The Star Formation History of Luminous Red Galaxies Hosting MgII Absorbers

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ABSTRACT

We present a spectroscopic sample of $z \approx 0.5$ luminous red galaxies (LRGs) that are located within physical projected distances $\rho \lesssim 350$ h$^{-1}$ kpc of a QSO sightline. Of the 37 LRGs in our sample, eight have associated MgII absorbers with rest-frame equivalent width $W_r(2796) > 0.3$ Å and velocity separation $|\Delta v| \lesssim 350$ km s$^{-1}$ and 29 do not have associated MgII absorbers to a 2-$\sigma$ limit of $W_r(2796) = 0.3$ Å. We perform a stellar population synthesis analysis using stacked spectra of the MgII absorbing and non-absorbing LRG subsamples. We find that LRGs with or without associated MgII absorbers share similar star formation histories and are best described by old stellar population models ($\gtrsim 1$ Gyr). Younger stellar populations ($\lesssim 1$ Gyr) fail to reproduce their spectra. These findings are consistent with the lack of [OII] emission features in the LRG spectra. The primarily old stellar populations in the LRGs indicate that starburst driven outflows are unlikely to explain the observed MgII absorbers at large distances from the LRGs. In addition, the spectroscopic LRG sample allows us to derive a sensitive constraint for the cool gas covering fraction of $\langle \kappa \rangle = 14 \pm 6\%$ in the LRG halos for absorbers of $W_r(2796) > 0.3$ Å. Finally, we speculate on the origin of the observed MgII absorbers around the LRGs.

Key words: Galaxies:evolution — Quasars:absorption lines.

1 INTRODUCTION

Tracing the origin of the baryonic content of galaxies is a key ingredient to a comprehensive theory of galaxy formation. In Gauthier et al. (2009,2010; hereafter G09,G10), we studied the cool gas content of luminous red galaxies (LRGs) using a sample of close QSO–LRG pairs. Cool gas is revealed by the presence of MgII λλ 2796,2803 absorption systems in the spectra of background QSOs at the redshifts of the LRGs (see also Bowen & Chelouche 2011). Our studies revealed a non-negligible amount of cool gas with covering fraction $\kappa \approx 20\%$ in LRG halos. The association between LRGs and MgII absorbers is unexpected, because LRGs inhabit dark matter halos of mass $\sim 10^{13}$ h$^{-1}$ M$_\odot$ (e.g., Blake et al. 2008) for which theoretical models and hydrodynamical simulations predict that little cool gas can survive (e.g., Birnboim & Dekel 2003; Keres et al. 2009; Stewart et al. 2010; Paucher-Giguere et al. 2011; Mo & Miralda-Escude 1996; Maller & Bullock 2004). In addition, LRGs constitute a homogeneous sample of passive galaxies characterized by old stellar populations giving rise to strong 4000-Å breaks. They are characterized by luminosities of $\sim 5$ L$_\odot$ and stellar masses of $\approx 3 \times 10^{11}$ M$_\odot$ at $z \approx 0.5$ (e.g., Tojeiro et al. 2011). Given the relatively old stellar populations of these galaxies, starburst-driven outflows are unlikely to produce the observed cool gas in LRG halos.

But while most LRGs are quiescent and show little star formation activity, Roseboom et al. (2006) showed that $\approx 10\%$ of the galaxies display [OII] λ 3727,3729. It is possible that the LRGs hosting MgII absorbers are a biased sub-population that contain on-going star formation. In this letter, we present a stellar population synthesis analysis of LRGs spectroscopically identified at physical projected separations $\lesssim 350$ h$^{-1}$ kpc from a QSO sightline. Comparing the stellar populations and star formation histories of MgII absorbing and non-absorbing LRGs allows us to examine whether or not MgII absorbers occurs preferentially in the star-forming subsample. In addition, the spectroscopic LRG sample enables us to constrain the incidence of MgII absorbers in LRG halos based on inspections of the QSO spectra.

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2 OBSERVATIONS AND DATA ANALYSIS

We conducted long-slit spectroscopy of 37 LRGs at projected separations $\rho \leq 350\;h^{-1}\;\text{kpc}$ from background QSO sightlines. The LRGs were photometrically identified in SDSS DR4 (Collister et al. 2007; Blake et al. 2007) and the QSOs were selected from the SDSS DR5 QSO spectroscopic catalog (Schneider et al. 2007). The maximum separation corresponds approximately to the virial radii of the LRGs (see G09), allowing us to probe gravitationally bound gas.

