THE INCIDENCE OF COOL GAS IN $\sim 10^{13} M_\odot$ HALOS

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ABSTRACT

We present the first results of an ongoing spectroscopic follow-up of close luminous red galaxies (LRGs) and Mg $\Pi$ absorption pairs for an initial sample of 15 photometrically selected LRGs at physical projected separations $\rho \lesssim 350 \, h^{-1}$ kpc from a QSO sight line. Our moderate-resolution spectra confirm a physical association between the cool gas ($T \sim 10^4$ K) revealed by the presence of Mg $\Pi$ absorption features and the LRG halo in five cases. In addition, we report an empirical estimate of the maximum covering fraction ($\kappa_{\text{max}}$) of cool gas in massive, $\geq 10^{13} h^{-1} M_\odot$ dark matter halos hosting LRGs at $z \sim 0.5$. This study is performed using a sample of foreground LRGs that are located at $\rho < 400 \, h^{-1}$ kpc from a QSO sight line. The LRGs are selected to have a robust photometric redshift $z_{\text{ph}}$ based on the incidence of Mg $\Pi$ absorption systems that occur within $z_{\text{ph}} \pm 3 \, \sigma_z$ in the spectra of the background QSOs. Despite the large uncertainties in $z_{\text{ph}}$, this experiment provides a conservative upper limit to the covering fraction of cool gas in the halos of LRGs. We find that $\kappa_{\text{max}} \approx 0.07$ at $W_r(2796) \geq 1 \, \AA$ and $\kappa_{\text{max}} \approx 0.18$ at $W_r(2796) \geq 0.5 \, \AA$, averaged over $400 \, h^{-1}$ kpc radius. Our study shows that while cool gas is present in $\geq 10^{13} h^{-1} M_\odot$ halos, the mean covering fraction of strong absorbers is no more than 7%.

Key words: dark matter – galaxies: evolution – quasars: absorption lines

Online-only material: color figures

1. INTRODUCTION

A detailed description of how galaxies acquire their gas is essential in order to establish a comprehensive theory of galaxy evolution. Analytical calculations and hydrodynamical simulations have shown that the gas in galaxy halos, with the Apache Point Observatory 3.5 m telescope, which is owned and operated by the Astrophysical Research Consortium.

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4 We define a halo as a region with an overdensity of 200 with respect to the mean mass density of the universe.

the cool gas content of dark matter halos can also be obtained by measuring the large-scale clustering amplitude of Mg $\Pi$ systems (Bouché et al. 2006; Tinker & Chen 2008, 2010).

In Gauthier et al. (2009), we calculated the clustering amplitude of strong Mg $\Pi$ absorbers (with rest-frame absorption equivalent width $W_r(2796) \geq 1 \, \AA$) using luminous red galaxies (LRGs) at $z \sim 0.5$. LRGs are old and passive galaxies (Eisenstein et al. 2001) residing in $M \geq 10^{13} h^{-1} M_\odot$ halos. (e.g., Zheng et al. 2008; Blake et al. 2008; Padmanabhan et al. 2008; Gauthier et al. 2009). They are identified using photometric redshift techniques that offer a typical redshift accuracy of $\sigma_z \approx 0.045$ at $z_{\text{ph}} \sim 0.5$ (Collister et al. 2007).

An interesting result from Gauthier et al. (2009) is the LRG–Mg $\Pi$ cross-correlation signal is comparable to the LRG auto-correlation on small scales ($\lesssim 300$ comoving $h^{-1}$ kpc) that are well within the virial radii of the halos. The results suggest the presence of cool gas inside the dark matter halos of LRGs.

Here, we report the first results of an ongoing spectroscopic follow-up of the close LRG–Mg $\Pi$ pairs found in Gauthier et al. (2009). In 5 of the 15 cases, the precise spectroscopic redshifts establish a physical connection between these LRG–Mg $\Pi$ pairs. The spectroscopic study of LRGs is supplemented with a survey of Mg $\Pi$ absorbers in the vicinity of photometrically identified LRGs in the Sloan Digital Sky Survey (SDSS) data archive. This survey allows us to utilize the vast survey data available in the SDSS archive to derive additional constraints on the covering fraction of cool gas in $10^{13} h^{-1} M_\odot$ halos. We adopt a $\Lambda$ cosmology with $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$, and a dimensionless Hubble parameter $h = H_0 / (100 \, \text{km s}^{-1} \text{Mpc}^{-1})$ throughout the paper. All distances are in physical units unless otherwise stated.

