On the Observed $W_{\text{Mg II}} - L_{\text{[O II]}}$ Correlation in SDSS QSO Spectra

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ABSTRACT

This paper investigates the effect of differential aperture loss with SDSS fibers and examines whether such selection bias would result in the observed correlation between rest-frame absorption equivalent width of Mg II absorbers, $W_r(2796)$, and mean associated [O II] luminosity, $L_{\text{[O II]}}$, in SDSS QSO spectra. We demonstrate based on a Monte Carlo simulation that the observed $W_r(2796)$ vs. $L_{\text{[O II]}}$ correlation of Mg II absorbers can be well-reproduced, if all galaxies found in deep surveys possess extended Mg II halos and if the extent of Mg II halos scales proportionally with galaxy mass as shown in previous studies. The observed correlation can be explained by a combination of (1) the known $W_r(2796)$ vs. $\rho$ anti-correlation in galaxy and Mg II absorber pairs and (2) an increasing aperture loss in the 3′′ diameter SDSS fiber for galaxies at larger $\rho$. Galaxies at larger projected distances produce on average weaker Mg II absorbers and weaker (or zero) $L_{\text{[O II]}}$ in SDSS QSO spectra. We show that such correlation diminishes when larger fibers are adopted and is therefore not physical. While under a simple halo model the majority of Mg II absorbers do not directly probe star-forming disks, they trace photo-ionized halo gas associated with galaxies. We show that because of the scaling relation between extended gas cross-section and galaxy mass, the number density evolution of the Mg II absorber population as a whole provides a good measure of the cosmic star formation history.

Key words: galaxies:halos – galaxy: star formation – quasars: absorption lines – survey

1 INTRODUCTION

Absorption line spectroscopy is a powerful tool for studying the structure of the distant universe. By observing the absorption features imprinted in the spectra of background QSOs, we can study otherwise invisible gaseous structures to redshift as high as background QSOs can be. The Sloan Digital Sky Survey (SDSS; York et al. 2000) has yielded optical spectra of $\sim 10^6$ k QSOs at $z = 0.065$ – 5.46 (Schneider et al. 2010). This unprecedentedly large sample of QSO spectra offers a rich resource for studying the distant universe using absorption spectroscopy. For example, Mg II $\lambda\lambda 2796,2803$ absorption doublets are commonly seen in QSO spectra obtained using ground-based spectrographs. They provide a uniform probe of intervening gas over a broad redshift range from $z = 0.4$ to $z \approx 2.5$. Several groups have conducted systematic searches of Mg II absorption features in SDSS QSO spectra, producing a large sample of these absorbers for constraining their statistical properties (e.g. Bouché et al. 2004; Nestor et al. 2005; Prochter et al. 2006; York et al. 2006; Quider et al. 2011).

Mg II absorbers are routinely found in the vicinities ($\lesssim 100$ kpc) of distant galaxies and provide a convenient probe of galactic halos at high redshifts (e.g. Bergeron 1986; Steidel et al. 1994; Kacprzak et al. 2008; Chen & Tinker 2008; Gauthier & Chen 2011). However, their physical origin, whether the absorbers arise in infalling clouds, outflows from nearby star-forming regions, or a combination thereof, is unclear. The ubiquitous presence of blueshifted Mg II absorption features along the sightlines into the star-forming regions of $z \sim 1$ galaxies indicates that starburst driven outflows are common in distant galaxies and that outflows contribute to some fraction of Mg II absorbers uncovered along random QSO sightlines (e.g. Weiner et al. 2009; Rubin et al. 2010). Although the extent of galactic-scale winds around these galaxies is unknown, the observed self-absorption of
Mg II doublets in distant star-forming galaxies has motivated recent works that attribute all strong Mg II absorbers (rest-frame absorption equivalent width \( W_r(2796) > 0.5 \) Å) along QSO sightlines to outflows (e.g. Ménard & Chelouche 2009; Chelouche & Bowen 2010; Ménard et al. 2011).

Using a sample of 8500 Mg II absorbers at \( z = 0.4-1.4 \) from SDSS DR4 quasar spectra, Ménard et al. (2011; hereafter M11) observed a strong correlation between \( W_r(2796) \) and their associated median \( \langle [\text{O II}] \rangle \) luminosity per unit area, \( \sum L_{\text{[O II]}} \) in stacked QSO spectra. The observed \( W_r(2796) \) vs. \( \sum L_{\text{[O II]}} \) correlation is characterized by
\[
\left< \sum L_{\text{[O II]}} \right>_\text{med} = a \left( \frac{W_r(2796)}{\text{1 Å}} \right)^b
\]
where \( a = (1.48 \pm 0.18) \times 10^{37} \) erg s\(^{-1}\) kpc\(^2\) and \( b = 1.75 \pm 0.11 \). This observed correlation applies to Mg II absorbers of \( W_r(2796) = 0.7 - 6 \) Å. A similar trend has also been mentioned in Noterdaeme et al. (2010), but these authors did not find a correlation between \( W_r(2796) \) and \( L_{\text{[O II]}} \) in \( \langle [\text{O II}] \rangle \)-emission selected Mg II absorbers. In addition, Noterdaeme et al. (2010) pointed out that part of their strong Mg II absorbers arise in low \( L_{\text{[O II]}} \) galaxies. Because \( \langle [\text{O II}] \rangle \) luminosity \( L_{\text{[O II]}} \) provides a measure of current star formation rate (e.g. Kennicutt 1998), M11 interpreted the observed strong correlation as Mg II absorbers tracing on-going star formation. In addition, M11 showed that the frequency distribution function of Mg II absorbers and the \( [\text{O II}] \) luminosity function share similar shape and amplitude, and that the number density evolution of Mg II absorbers follows the cosmic star formation history. Combining these empirical correlations, the authors argue that outflows are the mechanism responsible for the observed Mg II absorption in QSO spectra.