The LRGs were separated into two subsamples based on the prior knowledge of the presence of Mg II absorbers in the QSO spectra. In Sample A, photometrically-selected LRGs were found in the vicinity of known Mg II absorbers. In Sample B, the LRG–QSO pairs were composed of random LRGs near QSO sightlines for which we had no prior knowledge of the presence or absence of Mg II absorbers. Sample B was used to derive constraints on the covering fraction of cool gas. Of the 37 LRGs presented in this paper, 28 belong to Sample B and nine to Sample A. More details about the samples can be found in G10.

We used the Double Imaging Spectrograph (DIS) on the 3.5-m telescope at the Apache Point Observatory and the Boller & Chivens spectrograph (B&cC) on the du Pont telescope at the Las Campanas Observatory in Chile. Details about the spectroscopic observations and data reduction are presented in G10. In summary, we acquired long-slit galaxy spectra at intermediate resolution ($R \approx 1000$) in the wavelength range 5000–8500 Å. The raw spectra were flux-calibrated using a spectrophotometric standard. To examine the accuracy of the flux calibration, we compared the spectral energy distribution of our flux calibrated LRG spectra with available $g'$ $r'$ $i'$ $z'$ broad-band photometry from the SDSS data archive. We confirmed that our flux calibration yielded consistent continuum slopes for the LRGs at wavelengths $\lambda \lesssim 8000$ Å.

We determined the redshifts of the LRGs using a cross-correlation analysis with known SDSS galaxy templates. Typical redshift uncertainties were $|\Delta v| \approx 70\;\text{km}\;\text{s}^{-1}$ at $z \approx 0.5$. All galaxy spectra were corrected for atmospheric and Galactic extinction. A journal of the spectroscopic observations are presented in columns (1)-(6) of Table 1.

At the spectroscopic redshift of the LRGs, we inspected the QSO spectra and searched for Mg II absorbers within $|\Delta v| = 350\;\text{km}\;\text{s}^{-1}$. This velocity interval corresponds roughly to the virial velocity of the LRGs. When a Mg II absorber is found in the QSO spectrum, we measured the redshift and strength of the absorber using a Gaussian profile analysis. When no absorber was visually detected, we classify the LRG as a non-absorbing galaxy. Column (7) of Table 1 displays the Mg II absorption strength. In cases where no Mg II features are detected, we present a 2-$\sigma$ upper limit of the absorber strength. Two galaxies (SDSSJ114445.36, SDSSJ220703.36) in the absorbing sample have velocity separations of 380 and 360 km s$^{-1}$, which are larger than the considered limit $|\Delta v| = 350\;\text{km}\;\text{s}^{-1}$. Given that the redshift uncertainty of the galaxies is $|\Delta v| \approx 70\;\text{km}\;\text{s}^{-1}$, we cannot rule out the possibility that the absorbers are associated with the LRGs. We therefore included them in the absorbing sample. We tested whether assigning these galaxies to the absorbing sample altered the results of the population synthesis analysis or not and we found no changes. In summary, the spectroscopic observations of the LRGs yielded eight physical LRG-Mg II pairs and 29 LRGs without associated Mg II absorbers to a sensitive upper limit. Note that we retrieved the spectrum of one LRG (SDSSJ125300.00) from the SDSS archive and included it in our sample. Projected separations and velocity separation of the LRG–QSO pairs are presented in Columns (8)-(9) along with the LRG sample (A or B) in column (10) of Table 1.

Individual spectra of the LRGs in our sample have typical $S/N \approx 4$. To obtain robust results from the population synthesis analysis, we formed a stacked spectrum of each of the LRG subsamples. To generate a stacked spectrum, we first masked out strong sky emission lines and absorption bands. We then shifted the observed spectrum to the rest-frame of the galaxy and adopted a common pixel resolution of $\Delta v = 350\;\text{km}\;\text{s}^{-1}$. We employed a weighting scheme in which each galaxy spectrum is weighted by their mean $(S/N)^2$ to maximize the final $S/N$. The stacked spectrum of each sample covers the rest-frame wavelength range 3600–5500 Å and is shown in Figure 1.
3 STELLAR POPULATION SYNTHESIS ANALYSIS