2. EXPERIMENTS

To examine the cool gas content in massive halos, we have designed two experiments. The first one is a spectroscopic follow-up study of photometrically identified LRGs located near Mg $\Pi$
absorbers (Sample A below). The spectroscopic observations allow us to identify physically associated LRG–Mg ii absorber pairs for interpreting the small-scale clustering signal seen in Gauthier et al. (2009). In addition, the optical spectra offer additional knowledge for the stellar and interstellar medium properties of the LRGs. The second experiment is a survey of Mg ii absorbers in the vicinity of photometrically identified LRGs (Sample B below). This study allows us to make use of the vast amount of galaxy and QSO survey data already available in the SDSS archive and derive statistically significant constraints for the covering fraction of cool gas around LRGs.

2.1. Sample A—LRGs in the Vicinity of Known Mg ii Absorbers

The purpose of the spectroscopic study of LRGs is to establish a physical association between the cool gas traced by the Mg ii absorbers and the dark matter halos of the LRGs. The LRGs are selected based on their photometric redshifts, and typical photometric redshift uncertainties for these galaxies is $\sigma_z = 0.03(1 + z_{\text{ph}})$ for $i^* = 19$ (Collister et al. 2007). The identification of physical pairs requires precise spectroscopic redshifts for the galaxies.

To achieve this goal, we established a catalog of close Mg ii–LRG pairs for follow-up spectroscopy by cross-correlating the Prochter et al. (2006) Mg ii absorber catalog with the Collister et al. (2007) MegaZ–LRG sample. The Mg ii catalog is an extension of the SDSS DR3 sample to include DR5 QSO spectra. This sample of Mg ii absorbers has a 95% completeness for absorbers of $W_r(2796) > 1$ Å. The catalog contains 11,254 absorbers detected at $z_{\text{Mg ii}} = 0.37 - 2.3$ among 9,774 QSO sight lines. We excluded absorbers within 10,000 km s$^{-1}$ from the QSO redshift to avoid associated absorbers of the QSO. We excluded absorbers with $2z_{\text{Mg ii}} < 0.4$ or $z_{\text{Mg ii}} > 0.7$ to match the redshift interval of the LRGs. A total of 2461 Mg ii absorbers satisfied our selection criteria.

The MegaZ–LRG catalog is a photometric redshift catalog of approximately $10^6$ LRGs found in the SDSS DR4 imaging footprint. The catalog covers more than 5000 deg$^2$ in the redshift range $0.4 < z < 0.7$. When cross-correlating the two catalogs, we rejected LRGs located within the photometric redshift uncertainty $3 \times \sigma_z$ from the QSO redshift. We selected only those LRGs that are in the foreground of the QSO.

We found a total of 646 Mg ii–LRG pairs within projected separation $\rho = 400$ (physical) $h^{-1}$ kpc. Note that the sample of 64 close Mg ii–LRG pairs with $\rho \lesssim 300$ $h^{-1}$ kpc found in Gauthier et al. (2009) is included in this larger sample of 646 pairs. From this sample, we kept only isolated LRGs. Our final catalog for follow-up galaxy spectroscopy consisted of 331 “isolated” LRGs that are near a known Mg ii absorber. We call this sample “Sample A.”

The primary utility of Sample A was to understand the small-scale clustering signal seen in Gauthier et al. (2009). The sample of spectroscopically confirmed physical LRG–Mg ii pairs also allows us to (1) examine possible correlations between the stellar properties of the LRGs and the presence of cool gas at large radii, and (2) study the kinematics of cool gas in massive halos with follow-up echelle spectroscopy of the absorbers.

5 An isolated LRG is one that does not have a neighboring LRG within the volume defined by its virial radius and photometric redshift uncertainty. This approach allows us to reduce the ambiguity of attributing the Mg ii absorber to one or more LRGs. We address possible contamination due to blue satellite galaxies in Section 5. The treatment of groups is beyond the scope of this letter and will be discussed in a forthcoming paper (J.-R. Gauthier et al. 2010, in preparation).

2.2. Sample B—Random LRGs Near QSO Sight Lines

To derive constraints on the covering fraction of cool gas, we first established a QSO–LRG pair sample by cross-correlating the Schneider et al. (2007) QSO catalog and the MegaZ LRG catalog (Collister et al. 2007). The Schneider et al. (2007) catalog contains more than 77K QSOs in the SDSS DR5 archive. MegaZ is a photometric redshift catalog of approximately $10^6$ LRGs in the redshift range $0.4 < z_{\text{ph}} < 0.7$. The redshift uncertainties are estimated to be $\sigma_z/(1 + z_{\text{ph}}) = 0.03$.

