A Complete Census of Circumgalactic Mg II at Redshift $z \lesssim 0.5^*$

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ABSTRACT
This paper presents a survey of Mg II absorbing gas in the vicinity of 380 random galaxies, using 156 background quasi-stellar objects (QSOs) as absorption-line probes. The sample comprises 211 isolated (73 quiescent and 138 star-forming galaxies) and 43 non-isolated galaxies with sensitive constraints for both Mg II absorption and Hα emission. The projected distances span a range from $d = 9$ to 497 kpc, redshifts of the galaxies range from $z = 0.10$ to 0.48, and rest-frame absolute B-band magnitudes range from $M_B = -16.7$ to $-22.8$. Our analysis shows that the rest-frame equivalent width of Mg II, $W_r(2796)$, depends on halo radius ($R_h$), B-band luminosity ($L_B$) and stellar mass ($M_{\text{star}}$) of the host galaxies, and declines steeply with increasing $d$ for isolated, star-forming galaxies. At the same time, $W_r(2796)$ exhibits no clear trend for either isolated, quiescent galaxies or non-isolated galaxies. In addition, the covering fraction of Mg II absorbing gas $\langle \kappa \rangle$ is high with $\langle \kappa \rangle \gtrsim 60\%$ at $< 40$ kpc for isolated galaxies and declines rapidly to $\langle \kappa \rangle \approx 0$ at $d \gtrsim 100$ kpc. Within the gaseous radius, the incidence of Mg II gas depends sensitively on both $M_{\text{star}}$ and the specific star formation rate inferred from Hα. Different from what is known for massive quiescent halos, the observed velocity dispersion of Mg II absorbing gas around star-forming galaxies is consistent with expectations from virial motion, which constrains individual clump mass to $m_{\text{cl}} \gtrsim 10^5 M_\odot$ and cool gas accretion rate of $\sim 0.7 - 2 M_\odot \, \text{yr}^{-1}$. Finally, we find no strong azimuthal dependence of Mg II absorption for either star-forming or quiescent galaxies. Our results demonstrate that multiple parameters affect the properties of gaseous halos around galaxies and highlight the need of a homogeneous, absorption-blind sample for establishing a holistic description of chemically-enriched gas in the circumgalactic space.

Key words: surveys – galaxies: halos – intergalactic medium – quasars: absorption lines – galaxies: formation

1 INTRODUCTION
Over the past decades, extensive progress has been made to understand the impact of the baryon cycle on galaxy formation and evolution, with particular focus on gas reservoirs such as the circumgalactic medium (CGM). Located in the space between galaxies and the intergalactic medium (IGM), the CGM contains critical information on gas accretion and outflows, processes that drive the evolution of galaxies (see Chen 2017; Tumlinson et al. 2017, for recent reviews). Thus, the CGM provides an excellent laboratory for understanding the physical processes that drive the formation and evolution of galaxies.

Absorption-line spectroscopy of background quasars has provided a unique probe of the low-density CGM, which is

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otherwise too diffuse to be detected in emission beyond the local Universe. Over the last decade, statistically significant samples of galaxies at $z \approx 0 - 2$ have been assembled using a combination of space- and ground-based telescopes. The Cosmic Origins Spectrograph (COS) on the Hubble Space Telescope (HST) has enabled studies of a rich suite of absorption lines including the HI Lyman series (e.g., Chen et al. 1998; Tripp et al. 1998; Rudie et al. 2013; Tumlinson et al. 2013; Werk et al. 2014; Liang & Chen 2014; Borthakur et al. 2016), the O	extsc{iv} doublet (e.g., Chen & Mulchaey 2009; Prochaska et al. 2011; Tumlinson et al. 2011; Johnson et al. 2015b) and the C	extsc{iv} doublet (e.g., Borthakur et al. 2013; Bordoloi et al. 2014; Liang & Chen 2014).

From the ground, at $z \lesssim 2$ the majority of studies have focused on the measurement of the Mg	extsc{ii} λλ2796, 2803 doublets due to their strength and visibility in the optical range. This transition is thought to arise primarily in photoionized gas of temperature $T \sim 10^4$ K (Bergeron & Stasinski 1986; Charlton et al. 2003) and high neutral hydrogen column density clouds of $N$(H	extsc{i}) $\approx 10^{16} - 10^{22}$ cm$^{-2}$ (Rao et al. 2006). Many investigations have been carried out to characterize the statistical properties of Mg	extsc{ii} absorbers, including the frequency distribution function, redshift evolution of the absorber number density and kinematic signatures (e.g., Lanzetta et al. 1987; Petitjean & Bergeron 1990; Charlton & Churchill 1998; Churchill et al. 2000, 2003; Nestor et al. 2005). Studies also show that Mg	extsc{ii} absorbing gas probes the underlying gas kinematics around galaxies (e.g., outflow and inflow gas. Weiner et al. 2009; Kacprzak et al. 2012; Rubin et al. 2014; Ho et al. 2017; Ho & Martin 2020).

To have a comprehensive understanding of the baryonic structures around galaxies, significant progress has been made in constructing samples of galaxy-Mg	extsc{ii} absorber pairs to understand the transition between cool, enriched gas and galaxy properties. On the one hand, some galaxy-Mg	extsc{ii} pair associations begin with quasar spectra and then search for nearby galaxies responsible for the Mg	extsc{ii} absorption (e.g., Kacprzak et al. 2011). Such studies commonly target galaxies already known to have Mg	extsc{ii} absorption in the spectra of background quasars and therefore may result in biased galaxy populations. On the other hand, studies have investigated relationships between galaxies and their surrounding gas using unbiased samples, where the galaxy-QSO pairs are chosen without any prior knowledge of the presence or absence of absorbing gas, allowing detailed studies of the CGM as a function of galaxy properties (including stellar mass, star formation rate and color) and environment (e.g., Chen et al. 2010a; Johnson et al. 2015a; Huang et al. 2016; Zahedy et al. 2016; Lan & Mo 2018; Martin et al. 2019).

As the Mg	extsc{ii} doublet features start to be observable in the optical wavelengths at $z \sim 0.4$, this transition has not been studied as extensively at $z \lesssim 0.4$. Here we make use of the UV sensitive spectrograph, the Magellan Echellette Spectrograph (MagE; Marshall et al. 2008), to perform searches for Mg	extsc{ii} absorbers at redshifts as low as $z \sim 0.1$. Building upon the SDSS database, we conduct the Magellan MagE Mg	extsc{ii} (M3) Halo Project in the spectra of background QSOs at $z \lesssim 0.4$. The main goal of the M3 Halo Project is to establish an unbiased, statistically significant sample of $z \lesssim 0.4$ Mg	extsc{ii} absorbers to constrain the incidence, strength and extent of Mg	extsc{ii} absorbing gas around galaxies of different properties.

The first-year results of the M3 Halo Project is reported in Chen et al. (2010a) (hereafter C10). With a spectroscopic sample of 94 galaxies at a median redshift of $z = 0.24$ and projected distance $d \lesssim 170$ kpc, Chen et al. (2010a) investigated the possible correlations between the incidence and extent of Mg	extsc{ii} absorbers and galaxy properties. We found the rest-frame equivalent width of Mg	extsc{ii} ($W_{\lambda}(2796)$) declines steeply with increasing $d$ from the galaxies. Moreover, the extent of Mg	extsc{ii} gaseous halos scales strongly with the galaxy B-band luminosity and galaxy stellar masses, with slight dependence on specific star formation rate (sSFR) and no dependence on galaxy $B_{\rm{AB}} - R_{\rm{AB}}$ color. The first-year results clearly demonstrate that Mg	extsc{ii} absorbing gas is strongly connected to the physical properties of host galaxies. Using the full sample of the M3 Halo Project, we will show that we are able to observe a clear difference in surrounding gas properties between star-forming and quiescent galaxies.

The paper is organized as follows. In Section 2 we describe the experimental design of the M3 Halo Project, and the spectroscopic observations and data reduction of the photometrically selected galaxies and spectroscopically confirmed quasars in the SDSS archive. We present the catalogs of galaxies and Mg	extsc{ii} absorbers in Section 3. In Section 4 we describe our likelihood analysis and characterize the correlation between Mg	extsc{ii} absorption strength and galaxy properties. In Section 5 we discuss the covering fraction, the kinematics and the azimuthal dependence of Mg	extsc{ii} absorbing gas. We discuss the difference between different types of galaxies, the difference between isolated and non-isolated galaxies, and compare our results with previous studies. We present a summary of our findings in Section 6. We adopt the standard Λ cosmology, $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$ with a Hubble constant $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$.

## 2 OBSERVATIONS

### 2.1 Experiment Design

To investigate the correlation between galaxy properties and Mg	extsc{ii} absorbing gas at small projected distances, we need to obtain spectroscopic data of both galaxies and QSO absorbers along common sightlines. We utilize the Magellan Echellette Spectrograph (MagE; Marshall et al. 2008) on the Magellan Clay Telescope to conduct a survey of Mg	extsc{ii} absorbers at $z < 0.4$. The high UV throughput of MagE from $\lambda = 3100$ Å enables searches of Mg	extsc{ii} absorbers at redshift as low as 0.11. We refer the reader to C10 for a detailed description of the survey design. Briefly, the QSO and galaxy pairs are selected from the SDSS DR6 catalogs (Adelman-McCarthy et al. 2008). To maximize the efficiency of searching Mg	extsc{ii} absorbers, we consider galaxies at photometric redshifts of $z_{\text{phot}} \lesssim 0.4$ that have background QSOs in close projected distance $d < R_{\text{gas}}$. The $R_{\text{gas}} = 130$ kpc is the distinct boundary found by Chen & Tinker (2008) using 23 galaxy-QSO pairs at intermediate redshifts of $z \sim 0.4$, beyond which no Mg	extsc{ii} absorbers are found. Note that although we pre-select galaxy-QSO pairs with $d < R_{\text{gas}}$ for the spectroscopic followup survey, we search the SDSS DR14 sample (Abolfathi et al. 2018) to include galaxies with spectroscopic redshifts at $z \lesssim 0.4$ around our observed QSOs to study the gaseous halo beyond $R_{\text{gas}}$. In the following sections, we describe the galaxy spectroscopic sample either obtained from...
our own observations or SDSS DR14 archive and the observations of background quasars.

2.2 Galaxy Spectroscopy

To establish a physical connection between galaxies and MgII absorbing systems along nearby QSO sightlines, it is essential to have medium to high resolution spectra to obtain precise and accurate redshift measurements of these galaxies. We have obtained optical spectra of 218 galaxies that satisfy the criteria described above using the MagE Spectrograph (Marshall et al. 2008) at the Las Campanas Observatory and the Double Imaging Spectrograph (DIS; Lupton 1995) on the 3.5 m telescope at the Apache Point Observatory. Details about the spectroscopic observation setups and data reduction are presented in C10. In summary, we acquired 120 long-slit galaxy spectra using DIS over the period from 2008 August through 2010 September, and echelle spectra of 98 galaxies using MagE from 2008 August to 2011 March. The spectra obtained using DIS and MagE have intermediate resolution of $\text{FWHM } \approx 500 \text{ km s}^{-1}$ and $\approx 150 \text{ km s}^{-1}$ in the wavelength range between $\lambda \approx 4000 \AA$ and $1 \mu\text{m}$. We reduced the DIS spectroscopic data using standard long-slit spectral reduction procedures, and the MagE spectra using the software developed by G. Becker with a slight modification to work with binned spectral frames. The redshifts of these galaxies were determined using a cross-correlation analysis with a linear combination of SDSS galaxy eigen spectra. The typical redshift uncertainty is $\Delta z \approx 0.0003$ and 0.0001 for galaxy spectra taken using DIS and MagE.