We performed a stellar population synthesis analysis to constrain the ages of the stellar populations of the LRGs. To accomplish this task, we carried out a likelihood analysis that compares the stacked spectrum with model expectations for different stellar age, metallicity and star formation history. The likelihood function is defined as

\[ \mathcal{L}(t) = \prod_{i=1}^{N} \exp \left\{ -\frac{1}{2} \left[ \frac{f_i - \bar{f}_i(t)}{\sigma_i} \right]^2 \right\} \]  

(1)

where \( t \) is the age of the stellar populations, \( N \) is the number of spectral bins (\( N = 311 \)), \( f_i \) is the observed flux in the 3rd bin, \( \bar{f}_i \) is the model prediction, and \( \sigma_i \) is the corresponding error of the 3rd element. As described in § 2, the flux calibration became uncertain at \( \lambda \gtrsim 8000 \) Å, corresponding to rest-frame \( \lambda \gtrsim 5200 \) Å for these LRGs. We therefore limited our analysis to the spectral range 3600–5200 Å in the rest-frame of the LRGs (Figure 2).

The stellar population models were based on those described in Bruzual & Charlot (2003) revised to include a description of the TP-AGB evolution of low and intermediate mass stars (Marigo & Girardi 2007). We employed a Chabrier initial mass function for all models (Chabrier 2003). The star formation history (SFH) of the model galaxies was parameterized by either a single burst or by an exponentially declining model with an e-folding timescale \( \tau \). The ages \( t \) were equally separated in logarithmic space between 0.1 and 0.5 Gyr and we adopted metallicities of 0.02, 0.2, 1, and 2.5 solar. To directly compare between data and models, we convolved the model spectra with a top-hat function of width 350 km s\(^{-1}\) to match the resolution of the data.

Extinction by the host LRG was not included in the final model templates. However, we did generate a library of model spectra with host extinction following the Charlot & Fall (2000) prescription. We found that the LRG spectra systematically select the models with the least amount of extinction. For this reason, we did not include extinction by the host galaxy in the final library of synthetic spectra.

4 MEAN STELLAR POPULATION OF THE LRGs

Figure 1 shows the stacked spectra of both samples of LRGs along with the best-fit stellar population model in red. The LRGs in both samples exhibit spectral features dominated by absorption transitions, suggesting an old underlying stellar population and little star formation in the recent past. Visual inspections of individual LRG spectra show that three LRGs, (SDSSJ142312.00, SDSSJ220703.36, SDSSJ232924.13) exhibit traces of [O II] emission, one of which belongs to the absorbing sample (SDSSJ220703.36). These three LRGs represent 8% of the absorbing and non-absorbing LRGs combined. The fraction of [O II] emitting LRGs is consistent with the finding of Roseboom et al. (2006), who found that ~10% of LRGs show [O II] emission.

The spectra of the LRGs support the previous understanding that these galaxies are primarily quiescent, which is further supported by the results of the population synthesis analysis presented in Figure 2. The relative likelihood functions of the stellar age of these LRGs show that the Mg II absorbing LRG sample is best characterized by a \( \tau \) model of \( \tau = 0.15 \) Gyr, age \( t = 3.25 \) Gyr, and solar metallicity, while the non-absorbing LRGs are best-characterized by a single burst of age \( t = 8.25 \) Gyr and metallicity 0.2 solar. At \( \lesssim 1.6 \) Gyr, the LRGs can be characterized by a single burst of metallicity 2.5 solar. At 1.6 \( \lesssim t \lesssim 5 \) Gyr, the LRGs can be characterized by an exponentially declining SFR model of \( \tau = 0.2 \) to 0.5 Gyr and metallicity of solar or 2.5 solar. At older ages \( (\gtrsim 5 \) Gyr), the best-fit models are either single burst of sub-solar metallicity (0.2 solar) or exponentially declining models of \( \tau = 0.5 \) Gyr and solar metallicity.