We considered QSOs that are in the distant background from the LRGs with $(z_{\text{QSO}} - z_{\text{ph}}) > 3 \sigma_z$. In addition, we included only QSOs with $\delta_{\text{QSO}} < 18.5$ and at $z \leq 1.45$, in order to obtain sensitive limits for $W_r(2796)$ and to remove contaminations due to C iv absorption features. Furthermore, we excluded LRGs found in groups of two or more neighbors. Finally, we considered only pairs with $\rho < 400$ $h^{-1}$ kpc at $z_{\text{ph}}$, a maximum separation that is about the expected size of the host dark matter halos. This procedure yielded a total of 620 LRG–QSO pairs. We call this pair sample “Sample B.” This catalog contains no a priori information about the presence of Mg ii in the QSO spectra. It was designed to compute the covering fraction of cool gas in the dark matter halos of LRGs (see the analysis in Section 4.2).

3. OBSERVATIONS AND DATA REDUCTION

In 2009 May, we obtained medium-resolution spectra of three LRGs in Sample A (all within $\rho = 160$ $h^{-1}$ kpc of a known Mg ii absorber) using the Double Imaging Spectrograph (DIS) on the 3.5 m telescope at Apache Point Observatory. The blue and red cameras have a pixel scale of 0.4 and 0.42 pixel$^{-1}$, respectively, on the 3.5 m telescope. We used the B400/R300 grating configuration with a 1.5 slit. The B400 grating in the blue channel has a dispersion of 1.83 Å pixel$^{-1}$ and the R300 grating in the red channel has a dispersion of 2.31 Å pixel$^{-1}$. The blue and red channels with the medium-resolution gratings together offer contiguous spectral coverage from $\lambda = 3800$ Å to $\lambda = 9800$ Å and a spectral resolution of FWHM $\approx 500$ km s$^{-1}$ at $\lambda = 4400$ Å and FWHM $\approx 400$ km s$^{-1}$ at $\lambda = 7500$ Å. The observations were carried out in a series of two exposures of between 1200 s and 1800 s each, and no dither was applied between individual exposures. Flat-field frames were taken at the end of the night for each exposure. Calibration frames for wavelength solutions were taken immediately after each science exposure using the truss lamps on the secondary cage. The DIS observations are characterized by a typical seeing of 1.3′ (as measured with the slitviewer guide star). Note that we also retrieved the spectrum of one LRG in Sample A (SDSSJ113731.00+060748.6) from the SDSS archive and included it in our spectroscopic studies.

We pursued our spectroscopic observations of LRGs in 2009 September using the Boller & Chivens (B&C) spectrograph on the du Pont 2.5 m telescope at Las Campanas Observatory, Chile. We obtained long-slit medium-resolution spectra for seven additional LRGs in Sample A. In addition, we selected four LRGs from Sample B for the spectroscopic B&C observations. The B&C camera has a plate scale of 0.7 pixel$^{-1}$. We used the 300 in/mm grating with a central wavelength of 6500 Å and a grating angle of 6°. Since most spectral features of early-type galaxies at $z \sim 0.5$ are located at $\lambda > 5000$ Å, we employed the blocking filter GG4495 to block the light blueward of $\approx 5000$ Å, in order to avoid second-order contamination from the blue
part of the spectrum. The slit width for all observations was 1′.1. The adopted grating configuration had a dispersion of 3 Å pixel$^{-1}$ and a wavelength coverage of more than 6000 Å. For the calibration frames, we followed the methodology employed for the DIS observations. A series of dome and sky flats were taken each afternoon prior to the observations and calibration frames for wavelength solution were taken immediately after each science exposure. The typical seeing measured with the guide star was 1′−1′.4 during most observations.

All of the DIS and B&C spectroscopic data were reduced using standard long-slit spectral reduction procedures. The spectra were calibrated to vacuum wavelengths, corrected for the heliocentric motion, and flux-calibrated using a spectrophotometric standard. Redshifts of the LRGs were determined based on a cross-correlation analysis using known SDSS templates. The typical redshift uncertainty is $\Delta z \sim 0.0003$.