We include 17 additional SDSS DR14 galaxies which already have reliable spectroscopic redshifts in the SDSS archive with projected distance $d < R_{\text{gas}}$ in our galaxy sample. We have also extended our search to $d < 500 \text{kpc}$ in the SDSS archive and located 145 SDSS galaxies with accurate spectroscopic redshifts available. Combined with our own observations, we have a total of 380 galaxies at $d < 500 \text{kpc}$ in our final galaxy sample for searches of MgII absorbers. A journal of the observations of the full galaxy sample is presented in Table 1.

2.3 Echellette Spectra of QSOs

Echellette spectroscopic observations of 156 QSOs were obtained using the MagE spectrograph (Marshall et al. 2008) on the Magellan Clay telescope over the period from 2008 January through 2011 June. The majority of QSOs were observed using a 1″ slit, yielding a typical spectral resolution of $\text{FWHM } \approx 70 \text{ km s}^{-1}$. All the QSO spectra were processed and reduced using the data reduction software developed by G. Becker. We refer the reader to C10 for details of observations and spectral reduction procedures. In brief, we first performed the wavelength and flux calibrations, and co-added the individual echellette orders to form a single contiguous spectrum across the spectral range from $\lambda = 3050 \AA$ to $\lambda = 1 \mu\text{m}$. The individual order-combined exposures were then continuum normalized and finally were stacked to form the final reduced spectrum. The S/N per resolution element is $\gtrsim 10$ across the entire spectral range. We present a journal of the spectroscopic observations of the QSOs in Table 2.

### Table 1. Summary of Faint Galaxy Spectroscopy

| ID | RA(J2000)  | Dec(J2000)  | $z_{\text{phot}}$ | $r$ | Instrument | Exptime | UT Date     |
|----|------------|-------------|-------------------|----|------------|----------|------------|
| SDSSJ000548.29−084801.16 | 00:05:48.29 | −08:48:01.14 | 0.22 ± 0.07 | 19.4 | MagE       | 300 + 600 | 2009 Oct 19 |
| SDSSJ001335.12−141439.54 | 00:13:35.12 | +14:14:39.55 | 0.26 ± 0.11 | 20.9 | DIS        | 3 × 1800  | 2008 Dec 22 |
| SDSSJ001336.14−141428.04 | 00:13:36.14 | +14:14:28.01 | 0.25 ± 0.08 | 19.5 | DIS        | 1800 + 1200 | 2008 Dec 22 |
| SDSSJ000909.52+011445.25 | 00:09:09.52 | +01:13:45.25 | 0.15 ± 0.02 | 17.7 | SDSS       | ...      | ...         |
| SDSSJ000909.90+011323.95 | 00:09:09.90 | +01:13:33.95 | 0.53 ± 0.04 | 21.0 | SDSS       | ...      | ...         |
| SDSSJ001018.14+011219.92 | 00:10:18.14 | +01:12:19.92 | 0.17 ± 0.03 | 18.5 | SDSS       | ...      | ...         |
| SDSSJ001012.84+011131.36 | 00:10:12.84 | +01:11:31.36 | 0.08 ± 0.02 | 17.0 | SDSS       | ...      | ...         |
| SDSSJ003014.16+011359.19 | 00:30:14.16 | +01:13:59.14 | 0.40 ± 0.11 | 20.8 | DIS        | 1800     | 2009 Nov 9  |
| SDSSJ003016.41+011406.90 | 00:30:16.41 | +01:14:06.90 | 0.74 ± 0.05 | 21.2 | SDSS       | ...      | ...         |

The full table is available in the on-line version of the paper.

3 THE GALAXY AND MgII ABSORBER CATALOGS

3.1 Galaxy properties

We have constructed a full sample of 380 galaxies with robust redshift measurements in the vicinity of 156 distant background QSO sightlines. Among these galaxies, 103 galaxies are found to have at least one spectroscopic neighbor at projected distance $d \leq 500 \text{kpc}$ and radial velocity difference $\Delta v$ smaller than 1000 km s$^{-1}$. The presence of close neighbors imply that these galaxies are likely to reside in a group environment, where the interactions of group members may change the correlation between galaxy properties and their gaseous halos. We also performed a literature search and identified 9 galaxies that are either previously known merging systems, galaxy groups or clusters (e.g., Koester et al. 2007; Hao et al. 2010; Smith et al. 2012; Johnson et al. 2014). To avoid the confusion of associating MgII absorbers with host galaxies, we classify these galaxies as “non-isolated” galaxies and discuss them separately. The criteria yielded a sample of 277 “isolated” galaxies and 103 “non-isolated” galaxies.

We first present the projected distance $d$ versus redshift distribution of the full galaxy sample in Figure 1. The isolated and non-isolated galaxies are presented in solid and open symbols. The redshifts of the galaxies range from $z = 0.08$ to $z = 0.83$ with a median of $\langle z \rangle = 0.22$. Using our own DIS and MagE observations, we measure redshifts of 218 galaxies and find that the SDSS photometric redshift measurements are accurate to within a median residual of
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Table 2. Summary of the MagE Spectroscopic Observations of SDSS QSOs

| ID                   | RA(J2000)      | Dec(J2000) | z\_QSO | u' | Exptime | UT Date |
|----------------------|---------------|------------|--------|----|---------|---------|
| SDSSJ000548.24-084808.44 | 00:05:48.24   | -08:48:08.44 | 1.19   | 17.96 | 2 x 1200 | 2009 Oct 19 |
| SDSSJ001335.75+141424.07 | 00:13:35.75   | +14:14:24.07 | 1.54   | 19.32 | 1800 + 1300 | 2009 Oct 20 |
| SDSSJ003013.91+014054.15 | 00:30:13.91   | +01:40:54.15 | 1.46   | 18.12 | 2 x 1800 | 2010 Jul 13 |
| SDSSJ003340.21-005525.53 | 00:33:40.21   | -00:55:25.53 | 0.94   | 17.99 | 2 x 900 | 2008 Sep 23 |
| SDSSJ003407.35-085452.12 | 00:34:07.35   | -08:54:52.12 | 1.31   | 18.59 | 2 x 1200 | 2008 Sep 24 |
| SDSSJ003413.04-010026.86 | 00:34:13.04   | -01:00:26.86 | 1.29   | 17.33 | 2 x 600 | 2008 Sep 23 |
| SDSSJ010135.84-050609.08 | 01:01:35.84   | -05:06:09.08 | 1.01   | 19.31 | 2 x 1800 | 2008 Sep 24 |
| SDSSJ010156.32-084401.74 | 01:01:56.32   | -08:44:01.74 | 0.98   | 18.29 | 2 x 1800 | 2008 Sep 25 |
| SDSSJ010205.89+001156.99 | 01:02:05.89   | +00:11:56.99 | 0.72   | 17.59 | 1500 + 900 | 2009 Oct 18 |
| SDSSJ010352.47+003739.79 | 01:03:52.47   | +00:37:39.79 | 0.70   | 18.36 | 3 x 1200 | 2008 Sep 25 |

The full table is available in the on-line version of the paper.

We accepted the absorption lines according to a 2σ detection in g-band absolute magnitude, we calculate the stellar mass using the relation between stellar mass and single rest-frame r-band magnitude in Liang & Chen (2014), which is also derived using the NASA-Sloan Atlas sample.

We measure the equivalent width of the Hα emission line for each galaxy spectrum, adopting the window definitions from Yan et al. (2006). The stellar mass as a function of Hα equivalent width, EW(Hα), is presented in Figure 2. We also show on the right axis the inferred specific star-formation rate (sSFR) following Equations (2) & (4) in Fumagalli et al. (2012). We mark cyan squares around galaxies likely to be dominated by an AGN (active galactic nucleus), based on the classification scheme derived by Kewley et al. (2001) with the optical line ratios NII/Hα and [OIII]/Hβ. We find that there seems to be a clear distinction at EW(Hα) ~ 5 Å. Below EW(Hα) ~ 5 Å, only 15 out of 146 galaxies (10%) have detected Hα emission at a 2-σ level. At EW(Hα) > 5 Å, most galaxies (98%) have detected Hα, except for 3 galaxies with low S/N spectra. We therefore divide our galaxies into “star-forming” and “quiescent” galaxy samples using the criterion of whether their EW(Hα) are greater than 5 Å. A total of 327 out of 380 galaxies have high enough S/N measurements on the Hα emission, where 184 (143) are classified as star-forming (quiescent) galaxies. The cut essentially limits our galaxy sample to z < 0.5, beyond which the observed Hα emission is red-shifted to > 1 μm and falls outside of the wavelength range of the optical spectrographs. We find that our full sample spans a wide range in stellar mass, from log M\_star/M⊙ = 4 x 10\(^8\) M⊙ to log M\_star/M⊙ = 8.3 - 11.4 with a median of log M\_star/M⊙ = 10.3, while the quiescent galaxy sample has higher stellar mass from log M\_star/M⊙ = 9.3 - 11.6 with a median of log M\_star/M⊙ = 10.8.

3.2 Absorber Properties

For each galaxy in our sample, we searched for the corresponding MgII absorption doublet in the echellelette spectra of the background QSO within a radial velocity difference ∆v = ±1000 km s\(^{-1}\) of the galaxy redshift. When a MgII absorber was identified, we measured its rest-frame equivalent width and associated error by direct integration over the line region in our continuum normalized spectrum. We accepted the absorption lines according to a 2σ detection.

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tion threshold, which is appropriate since the searches are performed at known galaxy redshifts. We then determined the absorber redshift based on the best-fit line centroid of a Gaussian profile analysis of Mg II λ2796. In cases where no Mg II features are detected, we placed 2σ upper limits on the Mg II A2796 equivalent widths. For “non-isolated” systems, we calculate the luminosity-weighted projected position and redshift using members in each system and obtain its associated absorber properties following the same procedure.

In summary, the procedure yielded 85 physical galaxy-Mg II pairs and 126 upper limits in the vicinities of 211 isolated galaxies, and 18 Mg II absorbers and 25 upper limits around 43 “non-isolated” systems. We were not able to obtain significant constraints for Mg II absorption equivalent widths around 14 galaxies and 2 “non-isolated” systems, where the expected QSO spectra are contaminated by other strong absorption features (e.g. C IV λλ 1548, 1550) or the atmosphere O3 absorption complex at λ ∼ 3200. Also, six galaxies and two “non-isolated” systems were found at spectroscopic redshifts zspec < 0.09, falling outside the wavelength range of the MagE spectrograph. We present the properties of each spectroscopically confirmed galaxy sample in Table 2 (Columns 1–10), and the associated redshift and absorption equivalent width of Mg II absorbers in Columns 11 and 12 of Table 2.

The final isolated galaxy-absorber pair sample spans a projected distance range of d = 9–497 kpc with a median of ⟨d⟩med = 73 kpc. The redshifts of the isolated galaxies range from z = 0.10–0.48 with a median of ⟨z⟩med = 0.21, and the rest-frame absolute B-band magnitudes range from MB = −16.7 to MB = −22.8 with a median of ⟨MB⟩med = −20.5.

The “non-isolated” systems span a redshift range of z = 0.12–0.47 with a median of ⟨z⟩med = 0.19, with projected distance from d = 11–446 kpc with a median of ⟨d⟩med = 128 kpc.