Figure 2. Relative likelihood functions of the stellar age of LRGs with and without associated Mg II absorbers. The stellar age distribution shows that both galaxy samples are characterized by an evolved stellar population of age \( \gtrsim 1 \) Gyr. The model spectra are shown in Figure 1. The Mg II absorbing LRG sample is best characterized by a \( \tau \) model of \( \tau = 0.15 \) Gyr, age \( t = 3.25 \) Gyr, and solar metallicity, while the non-absorbing LRGs are best-characterized by a single burst of age \( t = 8.25 \) Gyr and metallicity 0.2 solar. At \( \lesssim 1.6 \) Gyr, the LRGs can be characterized by a single burst of metallicity 2.5 solar. At 1.6 \( \lesssim t \lesssim 5 \) Gyr, the LRGs can be characterized by an exponentially declining SFR model of \( \tau = 0.2 \) to 0.5 Gyr and metallicity of solar or 2.5 solar. At older ages \( (\gtrsim 5 \) Gyr), the best-fit models are either single burst of sub-solar metallicity (0.2 solar) or exponentially declining models of \( \tau = 0.5 \) Gyr and solar metallicity.

Our stellar population synthesis analysis confirms the results of visual inspections that the LRGs exhibit little recent (\( t < 1 \) Gyr) star formation activities. For both samples, the best-fit models at \( t \lesssim 1.6 \) Gyr are characterized by a single burst of 2.5 solar metallicity. Beyond 1.6 Gyr, the best-fit models have \( \tau \) ranging from \( \tau = 0.2 \) to 0.5 Gyr. The more extended \( \tau \) models are compensated by the corresponding older age. At still older ages of \( t > 5 \) Gyr, the best-fit models are either single burst of 0.2 solar metallicity or a \( \tau \) model of \( \tau = 0.5 \) Gyr and solar metallicity. The corresponding lower metallicity at older ages is consistent with the well-known age-metallicity degeneracy (Worthey 1994), making it difficult to determine a precise metallicity for the underlying stellar population. However, the results of our likelihood analysis shows that we can robustly constrain the minimum age of the stellar population to be \( > 1 \) Gyr.
Their mean spectra are best described by evolved stellar population synthesis models. By comparing the observed spectra of LRGs with models, we can confirm that these LRGs do not show recent star formation activities. Furthermore, absorbing LRGs share comparable star formation histories, which can be summarized as follows. First, Mg II absorbing and non-absorbing LRGs possess similar star formation histories. The results of the stellar population synthesis analysis can confirm these findings.

5 DISCUSSION

The results of the stellar population synthesis analysis can be summarized as follows. First, Mg II absorbing and non-absorbing LRGs share comparable star formation histories, confirming that the LRGs with associated Mg II do not constitute a biased population of star-forming galaxies. Second, these LRGs do not show recent star formation activities. Their mean spectra are best described by evolved stellar populations of at least 1 Gyr old.

A caveat of our analysis is that if star formation occurs in the outskirts of the LRGs, our analysis would not have detected the blue light and emission lines associated with these regions. In a recent analysis, Tal & van Dokkum (2011) have searched for extended light around LRGs based on stacked SDSS images of more than 40000 objects. These authors find that while excess light can be detected out to 100 kpc of the LRGs, the colors of the extended light are consistent with the colors of the LRGs. The consistent colors indicate that the stellar population does not vary significantly with radius in the LRG halos. Therefore we conclude that the observed Mg II absorbers are unlikely to be associated with star-forming regions in the outskirts of the LRGs. Here we discuss the implications of our analysis.

5.1 Transition in the cool gas content of dark matter halos

In Figure 3, we present $W_r(2796)$ versus $\rho$ for a subsample of LRGs. We obtained spectra of these LRGs without prior knowledge of the presence/absence of Mg II absorbers in the QSO spectra (Sample B). Because these LRGs were selected with no prior knowledge of Mg II absorbers, we can use this sample to measure the covering fraction, $\kappa$, of cool gas in LRG halos. The likelihood of detecting an ensemble of galaxies of which $n$ give rise to Mg II absorbers and $m$ do not is given by

$$L(\kappa) = (\kappa)^n (1 - \kappa)^m .$$

Within $\rho = 350 \ h^{-1} \ kpc$ four LRGs have associated Mg II absorbers ($n = 4$) and 24 do not ($m = 24$) show Mg II absorption features to 2-$\sigma$ upper limit better than $W_r(2796) = 0.3 \ \AA$. Using equation (2), we found $\kappa = 0.14 \pm 0.06$, where the error bars indicate the 68% confidence interval based on the likelihood function. We also calculated $\kappa$ within the gaseous radius, $R_{gas}$, defined by Chen et al. (2010). According to their model, a $10^{13} \ h^{-1} \ M_{\odot}$ halo possess a gaseous envelope of size $R_{gas} = 108 \ h^{-1} \ kpc$. Within this gaseous radius, there are two physical pairs and seven upper limits ($\kappa = 0.22 \pm 0.13$).