In summary, the spectroscopic sample consists of 11 galaxies in Sample A and four in Sample B. A journal summarizing the observations of the 15 galaxies can be found in Table 1.

4. RESULTS

4.1. Optical Spectra of LRGs

The optical spectra described in Section 3 confirmed that five of the LRGs occur within 350 km s$^{-1}$ of an Mg ii absorber. Four of these LRGs belong to Sample A and one to Sample B. Figure 1 shows the optical spectra and SDSS images of these five LRGs. The close proximity of these LRGs and Mg ii absorbers ($\rho \lesssim 300$ h$^{-1}$ kpc and $|\Delta v| \lesssim 350$ km s$^{-1}$) strongly argues for a physical association between the galaxy and the absorbing gas. We note that the volume spanned by $|\Delta v| = \pm 350$ km s$^{-1}$ and $\rho = 350$ h$^{-1}$ kpc is $\sim 5$ comoving ($h^{-1}$ Mpc)$^3$ at $z = 0.5$. Within this small volume, we estimate based on the best-fit luminosity functions determined for red galaxies at $z \sim 0.5$ ($M_\ast - 5 \log h = -19.8; \phi_\ast = 5.16 \times 10^{-3}$ ($h^{-1}$ Mpc)$^{-3}$; see, e.g., Brown et al. 2007, 2008) that the probability of the LRG being a random galaxy is negligible.

In Figure 2, we present absorption profiles of the Mg ii, Mg i, and Fe ii transitions from the SDSS QSO spectra for these five physical pairs. In each panel, zero velocity corresponds to the spectroscopic redshift of the LRG. All absorbers occur within $|\Delta v| \lesssim 350$ km s$^{-1}$ of the spectroscopically identified LRGs. Although the spectral resolution of SDSS spectra does not allow us to resolve individual components, the panels show that three of the Mg ii absorbers have associated Fe ii and Mg i absorption features.

All 15 LRG spectra exhibit spectral features dominated by absorption transitions, indicating an old underlying stellar population and little star formation in the recent past. A stellar population synthesis analysis done with the Bruzual & Charlot (2003) spectral library established that the most likely stellar population ages for these LRGs span 1−11.75 Gyr (J.-R. Gauthier et al. 2010, in preparation).

4.2. Incidence of Cool Gas in LRG Halos

We determined the covering fraction of cool gas in massive halos, based on the presence/absence of Mg ii absorbers in the spectrum of the background QSO near the redshifts of the LRGs in Sample B. For each LRG–QSO pair, we visually inspected the QSO spectrum in search of Mg ii absorbers in the redshift uncertainty range of the LRG, $z_{ph} \pm 3 \sigma_z$. For $\sigma_z \sim 0.045$ at $z_{ph} = 0.5$, this interval corresponds to approximately $\pm 400$ Å centered at $\sim 4200$ Å. We defined this interval as the search interval, which is large enough to identify all possible Mg ii absorbers that may be associated with the LRG. Despite the large redshift uncertainties, however, our search yielded a conservative maximum gas covering fraction $\kappa_{max}$ of Mg ii absorbing gas in LRG halos. If no absorber was visually detected, we measured a 2σ upper limit per spectral resolution element, $W_{lim}$, for the equivalent width of the Mg ii $\lambda 2796$ transition, using the noise spectrum. For each sight line with a measurement, we measured the redshift and strength of the absorber based on a Gaussian profile analysis. For these sight lines, we also determined $W_{lim}$ following the procedure described earlier. Because the signal-to-noise ratio (S/N) varies substantially between QSO spectra, $W_{lim}$ represents the minimum absorption strength that can be recovered in each QSO spectrum. It serves to define a homogeneous sample of QSO spectra that can be adopted to determine the incidence of Mg ii absorbers.

To determine the incidence of Mg ii absorbers with $W_{i}(2796) \geq W_0$ Å around LRGs, we first identified from the parent LRG–QSO pair sample the QSO spectra that satisfy $W_{lim} < W_0$ Å to ensure that the QSO spectra have sufficient S/N for revealing an Mg ii absorber of minimum strength $W_0$. Next, we determined $\kappa_{max}$ by evaluating the fraction of the QSO spectra that display an Mg ii absorber of $W_i (2796) > W_0$ in the vicinity of the LRGs. We calculate $\kappa_{max}$ for different values of $W_0$ in different $\rho$ intervals.
Figure 1. Spectra of the LRGs in our spectroscopic sample with associated Mg\textsc{ii} absorbers, along with the thumbnail images of the galaxies. The top four LRGs were selected from Sample A (Section 2.1) and the bottom one was selected from Sample B (Section 2.2). For each LRG, we show the reduced spectrum in thick solid histograms and the corresponding 1σ error array in thin solid histograms. The dotted features are contaminating skylines or artifacts. The thumbnail images are reproduced from the SDSS data archive to show the relative alignment of the LRG–QSO pairs. The LRG is at the center of each image and is connected to the background QSO by the arrow. The redshift of the LRG and the projected distance to the QSO sight line are listed in the bottom right corner. The velocity separation between the LRG and Mg\textsc{ii} absorber is listed in the bottom left along with $W_r(2796)$. (A color version of this figure is available in the online journal.)