We examine the relative velocity distribution of Mg II absorbers with respect to the systematic redshifts of the galaxies. In the left panel of Figure 3 we present the velocity dispersion of the detected Mg II absorbing gas around the full galaxy-absorber pair sample. We also show the velocity dispersion separately for isolated and non-isolated galaxy-absorber pairs in the central and right panels of Figure 3. We characterize the velocity distribution using a Gaussian profile with iterative 3-sigma clipping to exclude outliers. The velocity distribution of Mg II absorbing gas around galaxies can be characterized by a single Gaussian distribution of mean velocity difference ⟨v_{MgII−Galaxy}⟩ = 0 km s⁻¹ and dispersion σ_v = 84 km s⁻¹ (left-hand panel of Figure 3), while the velocity distribution for isolated galaxies is best represented by a Gaussian profile centered at ⟨v_{MgII−Galaxy}⟩ = −4 km s⁻¹ and σ_v = 80 km s⁻¹. For “non-isolated” systems, we find the associated Mg II absorbers have a broad velocity distribution with a standard deviation of σ_{v,std} = 235 km s⁻¹.

We present in Figure 1 the correlation between the strength of Mg II absorption and galaxy projected distance. Following the presentation in Figure 3, we show the distributions separately for isolated and non-isolated galaxies to
investigate the influence of galaxy environment. Similar to previous surveys (e.g. Chen et al. 2010a), we find a clear trend of decreasing absorption strength with increasing projected distance for isolated galaxies (see the middle panel of Figure 4). Beyond 70 kpc, no Mg II absorbing gas with $W_r(2796)>0.5\AA$ are found, and no detections are present beyond projected distance $d \gtrsim 150$ kpc ($d \gtrsim R_{gas}$). In contrast, while non-isolated systems do have lower Mg II covering fraction at larger projected distance $d$, we do not find a clear anti-correlation between the $W_r(2796)$ and $d$. The strong Mg II absorbers of $W_r(2796)\sim 0.5\AA$ are detected out to 150 kpc.

To determine whether the recent star formation of galaxies has an impact on Mg II absorbing gas, we further divide the isolated galaxy sample into star-forming and quiescent galaxy samples and show the distributions of $W_r(2796)$.

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versus projected distance in the upper panels of Figure 4. While both galaxy samples appear to occupy a similar $W_r(2796)$ versus $d$ space, qualitatively the star-forming galaxies show strong inverse correlation whereas only a modest trend is revealed for quiescent galaxies.

4 ANALYSIS

In the previous section, we use the samples of 211 isolated galaxies (73 quiescent galaxies and 138 star-forming galaxies) and 43 non-isolated galaxies to show that the strength and incidence of Mg II absorbing gas appear to depend on galaxy properties. In this section, we quantify the correlation between $W_r(2796)$ and different galaxy properties. We obtain and assess various models that well describe the data and present the best-fit results.

4.1 Fitting Procedure and Model Evaluation

We perform a likelihood analysis to obtain the best-fit models and to better characterize the correlation between galaxy properties and Mg II absorbers. The generalized functional form to describe the mean Mg II absorption equivalent width $W_r(2796)$ is

$$W_r(2796) = f(x_1, x_2, ...)$$

where $x_i$'s are independent measurements of galaxy properties including projected distance ($d$), rest-frame absolute $B$-band luminosity ($M_B$) and stellar mass ($M_{\text{star}}$). We adopt a simple power-law profile to describe the correlation between $W_r(2796)$, $d$ and other properties. In logarithmic space, the model is expressed as a linear equation

$$\log W_r(2796) = a_0 + a_1 \log d + a_2 X + ...$$

In addition, we introduce a non-parametric covering fraction $\epsilon$ in the model to describe the clumpy nature of Mg II gaseous halos. This is motivated by our findings that the covering fraction of Mg II absorbing gas may be less than unity and varying at different projected distances. As shown in Figure 4, a non-negligible fraction of galaxies at small projected distances ($d \lesssim 40$ kpc) do not give rise to Mg II absorption to a sensitive upper limits, and we find an increasing fraction of upper limits at larger projected distances. We divide the mean covering fraction $\epsilon_k$ ($k = 1 - 4$) into four projected distance intervals. To obtain a better sampling of $\epsilon$ at small projected distances, the first two bins ($k = 1, 2$) are designed for $d \lesssim 100$ kpc, where most Mg II absorbers are found. The other two bins ($k = 3, 4$) are used for larger projected distances, each with a roughly equal number of galaxies.

Here we perform the maximum likelihood analysis to determine the values of coefficients $a_i$ and four mean covering fractions that best represent the data. The likelihood function is defined as

$$L = \prod_{i=1}^{n} \left\{ (\epsilon(d_i) g_i + [1 - (\epsilon(d_i)] h_i \right\}$$

where $g_i$ represents the probability density function that the QSO sightline intercepts the Mg II gas around galaxy and its strength ($W_r(2796)$) follows the underlying power-law model, and $h_i$ denotes the pdf that the QSO sightline does not intercept any Mg II gas around galaxy $i$. Here $(\epsilon(d_i)$ is the non-parametric mean covering fraction given the projected distance of galaxy $i$ ($d_i$). The two probability density functions $g_i$ and $h_i$ are weighted according to the mean covering fraction $(\epsilon(d_i)$ and combined to get the likelihood function of a single galaxy $i$.
The first probability density function $g_i$ is expressed as

$$g_i = \int_0^\infty dW' \left( \frac{1}{\sqrt{2\pi} \sigma_{\text{masc}}} \exp \left( -\frac{1}{2} \left( \frac{\ln(W') - \ln(W)}{\sigma_{\text{masc}}} \right)^2 \right) \right) \times \left( \frac{1}{\sqrt{2\pi} \sigma_i} \exp \left( -\frac{1}{2} \left( \frac{W' - W_i}{\sigma_i} \right)^2 \right) \right)$$ (4)

where $W_i$ is the observed $W_r(2796)$ for galaxy $i$, $W$ is the model expectation, and $\sigma_i$ is the measurement error of $W_i$. Specifically, the first term takes into account the intrinsic scatter ($\sigma_{\text{masc}}$) of a given model expectation ($W$) due to variations between individual galaxies and between different sightlines probing the same galaxy (e.g., Chen et al. 2014). Motivated by Figure 4 and previous studies (e.g., Chen et al. 2010a), we model the intrinsic scatter as a constant in logarithmic space, independent of galaxy properties and projected distance. The second term represents the pdf of a normal distribution induced by measurement uncertainty $\sigma_i$.

On the other hand, $h_i$ is defined simply as a normal distribution with measurement error $\sigma_i$ and a mean consistent with absence of gas (i.e. zero)

$$h_i = \frac{1}{\sqrt{2\pi} \sigma_i} \exp \left( -\frac{1}{2} \left( \frac{W_i - 0.0}{\sigma_i} \right)^2 \right)$$ (5)

We note that for each non-detection, we also measure the rest-frame equivalent width by direct summation of the continuum normalized spectrum over a resolution element, centering at the systematic redshift of the galaxy. This allows us to appropriately exploit the constraints from both detections and non-detections the same way. We multiply the likelihood function of each galaxy $i$ over a total of $n$ target galaxies to obtain the total likelihood function in Equation 3. We assess the confidence intervals of derived model parameters using the Markov Chain Monte Carlo (MCMC) method.

### 4.2 Dependence of Extended Gas on Galaxy Projected Distance

First, we seek the best-fit models to describe the dependence of $W_r(2796)$ on $d$ (see the upper left panel of Figure 5 Model I). The maximum likelihood solution for isolated galaxies is

$$\log W_r(2796) = (0.83 \pm 0.38) - (0.72 \pm 0.25) \log d$$ (6)

with an intrinsic scatter $\sigma = 0.32 \pm 0.04$ in common logarithm. Note that $\sigma$ is a simple conversion of $\sigma_{\text{masc}}$ (see Equation 4) from natural to common logarithm. The errors in the coefficients are $1\sigma$ uncertainties. The non-parametric covering fractions are $\epsilon_1 = 0.87 \pm 0.05$, $\epsilon_2 = 0.49 \pm 0.06$, $\epsilon_3 = 0.19 \pm 0.12$, and $\epsilon_4 = 0.06 \pm 0.06$. The intervals of the covering fraction bins are listed in Table 4. The maximum likelihood solution shows a significant anti-correlation ($\sim 3\sigma$ level) between the Mg $\text{\textsc{ii}}$ absorption strength and projected distance $d$. Our results also show that the mean gas covering fraction declines steeply as the projected distance increases.

To understand the influence of galaxy types on their Mg $\text{\textsc{ii}}$ absorbing gas properties, we also obtain the best-fit models for isolated star-forming and quiescent galaxy samples (respectively the upper middle and right panels of Figure 5). For star-forming galaxies, we find based on the likelihood analysis a best-fit model

$$\log W_r(2796) = (0.94 \pm 0.30) - (0.78 \pm 0.20) \log d$$ (7)

with an intrinsic scatter $\sigma = 0.28 \pm 0.03$ and mean covering fractions of $\epsilon_1 = 0.92 \pm 0.05$, $\epsilon_2 = 0.56 \pm 0.09$, $\epsilon_3 = 0.19 \pm 0.12$, and $\epsilon_4 = 0.08 \pm 0.08$. Similar to the full sample, the $W_r(2796)$ and incidence of gas for star-forming galaxies both decrease as increasing projected distance. For quiescent galaxies, however, the dependence of Mg $\text{\textsc{ii}}$ absorbing gas and projected distance reveals a stark contrast. The best-fit power-law model from the likelihood analysis yields

$$\log W_r(2796) = (-0.17 \pm 0.20) - (0.08 \pm 0.34) \log d$$ (8)

with $\sigma = 0.34 \pm 0.06$ and covering fractions of $\epsilon_1 = 0.67 \pm 0.11$, $\epsilon_2 = 0.41 \pm 0.10$, $\epsilon_3 = 0.09 \pm 0.07$, and $\epsilon_4 = 0.04 \pm 0.04$. While the best-fit mean covering fractions decline with increasing $d$, they are $\sim 30\%$ lower compared to that of the star-forming ones at $d < 300$ kpc. Furthermore, the maximum likelihood solution shows no statistically significant dependence between Mg $\text{\textsc{ii}}$ absorption strength and $d$ among detections.

In Figure 5 we show that the star-forming galaxy sample spans a wide range of stellar masses from $M_{\text{star}} = 10^{9.6} - 10^{11.3}$, while quiescent galaxies have on average higher stellar masses ranging from $M_{\text{star}} = 10^{9.3} - 10^{11.4}$. It has been shown in observations (e.g., Chen et al. 2010b) and theoretical models (e.g., Mo & Miralda-Escude 1996, Maller & Bullock 2001) that more massive galaxies tend to have more extended gaseous halos. To address whether the apparent differential observed $W_r(2796)$ versus $d$ plane between star-forming and quiescent galaxy samples can be affected by the gaseous halos with various sizes, we estimate the dark matter halo radius ($R_h$) of individual galaxies and examine how Mg $\text{\textsc{ii}}$ absorption strength varies with $R_h$ normalized projected distance ($d/R_h$). The halo radius $R_h$ is calculated following the prescription in (Liang & Chen 2014). Specifically, we obtain halo mass ($M_h$) using the stellar-mass-to-halo-mass relation derived in (Kravtsov et al. 2018), and $M_h$ is then converted to $R_h$ with standard cosmology (Bryan & Norman 1998).

We present the correlation between $W_r(2796)$ and galaxy $R_h$-normalized projected distance ($d/R_h$) in the lower panels of Figure 5 (Model II). We note that Mg $\text{\textsc{ii}}$ absorbing gas declines steeply beyond 0.4 $R_h$. Essentially only one galaxy at $d = 0.66$ $R_h$ has an associated Mg $\text{\textsc{ii}}$ absorber. The maximum likelihood solution for the full isolated galaxy sample is

$$\log W_r(2796) = (-0.88 \pm 0.15) - (0.84 \pm 0.20) \log [d/R_h]$$ (9)

with an intrinsic scatter $\sigma = 0.29 \pm 0.03$ and covering fractions of $\epsilon_1 = 0.85 \pm 0.06$, $\epsilon_2 = 0.57 \pm 0.08$, $\epsilon_3 = 0.10 \pm 0.06$, and $\epsilon_4 = 0.07 \pm 0.07$.

