 4). This suggests that the continued feeding of galaxy clusters found in simulations is consistent with the observations. A more thorough investigation will be completed in a future paper. Although the K-S probability shows consistency, we see indications that there are a greater number of absorbers with densities between \(10^{13.3–14.5} \text{ cm}^{-2}\) in the observations. This may be due to either the volume in the observations being deeper or the Virgo Cluster’s irregular morphology with the multiple infalling substructures not being closely matched by the simulation. On the other hand, there are more high column absorbers \(>10^{15.5} \text{ cm}^{-2}\) in the simulation. Since the column densities in the simulation are obtained by integrating through the box, while the observations are broken up into multiple absorbers, some of the discrepancy may be resolved in future comparisons of individual absorbers in the simulation. While the gas in a galaxy sized halo has been studied extensively in simulations (Dekel et al. 2009; Kere\v{s} et al. 2009; Faucher-Gigu\`ere & Kere\v{s} 2011; Kimm et al. 2011), detailed studies of circumcluster gas are just beginning.

4.2. What Gives Rise to the Ly\textalpha{} Absorbers?

As shown, many Ly\textalpha{} absorbers are concurrent with the Virgo substructures. In particular, the strong absorbers coincide with the substructures. The K-S test shows that the distributions of the H\textsc{i} galaxies and the Ly\textalpha{} absorbers are not distinguishable. The coincidence of the Virgo infalling substructures traced in cold gas from the H\textsc{i} observations and warm gas by the Ly\textalpha{} absorbers may represent the accretion of both galaxies and intergalactic gas into the cluster and the growth of its diffuse gaseous, stellar, and dark matter components. This is in agreement with simulations that find the vast majority of Ly\textalpha{} absorbers are associated with the overdensities comparable to typical filaments (Davé et al. 2001, 2010; Shull et al. 2011).

We see evidence for a connected filament between the Southern Extension–W cloud–M cloud in the H\textsc{i} galaxy distribution (Figure 5) and the multiple Ly\textalpha{} absorbers in this study. This may be partially represented by the \(\sim 2000 \text{ km s}^{-1}\) component of the double sheet structure detected in galaxies (Binggeli et al. 1993, discussed in Section 2.5). Although the absorbers toward J1218+1015 and J1205+1042 have relatively few galaxies around them, they are in position–velocity proximity to the Southern Extension–W cloud–M cloud filament. The seven
Lyα absorbers along these two sightlines are relatively weak (<220 mÅ), which is consistent with them tracing a continuation of this filament, rather than gas in a yet unseen galaxy halo (Prochaska et al. 2011). Considering the transverse distance between PG1211+143 and RXJ1230.8+0115 (the two extremes of the filament), the gaseous filament extends for at least 3.6 Mpc. It most likely extends even further given the previous work has inferred the existence of a coherent 20 Mpc (in depth) gaseous structure for the sightlines 3C273 and RXJ1230.8+0115 in the Southern Extension (Penton et al. 2002).

In these infalling filaments, shocks will heat gas (Davé et al. 2001; Birnboim & Dekel 2003), and this $T = 10^{5–6}$ K gas can potentially be traced by O vi absorption lines (Shull et al. 2003; Furlanetto et al. 2005). We found four sightlines 3C273, RXJ1230.8+0115, PG1211+143, and PG1216+069 observed with FUSE (Sembach et al. 2001; Danforth et al. 2006; Danforth & Shull 2008; Tripp et al. 2008), and two of them, 3C273 (in the Southern Extension) and PG1211+143 (in the M cloud), show O vi absorption lines with a significance level $\gtrsim 4.5$ at the velocities of the Lyα absorbers at $cz = 1013\,\text{km\,s}^{-1}$ and $cz = 2130\,\text{km\,s}^{-1}$ (see Table 8). The origin of the O vi absorbers is still debated, so cannot be definitively linked to collisional ionization due to infalling cluster gas. Additional observations and comparisons to simulations are needed.

4.3. IGM versus Galactic Origins

The concurrence of the H i emission and Lyα absorbers can be attributed to either IGM gas in a filament that will most likely feed galaxies, or to cold or warm gas being stripped/ejected from galaxies. In either case, we expect to see both warm gas and cold gas in proximity; although most likely with less gas in galaxies in the latter case. This coincidence of the H i emission and Lyα absorbers also echoes the notion that optical and radio surveys are only seeing the tip of the iceberg. There is more mass, more diffuse warm gas, surrounding those dense regions.

Previous studies on Lyα absorbers did not consider the influence of an “active” environment, which is the case for the Virgo Cluster. Galaxies begin to lose their gas just outside the virial radius in the Virgo Cluster (Chung et al. 2007). The gas tails caused by environmental stripping can extend up to 100–500 kpc (Oosterloo & van Gorkom 2005; Haynes et al. 2007; Koopmann et al. 2008) and can produce a Lyα absorption line (Tonnesen & Bryan 2010). However, the stripped gas will be heated by thermal conduction from the ICM, as well as by turbulence and shocks (Tonnesen & Bryan 2010), and may not last long. Our finding that the Lyα absorbers avoid the observed X-ray gas may indicate this heating is relatively rapid in the region where the hot ICM is present. Lyα absorbers can only arise from stripped gas around the virial radius where gas stripping begins, but no hot ICM exists. Lyα absorbers well beyond the virial radius and the hot ICM (or in the substructures) may not be influenced by environmental gas stripping, but could still partially originate from galaxy interactions and feedback processes.