Here we assume that a Mg II absorber found within $\rho = 350 \ h^{-1} \ kpc$ and $|\Delta v| = 350 \ km s^{-1}$ of an LRG traces gas that is physically associated with the LRG, i.e. the gas inhabits the dark matter halo of the LRG. The absorber could also trace gas in correlated large-scale galactic structures found in the volume probed by $\rho$ and $|\Delta v|$ and centered on the LRG. In this case, the gas would not be physically associated with the LRG. However, G10 calculated the contribution of these correlated pairs for a sample of photometrically selected LRG-Mg II pairs and found the contamination level to be low ($\approx 3\%$ of the observed Mg II absorbers in the vicinity of LRGs are thought to arise from correlated structures). We thus considered the spectroscopic Mg II-LRG pairs to be physical pairs.

We can compare the covering fraction measurements with the upper limits on $\kappa$ derived in G10. While these authors do not provide an upper limit on the covering fraction for absorbers with $W_r(2796) > 0.3 \ \AA$, they found that for the limiting strength of $W_r(2796) > 0.5 \ \AA$, $\kappa < 0.18$. The upper limit derived for absorbers of $W_r(2796) > 0.3 \ \AA$ is expected to be higher than the one derived for absorbers of $W_r(2796) > 0.5 \ \AA$. A value of $\kappa = 0.14$ for absorbers with $W_r(2796) > 0.3 \ \AA$ is thus consistent with the upper limits derived in G10.

The value of $\kappa$ in LRG halos is significantly smaller than $\kappa \approx 0.7$ measured for L* and sub-L* galaxies in Chen et al. (2010) indicating a steep decline in the cool gas content of dark matter halos. In addition, we found that the cool gas cross-section extends well beyond $R_{gas}$. Such extended gaseous envelope is not detected around low-mass halos (Chen et al. 2010). The sharp decline in the gas covering fraction is consistent with the expectation of halo occupation distribution models of Tinker & Chen (2008, 2010) to explain the clustering amplitude of Mg II absorbers. Such declining trend of cool gas fraction with halo mass is also expected in theoretical models addressing the cool gas con-
tent of dark matter halos (e.g., Maller & Bullock 2004; Keres et al. 2009).

5.2 Physical properties of cool clouds probed by Mg II

The lack of recent star formation activity in the LRGs indicates that the Mg II absorbing gas is likely due to infalling clouds instead of starburst driven outflows. Under the infall scenario, different theoretical models have been studied to explain the presence of cool halo gas. These include cold flows (e.g., Faucher-Giguere et al. 2011), cool clouds condensed out of the hot halos due to thermal instabilities (Mo & Miralda-Escudé 1996; Maller & Bullock 2004, hereafter MB04), and stripped material from satellite galaxies (e.g. Wang 1993, Agertz et al. 2009). Irrespective of the physical mechanism that produces the observed Mg II absorbers near the LRGs, the cool clouds are expected to fall and fuel star formation at the center of the halo. At the same time, the galaxies are found to be quiescent for at least the past 1 Gyr, implying that these Mg II clouds do not survive the infall through the hot halo.

Whether or not cool clouds can reach the center of the halo depends on the infall time scale relative to the disruption time scale. Under hydrostatic equilibrium, the infall time scale is determined primarily by the ram pressure drag, while the disruption time scale is driven predominantly by heat conduction. If the evaporation time scale, $\tau_{\text{evap}}$, is shorter than the time scale needed for ram pressure drag to sap the energy, the clouds will likely evaporate before reaching the center of the halo. This allows us to constrain the physical properties of the cool clouds (e.g. Maller & Bullock 2004).