We find that after accounting for the mass scaling of gaseous radius, the slope of the anti-correlation is steepened by 17% and becomes more statistically significant. For the isolated star-forming galaxies, we obtain a similar improvement based on the likelihood analysis

$$\log W_r(2796) = (-0.98 \pm 0.17) - (1.03 \pm 0.22) \log [d/R_h]$$ (10)

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with an intrinsic scatter $\sigma_c = 0.26 \pm 0.03$ and covering fractions of $\epsilon_1 = 0.95 \pm 0.04$, $\epsilon_2 = 0.67 \pm 0.08$, $\epsilon_3 = 0.18 \pm 0.10$, and $\epsilon_4 = 0.12 \pm 0.12$. The best-fit result also shows a steeper slope by 32% and a $\sim 5\sigma$ significance of the anti-correlation. In contrast, including scaling with $R_h$ does not improve the observed $\overline{W_r}(2796)$ versus $R_h$ anti-correlation for the quiescent galaxy sample. We find a best-fit model of

$$\log \overline{W_r}(2796) = (-0.22 \pm 0.24) \times (M_B - M_B^\star)$$

with an intrinsic scatter of $\sigma_c = 0.26 \pm 0.03$ and covering fractions of $\epsilon_1 = 0.95 \pm 0.04$, $\epsilon_2 = 0.67 \pm 0.08$, $\epsilon_3 = 0.18 \pm 0.10$, and $\epsilon_4 = 0.12 \pm 0.12$. The observed $\overline{W_r}(2796)$ remains consistent with a flat distribution.

On the other hand, previous studies have shown that galaxy B-band luminosity, which is a direct observable, also has an impact on both the extent of MgII absorbing gas and absorption strength (e.g. Chen & Tinker 2008; Chen et al. 2010). Therefore, we include rest-frame B-band magnitude $M_B$ in the power-law model ($X \equiv M_B - M_B^\star$ in Equation 2) to examine how MgII absorber strength scales with $M_B$ (Model III). We adopt $M_B^\star = -20.6$ from Faber et al. (2007), the characteristic B-band magnitude for describing blue galaxy population at $z \sim 0.4$. Based on the maximum likelihood analysis, we find the MgII gaseous extent scales with $d$ and $M_B$ following

$$\log \overline{W_r}(2796) = (1.22 \pm 0.25) \times (M_B - M_B^\star)$$

with an intrinsic scatter of $\sigma_c = 0.26 \pm 0.03$ and covering

Figure 5. Rest-frame equivalent width $W_r(2796)$ versus projected distance $d$ (upper panels) and $R_h$-normalized projected distance $d/R_h$ (lower panels). The full isolated galaxy sample is shown in the left panels, and are separated into isolated star-forming and quiescent galaxy samples in the middle and right panels. Symbols are the same as in Figure 3. The orange solid lines represent the best-fit power-law models. The dark and light shaded bands represent the 68% and 95% confidence intervals from the Markov chain Monte Carlo realizations. The best-fit intrinsic scatter is marked in the lower left corner. At the top of each panel, we show the best-fit results of the 4 non-parametric mean covering fractions from the maximum likelihood analysis. The horizontal bars mark the full range of projected distance within each bin and vertical error bars represent the 68% confidence interval. The best-fit models are discussed in Equation (6) and in the text. For comparison, the green dashed curve in the upper left panel shows the log-linear maximum likelihood fit from Nielsen et al. (2013a).
fractions of $\epsilon_1 = 0.95 \pm 0.04$, $\epsilon_2 = 0.58 \pm 0.09$, $\epsilon_3 = 0.11 \pm 0.07$, and $\epsilon_4 = 0.04 \pm 0.04$. The results show that including the intrinsic $B$-band luminosity also leads to a steeper slope of the anti-correlation between $W_r(2796)$ and $d$. Note that $M_B$ has a negative correlation coefficient, consistent with the expectation that brighter galaxies have larger extent of gas.

For star-forming galaxies, we also perform the likelihood analysis and find the observed absorber strength is best described by

$$\log W_r(2796) = (1.57 \pm 0.28) - (1.14 \pm 0.18) \log d - (0.12 \pm 0.02) \times (M_B - M_B)$$  \hspace{1cm} (13)$$

with an intrinsic scatter $\sigma_\epsilon = 0.25 \pm 0.03$ and covering fractions of $\epsilon_1 = 0.97 \pm 0.02$, $\epsilon_2 = 0.60 \pm 0.08$, $\epsilon_3 = 0.18 \pm 0.11$, and $\epsilon_4 = 0.05 \pm 0.05$. The results show trends similar to the full isolated galaxy sample. We find a steeper anti-correlation between $W_r(2796)$ versus $d$ and an anti-correlation between absorption strength and $M_B$. The intrinsic scatter is slightly smaller than the results obtained without the scaling of $B$-band luminosity.

For quiescent galaxies, we obtain a best-fit model of

$$\log W_r(2796) = (0.09 \pm 0.33) - (0.27 \pm 0.20) \log d - (0.02 \pm 0.05) \times (M_B - M_B)$$  \hspace{1cm} (14)$$

with an intrinsic scatter $\sigma_\epsilon = 0.34 \pm 0.06$ and covering fractions of $\epsilon_1 = 0.54 \pm 0.17$, $\epsilon_2 = 0.37 \pm 0.17$, $\epsilon_3 = 0.07 \pm 0.07$, and $\epsilon_4 = 0.03 \pm 0.03$. Contrary to the star-forming galaxies, we do not find strong correlation between $W_r(2796)$ and $d$. A slight negative correlation between $W_r(2796)$ and $M_B$ is shown. The addition of $M_B$ scaling in the power-law model does not seem to reduce the intrinsic scatter of the $W_r(2796)$ versus $d$ relation.

It is notable that although $M_B$ is known to scale with halo mass (e.g., Zheng et al. 2007), it also correlates with [O ii] luminosity (e.g., Zhu et al. 2009) and thus might be coupled with recent star-formation. Here we inspect the correlation between $W_r(2796)$ and total stellar mass $M_{\text{star}}$, which is believed to be a good tracer of halo mass (More et al. 2011) (Model IV).

We obtain the best-fit models with the scaling of total stellar mass $M_{\text{star}}$ of

$$\log W_r(2796) = (1.35 \pm 0.25) - (1.05 \pm 0.17) \log d + (0.21 \pm 0.08) \times (M_{\text{star}} - M_{\text{star}})$$  \hspace{1cm} (15)$$

where $\log M_{\text{star}}/M_\odot = 10.3$. The best-fit intrinsic scatter is $\sigma_\epsilon = 0.28 \pm 0.03$ and best-fit covering fractions are $\epsilon_1 = 0.85 \pm 0.06$, $\epsilon_2 = 0.53 \pm 0.07$, $\epsilon_3 = 0.10 \pm 0.07$, and $\epsilon_4 = 0.07 \pm 0.07$. The best-fit coefficients show a positive correlation between $W_r(2796)$ and $M_{\text{star}}$, and an anti-correlation between $W_r(2796)$ and $d$, consistent with the results accounting for $M_B$.

Next, based on the likelihood analysis the star-forming galaxy sample has a best-fit model of

$$\log W_r(2796) = (1.42 \pm 0.25) - (1.05 \pm 0.17) \log d + (0.21 \pm 0.08) \times (M_{\text{star}} - M_{\text{star}})$$  \hspace{1cm} (16)$$

with an intrinsic scatter $\sigma_\epsilon = 0.27 \pm 0.02$ and covering fractions of $\epsilon_1 = 0.97 \pm 0.03$, $\epsilon_2 = 0.64 \pm 0.08$, $\epsilon_3 = 0.17 \pm 0.09$, and $\epsilon_4 = 0.02 \pm 0.02$.

For quiescent galaxies, the best-fit model with the scaling of stellar mass is

$$\log W_r(2796) = (0.01 \pm 0.36) - (0.24 \pm 0.21) \log d + (0.01 \pm 0.03) \times (M_{\text{star}} - M_{\text{star}})$$  \hspace{1cm} (17)$$

with an intrinsic scatter $\sigma_\epsilon = 0.38 \pm 0.04$ and covering fractions of $\epsilon_1 = 0.50 \pm 0.16$, $\epsilon_2 = 0.26 \pm 0.12$, $\epsilon_3 = 0.08 \pm 0.06$, and $\epsilon_4 = 0.09 \pm 0.09$. The results of the likelihood analyses are summarized in Table 4.

Finally, to assess the significance of the anti-correlation without model dependence, we also perform a non-parametric, generalized Kendall’s $\tau$ test (Feigelson & Nelson 1985) that accounts for the presence of non-detections. The results of Kendall’s $\tau$ test are presented in Table 5. We find that the $W_r(2796)$ versus $d$ for isolated galaxies deviate from a random distribution at more than 11$\sigma$ level. The $W_r(2796)$ is anti-correlated with $d > 10\sigma$ level of significance for isolated, star-forming galaxies. The distribution of $W_r(2796)$ versus $d$ after accounting for $R_{\text{HI}}$, $L_B$, or $M_{\text{star}}$ shows similar level of significance. It is notable that the significance of anti-correlation for the isolated, quiescent galaxy sample is at $\sim 4\sigma$ level using the generalized Kendall test. In our likelihood analysis, we treat an upper limit as either the QSO sightline intercepts Mg II gas but below the detection limit or simply does not intercept Mg II gas. The generalized Kendall test considers all data to follow a single distribution and therefore sensitive upper limits contribute significantly to the anti-correlation in the generalized Kendall test compared to the likelihood analysis.

5 DISCUSSION

We have established a spectroscopic sample of 211 isolated galaxies and 43 non-isolated galaxies with constraints on Mg II absorption from background quasars at projected distances of $d < 500$ kpc. We characterized the cool gas contents of galaxy host halos as a function of projected distance. We performed likelihood analysis for the isolated galaxies to study the dependence of Mg II gas on galaxy projected distance $d$. Here, we present the observed mean covering fraction ($\kappa$) of MgII absorbing gas and examine how the incidence of cool gas varies with galaxy properties (i.e. $B$-band magnitude, stellar mass and H$\alpha$ equivalent width). We discuss the kinematics, physical conditions and azimuthal dependence of these MgII absorbers. Finally, we discuss the properties of gaseous halos around different host galaxies and compare our results with previous studies.

5.1 Covering fraction of Mg II absorbers

In the previous section, we show that while Mg II absorption equivalent widths of individual absorbers decrease with increasing distance for star-forming galaxies, no clear trends are seen for quiescent galaxies. On the other hand, the best-fit results of the likelihood analysis suggest a strong anti-correlation between covering fraction of Mg II gas ($\epsilon$) and projected distance for both samples (Table 4). Take model I for example, the best-fit Mg II gas covering fraction for star-forming galaxies at $d < 40$ kpc is $\epsilon_1 = 0.87 \pm 0.05$, which declines to $\epsilon_2 = 0.49 \pm 0.06$ at
Figure 6. Similar to Figure 5 but the correlation between $W_r(2796)$ versus $d$ also accounts for the scaling with galaxy $B$-band luminosity in the upper panels and stellar mass in the lower panels. Note that the scaling coefficients $d' = d/[L_B/L_B^*]^{a'}$ and $a'' = -(a_2/a_1)$ in $d'' = d/[M_{star}/M_{star}^*]^{a''}$ are calculated based on the best-fit models in Equation (12)–(17). For comparison, the purple dashed curve in the upper left panel represents the best-fit isothermal model from Chen et al. (2010a).