This search allowed us to estimate the maximum possible covering fraction of cool gas based on the incidence of Mg\textsc{ii} in LRG halos (see Section 5 for a discussion on the contamination rate due to correlated and random galaxies). We first considered the incidence of Mg\textsc{ii} absorbers at different absorption threshold $W_\text{lim}$. All QSO spectra in the 620 close LRG–QSO pairs have sufficient S/N ($W_\text{lim} < 1$ Å) for uncovering an absorber of $W_r(2796) \geq 1$ Å. Our search showed that 45 of the 620 LRGs have a $W_r(2796) \geq 1$ Å absorber at $\rho < 400$ h$^{-1}$ kpc, indicating a mean covering fraction averaged over the entire LRG halos of $\kappa_{\text{max}}(\rho < 400) = 0.07$ for $W_r(2796) > 1$ Å absorbers. Next, we calculated $\kappa_{\text{max}}$ in different $\rho$ intervals. Figure 3 shows that for $W_r \geq 1$ Å $\kappa_{\text{max}}(\rho) \approx 10\%$ at $\rho < 300$ h$^{-1}$ kpc but declines to $\kappa_{\text{max}} \approx 5\%$ at larger $\rho$ (triangles).

Similarly, 575 QSO spectra in the 620 close LRG–QSO pairs have sufficient S/N ($W_\text{lim} < 0.5$ Å) for uncovering an absorber of $W_r(2796) \geq 0.5$ Å, and 105 of the 575 LRG members have a $W_r(2796) \geq 0.5$ Å absorber at $\rho < 400$ h$^{-1}$ kpc. The search therefore yielded a mean covering fraction averaged over the entire LRG halos of $\kappa_{\text{max}}(\rho < 400) = 0.18$ for absorbers of $W_r(2796) > 0.5$ Å. The estimated $\kappa_{\text{max}}$ versus $\rho$ for $W_r(2796) \geq 0.5$ Å absorbers are also presented in Figure 3 (squares).

The $\kappa_{\text{max}}$ results at small separations ($\rho \lesssim 100$ h$^{-1}$ kpc) are consistent with the covering fraction measurements from the spectroscopic Sample B. We found 1/4 LRGs physically associated with the Mg\textsc{ii} absorber and all four pairs are within $\rho = 100$ h$^{-1}$ kpc. We are currently increasing the number of spectroscopic pairs from Sample B to obtain a more accurate measurement of $\kappa$.

5. DISCUSSION

Our follow-up spectroscopic study of close LRG–Mg\textsc{ii} pairs has confirmed a physical association between the Mg\textsc{ii} absorber and the LRG in five of the 15 cases studied. The small velocity separations $|\Delta v| \lesssim 350$ km s$^{-1}$ and projected distances $\rho < 160$ h$^{-1}$ kpc demonstrate that at least some of the strong Mg\textsc{ii} absorbers [$W_r(2796) > 1$ Å] that contributed to the small-scale $r_p = (1+z) \times \rho < 600$ h$^{-1}$ kpc clustering signal in Gauthier et al. (2009) do indeed originate in the hosting dark matter halos of LRGs. According to a stellar population analysis (using the stellar templates from Bruzual & Charlot 2003) done on the LRG spectra, we found that these galaxies are characterized by a stellar population at least 1 Gyr old with a most likely age between 1–11.75 Gyr. The optical spectra are characteristic of an evolved stellar population with little recent star formation.