For this particular model, $\tau_{\text{evap}} \approx 16 m_6^{2/3} T_6^{-3/2} (\Lambda t_b)^{-1/3} \text{ Gyr} \text{ where } m_6 = \text{ the cloud mass in units of } 10^6 M_\odot \text{, } T_6 = T/10^6 \text{ K is the halo gas temperature, } \Lambda \text{, and } t_b = t/(8 \text{ Gyr}) \text{ are the cooling parameter and halo formation time scale (see equation } 35 \text{ and Appendix B in MB04)}. \text{ Assuming that the hot gas is isothermal with } T \sim 6 \times 10^6 \text{ K, } t_b \text{ is the age of the universe at } z \sim 0.5, \text{ and the metallicity of the gas is } 0.1 \text{ solar, we found that } \tau_{\text{evap}} \approx 1.1 m_6^{2/3} \text{ Gyr. The parameter } \tau_{\text{evap}} \text{ constitutes the typical time scale over which clouds will be disrupted due to heat conduction. To calculate the infall time scale, we first adopted the maximum rotation velocity of the halo to estimate the ram pressure drag force. The time scale over which ram pressure drag force is then given by } \tau_{\text{rp}} \approx 2.6 m_6^{1/3} T_6^{1/2} (\Lambda t_b)^{1/3} \text{ Gyr (see equation 43 in MB04). We found } \tau_{\text{rp}} \approx 1.1 m_6^{1/3} \text{ Gyr. Because the cool clouds are expected to be disrupted before reaching the center of the halo, } \tau_{\text{evap}} \lesssim \tau_{\text{rp}} \text{. This led to a mass limit of } m \lesssim 10^6 M_\odot \text{.}

We note a main caveat in this calculation. If the hot halo is out of equilibrium either due to supernova driven wind or AGN outflows, then the structure of halo gas distribution is expected to be different before hydrostatic equilibrium can be restored (e.g. Brighenti & Mathews 2003). The estimated mass limit is therefore very uncertain, depending on the thermal state of the halo. For example, outflows/winds are expected to increase the ram pressure, prolonging the infall time, and thereby increasing the mass limit.

It is also possible that the observed Mg II absorbers originate in the ISM of a satellite galaxy, directly intercepting the QSO sightline. However, we find this an unlikely scenario. Gauthier et al. (2010) have shown based on an analytic calculation that if the gas content of satellite galaxies remains intact as they orbit around the primary galaxy, then satellite galaxies could be a dominant contributor to the gas cross-section only at small distances ($\rho < 100 \ h^{-3} \ kpc$). Given that ram pressure and tidal stripping is effective in removing gas in satellite galaxies (e.g. Chynoweth et al. 2008), we consider this a conservative upper limit to possible satellite contributions to the observed Mg II absorption features. We expect that empirical knowledge of the satellite environment of the LRGs and gas kinematics of the absorbers will provide further insights into the physical origin of the observed extended gas in LRG halos.

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Table 1. Summary of the Absorbing and Non-Absorbing Samples of LRGs

| ID                | $z_{spec}$ | $v'$  | Instrument | Exptime (sec) | UT date       | $W_r$(2796) | $\rho$(h$^{-1}$kpc) | $|\Delta v|$ (km s$^{-1}$) | Sample |
|-------------------|------------|-------|------------|---------------|---------------|-------------|---------------------|--------------------------|--------|
| SDSSJ114445.36+071456.4 | 0.4906     | 19.26 | B&C        | 2700          | 2010-04-15    | 0.6 ± 0.1   | 70                   | 380                      | B      |
| SDSSJ114658.60+020716.8 | 0.5437     | 19.50 | DIS        | 2x1800        | 2009-05-26    | 1.2 ± 0.2   | 134                  | 0                        | A      |
| SDSSJ114242.72+041512.0 | 0.5512     | 19.85 | DIS        | 2x1800        | 2010-04-12    | 0.4 ± 0.1   | 148                   | 30                       | B      |
| SDSSJ115063.16+041906.9 | 0.6155     | 19.69 | B&C        | 2400+1800     | 2010-03-12    | 1.5 ± 0.3   | 33                    | 126                      | A      |
| SDSSJ114104.08+063443.1 | 0.5703     | 19.06 | DIS        | 2x1800        | 2010-04-12    | 0.5 ± 0.1   | 101                   | 79                       | B      |
| SDSSJ200703.36−090051.6 | 0.5604     | 19.60 | DIS        | 2x1800        | 2010-07-20    | 4.0 ± 0.1   | 171                   | 360                      | A      |

**Absorbing Galaxies**

**Non-absorbing Galaxies**

For non-absorbing galaxies, $W_r$(2796) is a 2-$\sigma$ upper-limit on Mg II λ2796 transition strength. $|\Delta v|$ is the absolute velocity separation between the Mg II absorber and the LRG redshift.