Table 4. Summary of Maximum Likelihood Solutions

| Model   | $a_0$   | $a_1$   | $a_2$   | $\sigma_c$ | $\epsilon_1[0, 40]$ | $\epsilon_2[40, 100]$ | $\epsilon_3[100, 300]$ | $\epsilon_4[300, 700]$ | Kendall’s $\tau$ |
|---------|---------|---------|---------|-------------|----------------------|-----------------------|-----------------------|---------------------|-----------------|
| full    | 0.83 ± 0.38 | −0.72 ± 0.25 | ...     | 0.32 ± 0.04 | 0.87 ± 0.05 | 0.49 ± 0.06 | 0.19 ± 0.12 | 0.06 ± 0.06 | −0.46 ± 0.04 |
| blue    | 0.94 ± 0.30 | −0.78 ± 0.20 | ...     | 0.28 ± 0.03 | 0.92 ± 0.05 | 0.56 ± 0.09 | 0.19 ± 0.12 | 0.08 ± 0.08 | −0.52 ± 0.05 |
| red     | −0.08 ± 0.34 | −0.17 ± 0.20 | ...     | 0.34 ± 0.06 | 0.67 ± 0.11 | 0.41 ± 0.10 | 0.09 ± 0.07 | 0.04 ± 0.04 | −0.22 ± 0.05 |
| Model II | $a_0$   | $a_1$   | $a_2$   | $\sigma_c$ | $\epsilon_1[0, 2]$ | $\epsilon_2[2, 0.5]$ | $\epsilon_3[0.5, 1.1]$ | $\epsilon_4[1.1, 4]$ | Kendall’s $\tau$ |
| Rh-full | −0.88 ± 0.15 | −0.84 ± 0.20 | ...     | 0.29 ± 0.03 | 0.85 ± 0.06 | 0.57 ± 0.08 | 0.10 ± 0.06 | 0.07 ± 0.07 | −0.45 ± 0.04 |
| Rh-blue | −0.98 ± 0.17 | −1.03 ± 0.22 | ...     | 0.26 ± 0.03 | 0.95 ± 0.04 | 0.67 ± 0.08 | 0.18 ± 0.10 | 0.12 ± 0.12 | −0.55 ± 0.05 |
| Rh-red  | −0.48 ± 0.27 | −0.12 ± 0.24 | ...     | 0.37 ± 0.09 | 0.53 ± 0.18 | 0.39 ± 0.15 | 0.07 ± 0.07 | 0.05 ± 0.05 | −0.21 ± 0.05 |
| Model III | $a_0$   | $a_1$   | $a_2$   | $\sigma_c$ | $\epsilon_1[0, 40]$ | $\epsilon_2[40, 100]$ | $\epsilon_3[100, 300]$ | $\epsilon_4[300, 700]$ | Kendall’s $\tau$ |
| MB-full | 1.22 ± 0.25 | −0.94 ± 0.16 | −0.09 ± 0.03 | 0.28 ± 0.03 | 0.95 ± 0.04 | 0.58 ± 0.09 | 0.11 ± 0.07 | 0.04 ± 0.04 | −0.47 ± 0.04 |
| MB-blue | 1.57 ± 0.28 | −1.14 ± 0.18 | −0.12 ± 0.02 | 0.25 ± 0.03 | 0.97 ± 0.02 | 0.60 ± 0.08 | 0.18 ± 0.11 | 0.05 ± 0.05 | −0.56 ± 0.05 |
| MB-red  | 0.09 ± 0.33 | −0.27 ± 0.20 | −0.02 ± 0.05 | 0.34 ± 0.06 | 0.54 ± 0.17 | 0.37 ± 0.17 | 0.07 ± 0.07 | 0.03 ± 0.03 | −0.23 ± 0.05 |
| Model IV | $a_0$   | $a_1$   | $a_2$   | $\sigma_c$ | $\epsilon_1[0, 40]$ | $\epsilon_2[40, 100]$ | $\epsilon_3[100, 300]$ | $\epsilon_4[300, 700]$ | Kendall’s $\tau$ |
| Mstar-full | 1.35 ± 0.25 | −1.05 ± 0.17 | 0.21 ± 0.08 | 0.28 ± 0.03 | 0.85 ± 0.06 | 0.53 ± 0.07 | 0.10 ± 0.07 | 0.07 ± 0.07 | −0.46 ± 0.04 |
| Mstar-blue | 1.42 ± 0.22 | −1.07 ± 0.14 | 0.28 ± 0.06 | 0.27 ± 0.02 | 0.97 ± 0.03 | 0.64 ± 0.08 | 0.17 ± 0.09 | 0.02 ± 0.02 | −0.56 ± 0.05 |
| Mstar-red | 0.01 ± 0.36 | −0.24 ± 0.21 | 0.01 ± 0.03 | 0.38 ± 0.04 | 0.50 ± 0.16 | 0.26 ± 0.12 | 0.08 ± 0.06 | 0.09 ± 0.09 | −0.22 ± 0.05 |

$^1$ $\epsilon_i[d_1, d_2]$ represents the mean covering fraction within $[d_1, d_2]$ in $d$ or normalized $d$. 

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Figure 7. Mean covering fraction of Mg II absorbers $\langle \kappa \rangle$ versus projected distance $d$ (left panel) and versus $d$ accounting for the galaxy B-band luminosity scaling relation (right panel). We show the gas covering fraction of isolated, star-forming galaxies as blue solid squares, and that of isolated, quiescent galaxies as red solid circles. For comparison, we also include covering fraction measurements from the SDSS LINER-like and passive luminous red galaxy (LRG) samples of Huang et al. (2016) in green dash-dotted triangles and purple dot-dashed pentagons and low-luminosity quasars (log $L_{\text{bol}}$/erg s$^{-1}$ > 45.5) in light blue and magenta dotted stars (Johnson et al. 2015a). The gas covering fraction is computed for a detection threshold of $W_0 = 0.3$ Å. Error bars represent the 68% confidence interval.

$d = 40 - 100$ kpc. For quiescent galaxies, the covering fraction is $\epsilon_1 = 0.67 \pm 0.11$ at $d < 40$ kpc, which subsequently declines to $\epsilon_2 = 0.41 \pm 0.10$ at $d = 40 - 100$ kpc. Beyond $d = 100$ kpc, both samples show covering fraction consistent with $\epsilon \approx 0$ within 2-σ level. Similar anti-correlations are also reported in the best-fit results of Model II - Model IV, regardless of various scaling relations with halo radius, $B$-band magnitude and stellar mass.

We note that the Mg II covering fraction $\langle \kappa \rangle$ derived using the likelihood analysis denotes the intrinsic incidence of Mg II gas, which does not depend on the absorption strength of Mg II. Here we also report the observed mean covering fraction $\langle \kappa \rangle$ of Mg II absorbing gas and examine how the incidence of cool gas varies with galaxy properties. Following the prescription in Chen et al. (2010a), we employ a maximum likelihood analysis to estimate $\kappa$ and its uncertainties. The likelihood of detecting an ensemble of galaxies of which $n$ galaxies with associated Mg II absorbers of $W_r \geq W_0$ and $m$ galaxies with no absorbers detected down to a sensitive limit of $W_r < W_0$ is

$$L(\kappa|W_0) = (\kappa)^n [1 - \langle \kappa \rangle]^m$$

We evaluate $\kappa$ for a detection threshold of $W_0 = 0.3$ Å. In the isolated galaxy samples, 201/211 MagE spectra of corresponding QSOs have sufficient S/N for detecting Mg II gas with absorption strength exceeding $W_r(2796) \geq 0.3$ Å. We evenly divide each sample into various projected distance intervals, and obtain best-fit observed covering fractions $\langle \kappa \rangle$ and associated uncertainties for each projected distance bin. The results are shown in the left panel of Figure 7.

For the star-forming galaxy sample, the covering fraction of $W_r(2796) \geq 0.3$ Å absorbers declines from $\langle \kappa \rangle = 0.83^{+0.06}_{-0.05}$ at $d < 40$ kpc to $\langle \kappa \rangle = 0.37^{+0.07}_{-0.06}$ at $d \approx 40 - 90$ kpc. Beyond $d \approx 100$ kpc, the covering fraction declines to $\langle \kappa \rangle \approx 0$. Quiescent galaxies exhibit similar but mildly lower observed Mg II covering fraction at inner projected distances ($< 90$ kpc). At $d < 40$ kpc, $\langle \kappa \rangle = 0.57^{+0.16}_{-0.18}$ for quiescent galaxies, which decreases to $\langle \kappa \rangle = 0.28^{+0.06}_{-0.09}$ at $d \approx 40 - 90$ kpc and subsequently to $\langle \kappa \rangle = 0.02^{+0.03}_{-0.01}$ beyond $d \approx 100$ kpc. The observed anti-correlations between covering fraction and projected distance for both samples are consistent with the best-fit results from the likelihood analysis. We find that star-forming galaxies seem to have elevated incidence of Mg II gas at inner projected distance of $d < 40$ kpc compared to our quiescent galaxy sample.

To take into account the possible correlation between covering fraction and galaxy properties, we also calculate the mean observed covering fractions in different $M_B$-normalized projected distance intervals, using the best-fit scaling relation of Equation (16). The results are shown in the right panel of Figure 7. After applying the $M_B$-scaling, the anti-correlation between covering fraction and normalized projected distance for star-forming galaxies is strengthened.

The Mg II gas covering fraction for star-forming galaxies is $\langle \kappa \rangle = 0.83^{+0.06}_{-0.05}$ at $d' < 40$ kpc and $\langle \kappa \rangle = 0.36^{+0.07}_{-0.06}$ at $d' = 40 - 100$ kpc, where $d' = d \times 10^{0.4(M_B-M_B^\star)}$ is the $M_B$-normalized projected distance. While for quiescent galaxies, we obtain $\langle \kappa \rangle = 0.55^{+0.14}_{-0.14}$ at $d' < 40$ kpc and $\langle \kappa \rangle = 0.28^{+0.08}_{-0.08}$ at $d' = 40 - 100$ kpc. At inner $d' \lesssim 40$ kpc, the incidence of Mg II gas seems to be suppressed in the quiescent galaxy sample compared to that of star-forming galaxies at $\sim 3$-σ level. The fact that the difference in covering fraction between the two samples is more evident after the $M_B$-scaling highlights that there is an unambiguous connection between the Mg II gas and host galaxy properties.

Indeed, the high Mg II gas covering fractions of both star-forming and quiescent galaxy samples at $d < 90$ kpc are in stark contrast to what we have seen in luminous red
galaxies (LRGs; Huang et al. 2016), which we also show in the left panel of Figure 7 for comparison. In Huang et al. (2016), we utilized ~38000 LRG-QSO pairs in SDSS DR12 and divided the LRGs into passive (purple diamonds) and LINER-like subsamples (green triangles) according to whether they exhibit [OIII]-emission features. We reported a constant Mg II gas covering fraction of merely ~15% at d < 120 kpc for passive LRGs, which comprises the majority of the LRG sample (~90%). The LINER-like LRGs have a slightly elevated covering fraction of ~40% at d < 40 kpc, which declines to a similar level of ~15% at d > 100 kpc. We also display the measurement of quasar host halos from Johnson et al. (2015a) for comparison. The luminous quasars are primarily fainter, spanning a broad range of stellar gas radius, $d$.