In addition, our search of Mg\textsc{ii} absorption features in the vicinity of LRGs has yielded a conservative estimate of the maximum covering fraction of cool gas in LRG halos. Because of the redshift uncertainties of the LRGs, we cannot distinguish between whether the observed Mg\textsc{ii} absorbers are physically associated with the LRG halos or these absorbers occur due to chance coincidence, correlated galaxies, or surrounding satellite galaxies. Despite these various uncertainties, the observed incidence of Mg\textsc{ii} absorbers places a strong constraint on the maximum covering fraction of cool gas in massive LRG halos as probing by the Mg\textsc{ii} absorbers. We find that the cool gas covering fraction of absorbers with $W_r(2796) \geq 0.5$ Å in massive LRG
Figure 2. Absorption profiles of the five physical LRG–Mg II absorber pairs in our spectroscopic sample of LRGs. The first four objects belong to Sample A and the last one belongs to Sample B. We included the associated Mg II λ2852 and Fe II λ2600 transitions. Zero velocity corresponds to the spectroscopic redshift of the associated LRG. Contaminating features are shown in gray.

Figure 3. Incidence of cool gas as probed by the presence/absence of Mg II absorption features, κmax, at different projected radius of massive LRG halos in Sample B. The vertical dashed line represents the typical virial radius of the LRG population (see Gauthier et al. 2009). Despite the large redshift uncertainties of the LRGs, the observed incidence of Mg II absorbers places a strong constraint on the maximum covering fraction of cool gas around LRGs. We estimate the contribution due to random background absorbers that occur within the redshift interval of the LRGs by coincidence. The result is shown in the dotted line. Including correlated absorbers due to large-scale matter clustering does not increase the background contribution to beyond 3%. The solid curve corresponds to the expected maximum contribution from satellite galaxies to the observed incidence of Mg II absorbers in the vicinity of LRGs. Note that the error bars on κmax are derived from the Poisson distribution.

Under the assumption that the gaseous halos of satellite halos are the same as field halos of similar mass, Equation (1) yields a maximal covering fraction of 1.8% at ρ ≲ 350 h⁻¹ kpc. This is the maximum value because tidal stripping and ram pressure are not taken into account (e.g., Gunn & Gott 1972; Balogh et al. 2000).
assumes that the subhalos have a random distribution within the parent halo. If we further assume that the subhalos follow a Navarro–Frenk–White profile (Wetzel & White 2010), $\tilde{N}_{\text{sub}}$ depends on impact parameter as shown in Figure 4. The satellite contribution is at most comparable to the $k_{\text{max}}$ measurements at $\rho < 100 h^{-1} \text{kpc}$, but the satellite covering factor of cool gas is $\gtrsim 1$ dex below $k_{\text{max}}$ at $\rho > 200 h^{-1} \text{kpc}$.

To estimate the incidence of Mg ii absorbers due to structure along an LOS that intersects a large halo, we adopt the observed mean number density of $W_{\lambda}(2796) \gtrsim 1 \text{Å}$ absorbers from Nestor et al. (2005) and Prochter et al. (2006). These authors report a mean number density of

$$N_{\text{LOS}} = 1.2 \times 10^{-5} \text{cm}^{-2} \text{Å}^{-1}$$

along an LOS that intersects a large halo, we adopt the observed contamination of 0.027 absorbers per LOS. To estimate the expected incidence of Mg ii absorbers in the vicinity of LRGs, the maximum covering fraction therefore reflects the differences in the cold gas content of halos on different mass scales (see, e.g., Tinker & Chen 2008; Chen et al. 2010). This implies that the typical mass of the dark matter halos hosting QSOs is around $log M/h \sim 12.3$ (see Figure 12 in Ross et al. 2009), which is about 1 dex smaller than what is found for LRGs in Gauthier et al. (2009).

Recall that Mg ii absorbers trace high column density gas of neutral hydrogen column density $N(H) > 10^{18} \text{cm}^{-2}$ (Bergeron & Stasińska 1986; Rao et al. 2006). Furthermore, Rao et al. (2006) have shown that on average 42% of $W_{\lambda}(2796) > 0.6 \text{Å}$ Mg ii absorbers with associated strong Fe ii and Mg i absorption transitions are likely to contain neutral gas of $N(H) > 2 \times 10^{20} \text{cm}^{-2}$. Two of the Mg ii absorbers presented in Figure 2 satisfy these criteria and are therefore likely damped Ly$\alpha$ absorbers. Our study therefore provide direct empirical evidence for the presence of high column density cool gas in $10^{13} h^{-1} M_{\odot}$ halos. A large spectroscopic sample of LRGs will not only improve the constraints for $k_p$ in massive halos but also provide additional insights into the origin of the cool gas.

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