Since the substructures are gas-rich in galaxies and absorbers, many of the absorbers may represent gas in a filament that will eventually feed galaxies. Due to the lack of distance and three-dimensional kinematic information for the Lyα absorbers, one promising method to discriminate infalling gas from gas that has originated from a galaxy is to look at metallicity. At high and intermediate redshifts most of the accreting IGM is likely to have low metallicities (Faucher-Giguère & Kereš 2011; Fumagalli et al. 2011; Kimm et al. 2011), and, thus far, at $z = 0$ the IGM metallicity in local filaments still appears to be low (Ferrara et al. 2000; Danforth & Shull 2005; Barai et al. 2011, $Z \lesssim 0.1\,Z_\odot$). To help determine the metallicity of warm gas, there are a few metal lines, such as Si ii [1206], Si ii [1260], O i [1302], and C ii [1334] in the spectral range of our COS data (1150–1450 Å); however, the column densities of our Lyα absorbers are too low to detect any corresponding metal lines. In previous observations, the metallicity of two Lyα absorbers at 1013 km s$^{-1}$ and 1582 km s$^{-1}$ with $N_{\text{H}i} > 10^{14}\,\text{cm}^{-2}$ toward 3C273 turned out to be low ($[\text{O}/\text{H}] \therefore \lesssim -2.0$ and $[\text{C}/\text{H}] = -1.2$; Tripp et al. 2002). In addition, one of the two Lyα absorbers toward PG1216+069 at 1890 km s$^{-1}$, in the proximity of the W cloud, was found to be a pristine sub-DLA system without any bright galaxies close by (Tripp et al. 2005). This implies the presence of the relatively un-enriched IGM and is consistent with much of the gas in the substructure filaments being galactic fuel rather than galactic waste.

5. CONCLUSION

The distribution of warm gas in a galaxy cluster is studied for the first time in this paper with observations of multiple QSO sightlines. We performed COS observations of bright background QSOs and found 25 Lyα absorbers ($N_{\text{H}i} = 10^{13.1–15.4}\,\text{cm}^{-2}$) toward 9 of 12 QSO sightlines in and around the virial radius of the Virgo Cluster in the velocity range $700 < cz < 3000\,\text{km\,s}^{-1}$. Eighteen Lyα absorbers ($N_{\text{H}i} = 10^{12.7–19.3}\,\text{cm}^{-2}$) from STIS and GHRs observations are added to our sample by searching the literature and using a more extended region around the Virgo Cluster. The absorbers’ overall distribution, covering fraction, and relation to substructures/filaments and gas-rich (H i) galaxies are investigated and compared to a cosmological simulation. Our findings can be summarized as the following.

1. Warm gas prefers the outskirts of the cluster and avoids the region of the hot ICM. Also, there is an indication for an increase in the strength of the Lyα absorbers with cluster impact parameter when only the nonsubstructure absorbers are considered. While the Lyα absorbers in the cluster center are suppressed, the high column density absorbers ($W > 160\,\text{mÅ}, N_{\text{H}i} > 10^{13.6}\,\text{cm}^{-2}$) are coincident with the Virgo substructures or reside in the outskirts.

2. Warm gas preferentially found in the filamentary substructures is coincident with an abundance of H i galaxies. The distributions of the H i galaxies and the Lyα absorbers show no statistical difference. This coexistence is consistent with the interpretation that we are seeing the flow of gas in different phases into the Virgo cluster along the filaments.

3. The covering fraction of warm gas increases with a projected radius and is consistent with a high-resolution cosmological grid simulation of a cluster. The warm gas covering fraction in the non-cluster environments ($f_{\text{cover}} = 0.33$ at $N_{\text{H}i} > 10^{13.1}\,\text{cm}^{-2}$) is lower than that in the cluster.
Our findings of warm gas being dominant in the outskirts of the cluster and overall avoiding the hot ICM are consistent with the expected properties of gas flowing into a massive dark matter halo and being shock heated. It is also consistent with the stripped gas from galaxies being rapidly heated as it enters the virial radius of a cluster. Since we find gas in the regions with abundant HI galaxies and where there is not active stripping going on, much of the warm gas may represent potential galactic fuel, rather than waste. Metallicity can be an important future diagnostic of whether the material has been ejected from the nearby galaxies. There is some evidence from the literature that one of the Virgo substructure filaments represents low-metallicity warm gas. More detailed comparisons to simulations and studies of individual galaxies near sightlines will also be important to clarify the origin of the gas.

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ERRATUM: “WARM GAS IN THE VIRGO CLUSTER. I. DISTRIBUTION OF \lya\ ABSORBERS” (2012 ApJ, 754, 84)

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We report here an error in the analysis of the numerical simulations used to compare to the observations in this paper. In particular, we inadvertently used an output from the simulation at \(z = 0.55\) instead of \(z = 0\). The effect of this was to increase the densities in the simulation by a factor of \(1 + z\)\(^3\) \(\approx 3.7\). For a fixed ionizing background, this results in an increase in the neutral H\(_1\) density by \(3.7^2 \approx 14\), for gas which is in ionization equilibrium (e.g., Zhang et al. 1998). This increase in the H\(_1\) density therefore led directly to a shift of more than an order of magnitude in the predicted column densities. Since the published version of this paper found agreement between these simulations and the observations, this implies that the (corrected) simulations predict an order of magnitude too few absorbers for a given column density (or, equivalently, a covering fraction significantly below that observed); however, the uncertainty in this prediction is quite large both because of the uncertain photo-ionizing background level at \(z = 0\), and the relatively simple methodology used to predict the covering fraction from the simulations. Although the original simulation outputs are no longer available, preventing us from reanalyzing the original simulation, we confirmed this approximate scaling using an updated simulation (Emerick et al. 2015). We have carried out an extended analysis of the new simulations and refer the reader to that paper for an updated comparison between simulations and observations.

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