At the boundary at haloes is well described by an isothermal density profile with $\rho(\rho_c) = 30, 60, 90$ kpc (from outside to inside) with respect to mass. No significant trends are observed between the relative velocity and the projected distance between QSO-galaxy pairs. Below projected distance $d < 40$ kpc, we find the median relative velocity difference to be $\langle \Delta v \rangle = 48$ km s$^{-1}$. While at $d > 40$ kpc, the relative velocity difference is $\langle \Delta v \rangle = 47$ km s$^{-1}$. At similar stellar masses, quiescent galaxies seem to have higher relative velocity offsets from the galaxy systematic redshifts compared to that of star-forming galaxies. The majority of the detected Mg II absorbing gas is found at velocities below the expected projected escape velocities, indicating that these Mg II gas complexes are likely to be gravitationally bound.

Using the large sample of galaxy and absorber pairs in the M3 Halo Project, we are able to constrain how the ensemble average of the velocity distribution of absorbing gas changes with their host galaxy properties. We divide isolated galaxy sample into low-mass ($\log(M_{\text{star}}/M_{\odot}) \approx 9.7$) and high-mass ($\log(M_{\text{star}}/M_{\odot}) \approx 10.6$) galaxies to investigate the correlation between mass and velocity dispersion in the middle panels of Figure 9. The velocity distribution is well characterized by a Gaussian of dispersion $\sigma = 69$ km s$^{-1}$ around low-mass galaxies and $\sigma = 117$ km s$^{-1}$ for high-mass galaxies. Quiescent galaxies seem to have higher relative velocities than that of star-forming galaxies. If we consider only star-forming galaxies, we find that the relative velocity dispersion of low-mass galaxies is $\sigma = 67$ km s$^{-1}$, and is $\sigma = 83$ km s$^{-1}$ for high-mass galaxies. The velocity dispersion of the high-mass sample is $\approx 20\%$ more elevated than the low-mass sample.

We use bootstrap method to estimate the 68% confidence levels of the relative velocity dispersion. For isolated star-forming galaxies, the low-mass sample gives $\sigma = 58 - 73$ km s$^{-1}$, while the high-mass sample gives $\sigma = 73 - 90$ km s$^{-1}$. There seems to be a positive correlation between $\approx 10 - 15\%$ around massive LRGs. The strong mass dependence of Mg II covering fraction qualitatively agrees with the expectation from the observed clustering of Mg II absorbers, where the Mg II covering fraction peaks at $M_{\text{halo}} \approx 10^{12} M_{\odot}$ ($\sim L_\odot$ galaxies) and rapidly falls off at smaller and higher masses (Tinker & Chen 2008, 2010).

In the right panel of Figure 8, we present the mean gas covering fraction (κ) within $R_{\text{gas}}$ as a function of Hα equivalent width for our MagE galaxies and the LRG samples in Huang et al. (2016). The symbols are the same as in the left panel. We find that there is a positive correlation between (κ) and Hα equivalent width (or star formation rate).

We note that although LINER-like LRGs (green triangles) have significantly lower (κ) compared to the MagE quiescent galaxy sample, in Huang et al. (2016) we find that their Hα is likely contributed by post-asymptotic giant branch (post-AGB) stars. Therefore, the star-formation rates of LRG samples represent upper limits.

5.2 Kinematics

The line-of-sight velocity dispersion of Mg II absorbers provides important insights into the underlying motion and physical nature of cool clumps within host halos. The left panel of Figure 9 displays the relative velocity between MgII absorbers and their host galaxies as a function of inferred dark matter halo mass. The dashed curves mark the projected escape velocities at $r = 30, 60, 90$ kpc (from outside to inside) with respect to mass. No significant trends are observed between the relative velocity and the projected distance between QSO-galaxy pairs. Below projected distance $d < 40$ kpc, we find the median relative velocity difference to be $\langle \Delta v \rangle = 48$ km s$^{-1}$. While at $d > 40$ kpc, the relative velocity difference is $\langle \Delta v \rangle = 47$ km s$^{-1}$. At similar stellar masses, quiescent galaxies seem to have higher relative velocity offsets from the galaxy systematic redshifts compared to that of star-forming galaxies. The majority of the detected Mg II absorbing gas is found at velocities below the expected projected escape velocities, indicating that these Mg II gas complexes are likely to be gravitationally bound.

Using the large sample of galaxy and absorber pairs in the M3 Halo Project, we are able to constrain how the ensemble average of the velocity distribution of absorbing gas changes with their host galaxy properties. We divide isolated galaxy sample into low-mass ($\log(M_{\text{star}}/M_{\odot}) \approx 9.7$) and high-mass ($\log(M_{\text{star}}/M_{\odot}) \approx 10.6$) galaxies to investigate the correlation between mass and velocity dispersion in the middle panels of Figure 9. The velocity distribution is well characterized by a Gaussian of dispersion $\sigma = 69$ km s$^{-1}$ around low-mass galaxies and $\sigma = 117$ km s$^{-1}$ for high-mass galaxies. Quiescent galaxies seem to have higher relative velocities than that of star-forming galaxies. If we consider only star-forming galaxies, we find that the relative velocity dispersion of low-mass galaxies is $\sigma = 67$ km s$^{-1}$, and is $\sigma = 83$ km s$^{-1}$ for high-mass galaxies. The velocity dispersion of the high-mass sample is $\approx 20\%$ more elevated than the low-mass sample.

We use bootstrap method to estimate the 68% confidence levels of the relative velocity dispersion. For isolated star-forming galaxies, the low-mass sample gives $\sigma = 58 - 73$ km s$^{-1}$, while the high-mass sample gives $\sigma = 73 - 90$ km s$^{-1}$. There seems to be a positive correlation between...
the velocity dispersion of Mg II absorbing gas and mass of associated host halos. Assuming a NFW profile (Navarro et al. 1997) with halo concentration of $c_h = 10$, we can calculate the expected line-of-sight velocity dispersion for virialized motion within $d = 100$ kpc, beyond which no Mg II gas is detected in the isolated star-forming galaxy sample. The expected line-of-sight velocity dispersion for low-mass and high-mass galaxies are respectively $\sigma = 52 \, \text{km} \, \text{s}^{-1}$ and $\sigma = 86 \, \text{km} \, \text{s}^{-1}$, comparable to the observed velocity dispersion. The recent work on Mg II absorbing gas around 50 star-forming galaxies at $z \approx 0.2$ (Martin et al. 2019) also shows a consistent result. With a median stellar mass of $M_{\text{star}} = 10^{10} \, M_\odot$, the sample has a relative velocity dispersion of $\sigma = 42 - 54 \, \text{km} \, \text{s}^{-1}$, comparable to the expected line-of-sight velocity dispersion of $\sigma = 56 \, \text{km} \, \text{s}^{-1}$.

Our result is in stark contrast to the Mg II gas in LRG halos, where the line-of-sight velocity dispersion is merely 60 percent of what is expected from virial motion (Huang et al. 2016; Zhu et al. 2014; Zahedy et al. 2019; Afruni et al. 2019). In the right panel of Figure 9 we display the relative velocity distributions of Mg II absorbers divided by the line-of-sight projected halo escape velocity for our isolated galaxies (filled histogram) and passive LRGs in Huang et al. 2016 (open histogram). It is clear that while for both samples the majority of the detected Mg II absorbing gas is at velocities well within the expected projected escape velocities, Mg II gas found around passive LRGs have suppressed velocity dispersion compared to our isolated galaxies. A Kolmogorov-Smirnov (K-S) test shows that the probability of the two velocity dispersions of Mg II absorbers to be drawn from the same distribution is $P = 12.5\%$. The comparable velocities between observation and the expectation from virial motion support the physical formalism for a two-phase CGM, where QSO absorption systems in the vicinity of galaxies originate in cool clumps which are in thermal pressure equilibrium with the hot halo (Mo & Miralda-Escude 1996). The positive correlation between the mean gas covering fraction $\langle \kappa \rangle$ and Hα equivalent width (sSFR) on the right panel of Figure 8 also hints on the possibility that the cool clumps may be able to survive and reach the central galaxy.

If clouds are sufficiently massive, they can travel at a characteristic speed equal to the halo velocity as the clouds move through host halo. Following Maller & Bullock (2004), we are able to place a lower limit on the cloud mass using their Equation (40),

$$m_{cl} \approx 5.1 \times 10^4 \, M_\odot \, T_6^{-3/8} (\alpha_{cl} t_8)^{1/2}$$

where $T_6 = T/10^6 \, \text{K}$ is the temperature of hot halo gas, $\alpha_c$ is a cooling parameter that depends on the gas metallicity and $t_8 = t_f/8 \, \text{Gyr}$ is the halo formation timescale. For our low-mass and high-mass galaxy samples of $\log (M_{\text{star}}/M_\odot) \approx 9.7$ and $10.6$, $T \sim 5 \times 10^5 \, \text{K}$ and $T \sim 10^8 \, \text{K}$ assuming an isothermal gas, and $t_f \sim 9 \, \text{Gyr}$ according to N-body simulations (Wechsler et al. 2002). We find the lower limits of cloud mass are $m_{cl} \approx (0.7, 1.5) \times 10^5 \, M_\odot$ for low-mass galaxies and $m_{cl} = (0.5, 1.1) \times 10^5 \, M_\odot$ for high-mass galaxies assuming $(0.1, 1.0)$ solar metallicity. The cloud mass is qualitatively consistent with the initial cloud mass of $\approx 10^{3–5} \, M_\odot$ at the virial radius in Afruni et al. 2019. Unlike massive LRG halos, the inflow accretion of gas clouds from external parts of $L_\star$ galaxy halos does not suffer from severe deceleration by...
Assuming galaxies at various projected distances according to the color bars in the top left halo mass for isolated, star-forming (blue squares) and quiescent (red circles) galaxies. The darkness of the blue/red symbols indicates $m_{33}$ kpc, $r_{1}$ and consistent measurements from the SDSS database. The azimuthal angle ($\Phi$) is defined as the angle from the galaxy’s major axis to the line connecting the center of the galaxy to the location of the QSO. A QSO sightline that occurs along the major axis of the galaxy has $\Phi = 0^\circ$ and one that occurs along the minor axis of the galaxy has $\Phi = 90^\circ$.

To ensure a high confidence in the following azimuthal dependence investigation, we restrict our sample to those galaxies with measured ellipticities $e > 0.2$ and consistent measurements of PA in both SDSS $r$ and $i$ bands. SDSS $r$ and $i$ bands are the most sensitive bandpasses for measuring the surface brightness profiles and $\Phi$ for galaxies at $z \approx 0.2$ in our sample. A total of 128 out of 201 galaxies meet this criterion. We then divide these galaxies into three bins of $\Phi$, where the bin size is chosen to be larger than the typical uncertainty in our data ($\Delta \Phi < 10^\circ$). In Figure 10 we display 15 galaxy-QSO pairs to illustrate typical cases with azimuthal angles falling in the three bins: $0^\circ < \Phi < 30^\circ$ (top), $30^\circ < \Phi \leq 60^\circ$ (middle), and $60^\circ < \Phi < 90^\circ$ (bottom) that go into the calculations in Figure 11. From visual
the isolated galaxy sample beyond 0.4 \sigma 10 percent at 1 \sigma level) of Mg II absorption closer to the minor axis (\Phi \geq 30^\circ) of star-forming galaxies at d < 0.4 R_h with the rest-frame equivalent width of Mg II no greater than W_r(2796)/\AA. The galaxies with azimuthal angle \Phi < 45^\circ are shown in dashed green line and galaxies with \Phi > 45^\circ as magenta solid line. The cumulative distributions are estimated using Kaplan-Meier estimator. The shaded bands represent 68% confidence intervals including uncertainties due to sample variance and measurement errors with combined bootstrapping and Monte-Carlo resampling.

Figure 11. (a) Dependence of \langle \kappa \rangle on the azimuthal angle for isolated, star-forming galaxies (blue squares) and quiescent galaxies (red circles) at projected distance d < 0.4 R_h. (b) Dependence of \langle \kappa \rangle on the azimuthal angle in different projected distance intervals for isolated, star-forming galaxies. Triangles represent galaxies within projected distance d of d \leq 0.2 R_h from a background QSO sightline, and diamonds represent 0.2 R_h < d < 0.4 R_h. The horizontal error bars show the full range of galaxy-QSO projected distances within each bin and vertical error bars represent the 68% confidence interval. (c) Cumulative fraction (P) of isolated, star-forming galaxies at d < 0.4 R_h, with the rest-frame equivalent width of Mg II no greater than W_r(2796)/\AA. The galaxies with azimuthal angle \Phi < 45^\circ are shown in dashed green line and galaxies with \Phi > 45^\circ as magenta solid line. The cumulative distributions are estimated using Kaplan-Meier estimator. The shaded bands represent 68% confidence intervals including uncertainties due to sample variance and W_r(2796) measurement errors with combined bootstrapping and Monte-Carlo resampling.

inspection of Figure 10 it is clear that the measurements of \Phi for the restricted sample are sufficiently adequate for the adopted bin size \Delta \Phi = 30^\circ.

We present in the left panel of Figure 11 the \langle \kappa \rangle as a function of \Phi for our star-forming and quiescent galaxy samples. As we only have one detected Mg II absorber for the isolated galaxy sample beyond 0.4R_h, we limit our investigation to d < 0.4 R_h. We find no strong dependence of \langle \kappa \rangle on \Phi for either star-forming or quiescent galaxies. While we find a modest enhancement (\approx 10 percent at 1\sigma level) of Mg II absorption closer to the minor axis (\Phi \geq 60^\circ) of star-forming galaxies, no azimuthal angle preference is found for quiescent galaxies. In the middle panel of Figure 11 we further divide star-forming galaxies into two projected distance intervals.
bins. We find no azimuthal angle dependence of (κ) for star-forming galaxies at small projected distance 0 < d ≤ 0.2 R_h and a mild elevated covering fraction along the minor axis (∼ 1σ level) at 0.2 < d ≤ 0.4 R_h. To further investigate the strength of Mg II absorbers around galaxies closer to the major (Φ < 45°) and minor (Φ ≥ 45°) axis, we use the Kaplan-Meier estimator (Feigelson & Nelson 1985) to derive the median rest-frame equivalent width of Mg II forming galaxies at small projected distance 0 < d ≤ 0.2 R_h. Based on the Kaplan-Meier curves, we infer a median W_r(2796) ≈ 0.39 ± 0.08 A for galaxies with Φ < 45° and W_r(2796) ≈ 0.53^{+0.14}_{-0.11} A for galaxies with Φ ≥ 45°. The excess W_r(2796) around galaxies closer to the minor axis (Φ ≥ 45°) is at ≤ 1σ level. We find no statistical significant dependence of (κ) or W_r(2796) on azimuthal angle Φ.

5.4 Comparison between Star-forming and Quiescent Galaxies

With the large isolated galaxy samples, here we compare the physical properties of Mg II absorbing gas around star-forming and quiescent galaxies. Using our likelihood analysis, we have noted that there is a significant anti-correlation (∼ 3σ) between the Mg II absorption strength and projected distance d for star-forming galaxies. The anti-correlation becomes even stronger when including scaling with B-band luminosity (∼ 6σ) and stellar mass (∼ 8σ). In contrast, the results of likelihood analysis show that the quiescent galaxies do not have a trend in Mg II abundance strength versus projected distance within a ∼ 1σ level. Including the scaling of B-band luminosity or stellar mass has little improvement on the anti-correlation.

In Figure 8(a) we show that both star-forming and quiescent galaxies show steep declining covering fraction (κ) with increasing d. For the star-forming galaxy sample, the covering fraction of W_r(2796) ≥ 0.3 A absorbers declines from ⟨κ⟩ ≈ 0.83 at d < 40 kpc to ⟨κ⟩ ≈ 0.37 at d ≈ 40 − 90 kpc (∼ 53% decline), similar to that of the quiescent galaxy sample (∼ 51% decline). Beyond d ≈ 100 kpc, the covering fraction of both samples is consistent with ⟨κ⟩ ≈ 0. The dependence of ⟨κ⟩ and d for our galaxies are in stark contrast to the massive LRG samples (Huang et al. 2016). Specifically, the passive LRGs display flat distribution of ⟨κ⟩ ∼ 15% at d ≤ 120 kpc, and an overall ⟨κ⟩ ~5% out to d ~ 500 kpc.

Next, in Figure 8(a) we show that in addition to the strong dependence of covering fraction on galaxy mass, at a similar mass range of log M_{star}/M_☉ ≈ 10.4 − 11.1, star-forming galaxies reveal an elevated covering fraction than that of quiescent galaxies. Note that despite the higher ⟨κ⟩ we obtain for the star-forming galaxies, the sample has on average a slightly lower stellar mass log(M_{star}/M_☉) of ∼ 10.5 compared to that of the quiescent galaxy sample (log(M_{star}/M_☉) ∼ 10.7). To investigate whether the elevated ⟨κ⟩ for star-forming galaxies is due to the physical properties of associated galaxies or simply a steep dependence on mass, we restrict the two samples to a narrow stellar mass range of log M_{star}/M_☉ = 10.4 − 10.7, making both samples similar stellar mass distributions with log(M_{star}/M_☉) = 10.55. We find the resultant covering fraction of star-forming galaxies is 0.64 ± 0.10, while that of quiescent galaxies is 0.29 ± 0.13. With the same stellar mass distribution, the quiescent galaxies have merely 45% gas covering fraction compared to the star-forming galaxies. We find the resultant covering fraction of star-forming galaxies is 0.64 ± 0.10, while that of quiescent galaxies is 0.29 ± 0.13. With the same stellar mass distribution, the quiescent galaxies have merely 45% gas covering fraction compared to the star-forming galaxies. The positive correlation between specific star formation rate and gas covering fraction is manifest in Figure 8(b). An enhanced Mg II covering fraction around star-forming galaxies seems to imply an outflow origin. However, the origin is complicated by the fact that the majority of Mg II absorbers around isolated galaxies are gravitationally bound (Figure 6). In addition, no statistically significant dependence of (κ) or W_r(2796) on the azimuthal angle is found in Section 5.3. Furthermore, the kinematics discussed in Section 5.2 indicates that while cool clumps around star-forming galaxies can reach the center of the halo, the clumps in massive quiescent halos are likely to be destroyed during the infall before reaching the LRGs (e.g., Gauthier & Chen 2011; Huang et al. 2016; Zahedy et al. 2019).

5.5 Comparison between Isolated and Non-isolated Systems

In the right panel of Figure 4, we find that the 43 non-isolated systems exhibit no hint of a trend between Mg II absorber strength W_r(2796) and galaxy projected distance d among detections, contrary to the clear anti-correlation shown in isolated galaxies (central panel). Specifically, while we do not find any detection beyond ∼ 100 kpc for isolated, star-forming galaxies, strong systems of W_r(2796) ≥ 0.5 A are detected for non-isolated systems at large distances. The result is in line with previous findings that detections of W_r(2796) ≥ 0.5 A absorbers are frequently found in non-isolated or group systems at beyond d ≥ 100 kpc (e.g., Chen et al. 2010; Nielsen et al. 2018; Fossati et al. 2019). Indeed, previous studies have discovered strong Mg II absorbers W_r(2796) > 1 A associated with galaxy groups (e.g., Whiting et al. 2006; Fossati et al. 2019), LRGs (Gauthier 2013; Huang et al. 2016) and luminous quasar hosts (Johnson et al. 2015), whereas such absorbers are only found at d ≤ 50 kpc in our 211 isolated galaxy samples.

Recently, new wide-field integral field spectrographs such as the Multi Unit Spectroscopic Explorer (MUSE; Bacon et al. 2010) have enabled discoveries of spatially extended line-emitting nebula on scales reaching ∼ 100 kpc in group or cluster environments (e.g., Epinat et al. 2018; Johnson et al. 2018; Chen et al. 2019). Johnson et al. (2018) found that these giant [O III] nebulae correspond both morphologically and kinematically to interacting galaxy pairs in the group, likely arising from cool filaments and interaction-related debris. Furthermore, covering ∼ 20% of the area around the quasar at ≤ 100 kpc, the nebulae may be an explanation of the high covering fraction of Mg II absorbing gas around luminous QSO hosts in Johnson et al. (2015b). Chen et al. (2019) also uncovered a giant nebula (∼ 100 physical kpc) associated with a low-mass galaxy group at z ∼ 0.3, where the line-emitting gas connects between group galaxies and follows closely the motion of member galaxies. The study demonstrates that gas stripping in low-mass groups may be effective in releasing metal-enriched gas from star-forming regions, producing absorption systems (e.g., Mg II absorbers) in QSO spectra.
The case studies of spatially-extended line-emitting nebulae associated with galaxy groups provide unambiguous evidence of the importance of interactions in distributing metal-enriched gas on large scales. Despite the lack of morphological information in our absorption-line survey, the commonly found strong Mg\textsc{ii} absorbers ($W_r(2796) \gtrsim 0.5$ \AA) at \(d \gtrsim 100\) kpc in the 43 non-isolated systems support the idea that interactions between group galaxies may contribute to the presence of strong absorbers at large scales.

5.6 Comparison with Other Studies

The M3 Halo Project consists of 211 isolated and 43 non-isolated galaxies with \(z = 0.10 - 0.48\) at projected distance \(d_{\text{med}} = 73\) kpc from a background QSO, chosen without any prior knowledge of the presence or absence of Mg\textsc{ii} absorbing gas. The absorption-blind sample chosen from SDSS enables an unbiased characterization of the correlation between Mg\textsc{ii} absorbing gas and physical properties of associated galaxies. Our survey shows a distinct difference in the \(W_r(2796)\) versus \(d\) inverse correlation between star-forming and quiescent halos. While there is a significant anti-correlation (\(\gtrsim 3\sigma\)) between \(W_r(2796)\) and \(d\) for star-forming galaxies, there is no hint of a correlation among Mg\textsc{ii} detected quiescent galaxies. We also show that while star-forming galaxies have elevated \((\kappa) \approx 83\%\) at \(d < 40\) kpc, both star-forming and quiescent galaxies show \((\kappa) \approx 0\) beyond 90 kpc. These findings are different from the results of MAGiCAT (Nielsen et al. 2013a,b). At the \(W_0 = 0.3\) \AA\ threshold, MAGiCAT galaxies reveal a non-negligible Mg\textsc{ii} gas covering fraction \((\kappa) \approx 10 - 40\%\) at \(d = 100 - 200\) kpc.

It is worth noting that even though 69 out of 182 galaxies in MAGiCAT come from our M3 Halo Project (Chen & Tinker 2008; Chen et al. 2010a), MAGiCAT consists of galaxy-Mg\textsc{ii} absorber pairs from different programs. While some of these programs were designed to be absorption-blind like the M3 Halo Project, others select galaxies at the redshifts of known Mg\textsc{ii} absorbers. The galaxy-absorber pairs from these other programs have associated Mg\textsc{ii} absorbers by design, therefore imposing a strong bias on the calculated gas covering fraction. Similarly, the lack of mass dependence on the covering fraction of Mg\textsc{ii} absorbing gas in Churchill et al. (2013) can be understood by an over estimation of covering fraction at high mass, where detections at this mass range come mostly from absorber centric surveys.

Martin et al. (2019) constructed a sample of 50 \(z \approx 0.2\) star-forming galaxies with \(M_{\text{star}} \approx 10^{10.3} M_\odot\) at close projected distances \(d < 100\) kpc, properties similar to our star-forming galaxies. For absorbers with a detection threshold of \(W_0 = 0.3\) \AA, this sample yields \((\kappa) \approx 75\%\) at \(d < 40\) kpc, which declines to \((\kappa) \approx 0.24\%\) at \(40 < d < 100\) kpc (through private communication). The steep anti-correlation and the mean covering fraction is roughly consistent with our results, where we find \((\kappa)\) declines from \((\kappa) = 0.83^{+0.06}_{-0.05}\) at \(d < 40\) kpc to \((\kappa) = 0.37^{+0.07}_{-0.06}\) at \(d \approx 40 - 90\) kpc.

It is clear from our results that Mg\textsc{ii} absorbing gas is tightly coupled with the physical properties of host galaxies. In particular, our survey displays a strong dependence of mean covering fraction of Mg\textsc{ii} absorbing gas \((\kappa)\) on the stellar mass of host galaxies, where \((\kappa)\) increases with mass at \(\log M_{\text{star}}/M_\odot \lesssim 10.6\) and decreases steeply at higher masses.

We further demonstrate in Section 5.2 that at the same stellar masses of \(\log (M_{\text{star}}/M_\odot) = 10.55\), star-forming galaxies have in average twice of the mean Mg\textsc{ii} gas covering fraction (64\%) compared to that of quiescent galaxies (29\%). The properties of Mg\textsc{ii} absorbing gas are shown to strongly depend on multiple host galaxy properties. Here we highlight the importance of having a homogeneous, absorption-blind galaxy sample, in order to identify different dependences (e.g. stellar mass and star-formation) and carefully study how Mg\textsc{ii} gas correlates with their host galaxy properties.

6 SUMMARY

We have carried out the M3 Halo Project of galaxies and Mg\textsc{ii} absorbers in the spectra of background QSOs that are within close projected distances at \(z < 0.5\). The catalog contains 211 isolated and 43 non-isolated galaxy-QSO pairs with spectroscopic redshifts of \((z)_{\text{med}} = 0.21\) and projected distances of \((d)_{\text{med}} = 86\) kpc. This is the largest homogeneous, absorption-blind sample at \(z \approx 0.2\) to date, allowing us to conduct a comprehensive study of the correlation between Mg\textsc{ii} absorbing gas and the physical properties of host galaxies at low-redshift. The main findings of our survey are summarized as the following:

1. We observe a stark contrast in the distribution of Mg\textsc{ii} absorber strength \(W_r(2796)\) versus galaxy projected distance \(d\) between isolated and non-isolated galaxies (Figure 4). While both galaxy samples appear to occupy a similar \(W_r(2796)\) versus \(d\) space, isolated galaxies show strong inverse correlation but non-isolated galaxies exhibit no hint of a trend among detections. When dividing isolated galaxies into star-forming and quiescent galaxy samples, star-forming galaxies show a strong anti-correlation between \(W_r(2796)\) and distance \(d\), in contrast to the moderate trend revealed in quiescent galaxy sample.

2. Based on the likelihood analysis, we confirm that \(W_r(2796)\) declines with increasing \(d\) for isolated galaxies. The anti-correlation between \(W_r(2796)\) and \(d\) is strengthened when considering only isolated, star-forming galaxies. The inverse correlation is further enhanced for star-forming galaxies after accounting for either mass scaling of gaseous radius \((R_h)\), \(B\)-band luminosity \((L_B)\) or stellar mass \((M_{\text{star}})\) of host galaxies. On the contrary, Mg\textsc{ii} detected quiescent galaxies exhibit little correlation between \(W_r(2796)\) and \(d\), whether or not accounting for scaling (see Figures 5 & 6).

3. In Figure 7, we show that the covering fraction of Mg\textsc{ii} absorbing gas \((\kappa)\) is high for isolated galaxies at small projected distances \(d\) and declines rapidly to \((\kappa) \approx 0\) at \(d \gtrsim 100\) kpc for absorbers of \(W_r(2796) \gtrsim 0.3\) \AA. At \(d < 40\) kpc, we find an elevated covering fraction \((\kappa) \approx 0.83\) for star-forming galaxies compared to \((\kappa) \approx 0.57\) for quiescent galaxies. After the scaling of \(B\)-band luminosity, the inverse correlation between \((\kappa)\) and \(d\) is strengthened and the difference in covering fraction between star-forming and quiescent galaxies become more evident (\(\approx 3\sigma\)).

4. The high Mg\textsc{ii} gas covering fraction for both our star-forming and quiescent galaxy samples at \(d < 90\) kpc \((\langle \kappa \rangle \approx 0.3 - 0.8)\) is in stark contrast to what we have
seen in the massive LRGs. Within $R_{\text{gas}}$, we find a sharp decline of $\text{MgII}$ covering fraction ($\kappa$) from 30-70% around $L_*$ galaxies to 10-15% around massive LRGs (Figure 5a). The strong mass dependence of $\text{MgII}$ incidence is qualitatively consistent with the expectation from the observed clustering of $\text{MgII}$ absorbers. In addition, at stellar mass of $\log(M_{\ast}/M_\odot) \approx 10.6$, the MgII gas covering fraction for quiescent galaxies ($\langle \kappa \rangle = 0.29$) is merely half of what we find for star-forming galaxies ($\langle \kappa \rangle = 0.64$). We also find a positive correlation between specific star formation rate and MgII gas covering fraction (Figure 5b).

(5) We find that most of the galaxy-MgII absorber pairs have relative velocities smaller than the expected projected escape velocity of their host halos, implying that the MgII absorbers are likely to be gravitationally bound (Figure 5c). In addition, MgII absorbers have line-of-sight velocity dispersion of $\sigma = (58-73, 73-90)$ km s$^{-1}$ for low-mass and high-mass star-forming galaxies, consistent with the expected line-of-sight velocity dispersion $\sigma = (52, 86)$ km s$^{-1}$ for virialized motion. If the clouds are massive enough to travel through the hot gas at the halo velocity without significant deceleration by the hot gas drag force, we are able to place lower limits on the cloud mass of $m_{\text{cl}} \sim 10^7 M_\odot$ and the cool gas accretion rate of $\sim 0.7 - 2 M_\odot$ yr$^{-1}$.

(6) In Figure 11 we investigate the possible azimuthal dependence in the covering fraction of MgII absorbers for isolated, star-forming and quiescent galaxies. While no apparent trend is seen for quiescent galaxies at $d \lesssim 0.4 R_h$, there is a modest enhancement in the gas covering fraction along the minor axis of star-forming galaxies at $0.2 < d \leq 0.4 R_h$. We find excess $W_r(2796)$ around galaxies closer to the minor axis ($\phi < 45^\circ$) at $\lesssim 1\sigma$ level. No statistical significant dependence of $(\kappa)_{\text{MgII}}$ or $W_r(2796)$ on azimuthal angle $\Phi$ is shown in our isolated galaxy sample.

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DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

REFERENCES

Abolfathi B., Aguado D. S., Aguilar G., Allende Prieto C., Almeida A., Ananna T. T., Anders F., Anderson S. F., Andrews B. H., Anguiano B., et al., 2018, ApJ, 235, 42
Adelman-McCarthy J. K., Agüeros M. A., Allam S. S., Allende Prieto C., Anderson K. S. J., Anderson S. F., Annis J., Bahcall N. A., Bailer-Jones C. A. L., Baldry I. K., Barentine J. C., Basnett B. A., Becker A. C., Beers T. C., Bell E. F., Berlind A. A., Bernardi M., Blanton M. R., Bochanski J. J., Bosoris V. N., Brinchmann J., Brinkmann J., Brunner R. J., Budavári T., Carliles C., Carr M. A., Castander F. J., Cinabro D., Cool R. J., Covey K. R., Csabai I., Cunha C. E., Davenport J. R. A., Dilday B., do Nascimento D. J., Evans M. L. F., Fan X., Finkbeiner D. P., Friedman S. D., Frieman J. A., Fuliguita M., Gänside B. T., Gates E., Gillespie B., Glazebrook K., Gray J., Grebel E. K., Gunn J. E., Gurvani M. K., Hall P. B., Harding P., Harvanek M., Hawley S. L., Hayes J., Heckman T. M., Hendry J. S., Hindsley R. B., Hirata C. M., Hogan C. J., Hogg D. W., Hyde J. B., Ichikawa S.-i., Ivezic Z., Jester S., Johnson J. A., Jongensen A. M., Juric M., Kent S. M., Kessler R., Kleinman S. J., Knapp G. R., Kron R. G., Krzesinski J., Kurokapiotik N., Lamb D. Q., Lampeitl H., Lebedeva S., Lee Y. S., Leger R. F., Lépine S., Lima M., Lin H., Long D. C., Loomis C. P., Loveday J., Lupton R. H., Malanushenko O., Malanushenko V., Mandelbaum R., Margon B., Marriner J. P., Martinez-Delgado D., Matsubara T., McGeehe P. M., McKay T. A., Meiksin A., Morrison H. L., Munn J. A., Nakajima R., Neilsen Jr. E. H., Newberg H. J., Nichol R. C., Nicinski T., Nieto-Santisteban M., Nitta A., Okamura S., Owen R., Oyaizu H., Padmanabhan N., Pan K., Park C., Peoples Jr. J., Pier J. R., Pope A. C., Purger N., Raddick M. J., Re Fiorentin P., Richards G. T., Richmond M. W., Riess A. G., Rix H.-W., Rockosi C. M., Sako M., Schlegel D. J., Schneider D. P., Schreiber M. R., Schwepe A. D., Seljak U., Sesar B., Sheldon E., Shimakaw K., Sivarani T., Smith J. A., Snowden S. A., Steinmetz M., Strauss M. A., Subba Rao M., Suto Y., Szalay A. S., Szapudi I., Szkody P., Teegmark M., Thakar A. R., Tremonti C. A., Tucker D. L., Uomoto A., Vanden Berk D. E., Vandenberk J., Vidrih S., Vogely M. S., Voges W., Vogt N. P., Wadadekar Y., Weinberg D. H., West A. A., White S. D. M., Wilhite B. C., Yanny B., Yocum D. R., York D. G., Zehavi I., Zucker D. B., 2008, ApJS, 175, 297
Afruni A., Fraternali F., Pezzulli G., 2019, A&A, 625, A11
Bacon R., Accardo M., Adjali L., Anwand H., Bauer S., Biswas I., Blaziot J., Boudon B., Brua-Nogue S., Brinchmann J., Caillier P., Capano L., Carollo C. M., Contini T., Couderc P., Daguisé E., Deiries S., Delabre B., Dreizler S., Dubois J., Dupieux M., Dupuy C., Emsellem E., Fechner T., Fleischmann A., François M., Gallou G., Ghasra T., Glimmendahm A., Gojak D., Guiderdoni B., Hansali G., Hahn T., Jarno A., Kelz A., Koehler C., Kosmalski J., Le Floch M., Lilly S. J., Lincoln P., Smith J. A., Snedden S. A., Steinmetz M., Strauss M. A., Tegmark M., Thakar A. R., Tremonti C. A., Tucker D. L., Uomoto A., Vanden Berk D. E., Vandenberk J., Vidrijh S., Vogely M. S., Voges W., Vogt N. P., Wadadekar Y., Weinberg D. H., West A. A., White S. D. M., Wilhite B. C., Yanny B., Yocum D. R., York D. G., Zehavi I., Zucker D. B., 2008, ApJS, 175, 297

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