The conclusion of outflows being responsible for the observed Mg II absorbers appears to be discrepant from previous findings that \( W_r(2796) \) correlates more strongly with galaxy mass and weakly with galaxy colors or recent star formation history (e.g. Steidel et al. 1994; Chen et al. 2010a,b). Such conclusion also makes it difficult to understand the identifications of strong Mg II absorbers in the vicinities of quiescent galaxies (e.g. Gauthier et al. 2010; Bowen & Chelouche 2011; Gauthier & Chen 2011).

While M11 presented a clever approach to estimate the co-moving star formation rate density \( \dot{\rho}_* \) based on the observations of Mg II absorbers in SDSS QSO spectra, it is important to understand the underlying factors that shape the observed strong \( W_r(2796) \) vs. \( \sum L_{\text{[O II]}} \) correlation in SDSS data. We note that the SDSS fibers have a finite size of 3\(^\prime\) diameter on the sky, which corresponds to projected physical separations of 11 – 18 h\(^{-1}\) kpc at \( z = 0.4 - 1.4 \). The observed \( W_r(2796) \) vs. \( \rho \) anti-correlation (e.g. Chen et al. 2010a) implies that galaxies at larger projected distances produce on average weaker Mg II absorbers and lower (or zero) \( L_{\text{[O II]}} \) (when the star-forming disks occur at angular distances \( \theta > 1.5^\circ \), or \( \theta > 6 - 9 \) h\(^{-1}\) kpc, of the QSO sightlines; see Figure 1). This selection bias strengthens the apparent correlation of Equation (1)\(^\text{1} \) A similar point on the potential missed galaxy light in the SDSS fibers has also been made in Noterdaeme et al. (2010).

To investigate the selection bias as a result of differential aperture loss, we have carried out a Monte Carlo simulation study. Adopting a empirical model for describing gaseous clouds around galaxies from Chen et al. (2010a) and empirical relations for describing the luminosity and size distributions of the general galaxy population, we demonstrate in this paper that the observed \( W_r(2796) \) vs. \( L_{\text{[O II]}} \) correlation can be well re-produced without any fine-tuning after accounting for the differential aperture loss of galaxy fluxes in the SDSS fiber. While under the simple halo model the majority of Mg II absorbers do not directly probe star-forming disks like high column density damped Ly\( \alpha \) absorbers (e.g. Wild et al. 2007), they do probe photo-ionized clouds around galaxy.\(^2 \) If more massive galaxies are surrounded by more extended Mg II absorbing gas, then the number density evolution of Mg II absorbers naturally follows the cosmic star formation history. Because models which do not require \( L_{\text{[O II]}}(z)/A_{\text{fiber}}(z) \) where \( A_{\text{fiber}}(z) \) represents the corresponding physical area of SDSS fiber at redshift \( z \). However, as illustrated in Figure 1, the reduction from total observed fluxes to flux surface density does not correct for the differential aperture loss of galaxy fluxes in SDSS QSO spectra.

\(^{1}\) Ménard et al. (2011) applied a fiber selection correction by considering luminosity surface density, \( \sum L_{\text{[O II]}} \) =

\(^{2}\) Note that the empirical \( W_r(2796) \) vs. \( \rho \) relation of Chen et al. (2010a) was established based on a sample of galaxies at close projected distances to a QSO sightline, including those that may produce a damped Ly\( \alpha \) absorption feature in the QSO spectrum. We therefore expect that absorber samples generated based on the mean \( W_r(2796) \)–\( \rho \) relation and the observed scatter include contributions from star-forming disks. Based on the observed number densities of damped Ly\( \alpha \) absorbers (Rao et al. 2006) and Mg II absorbers of \( W_r(2796) > 0.5 \) Å (Neslot et al. 2005) at \( z < 1 \), we estimate that no more than 20% of these strong Mg II absorbers have contributions from star-forming disks.
outflows can also reproduce the empirical correlations between absorber abundances and star formation properties, we caution drawing conclusions in favor of an outflow origin for QSO absorbers based on these simple correlations. Throughout this paper, we adopt a ΛCDM cosmology with $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$ and a dimensionless Hubble constant of $h = H_0/(100 \text{ km s}^{-1} \text{ Mpc}^{-1})$.

2 MOCK GALAXY AND ABSORBER CATALOGS

To simulate the SDSS observations, we first generate a mock catalog of 200,000 galaxies distributed uniformly within $\approx 10''$ angular radius of a QSO sightline at redshift between $z = 0.4$ and $z = 1.4$. The large number is necessary to provide a representative sampling of a wide range of galaxy properties (such as size and luminosity) and to minimize statistical noise in our simulations. The redshift range is selected to match the study of M11. Over the redshift range of $z = 0.4 - 1.4$, the angular radius of $10''$ corresponds roughly to $\rho = 37 - 59 \text{ h}^{-1} \text{kpc}$.

The working hypothesis of this exercise is that all galaxies are surrounded by extended gaseous halos. This hypothesis is supported by empirical observations that reveal a high gas covering fraction around galaxies of a wide range of luminosity and color (e.g. Chen et al. 2010a). The gaseous halos are expected to produce MgII absorption features in the spectrum of a background QSO when intercepting the QSO sightline. For every MgII absorber in the mock catalog, the location and intrinsic properties of the absorbing galaxy are known. It is therefore possible to compute the emission fluxes of the absorbing galaxies recorded in QSO spectra.

2.1 The Mock Galaxy Catalog

We first generate random galaxies following a Schechter probability function of their rest-frame absolute $B$-band magnitude $M_B$,

$$p(M_B) \propto 10^{0.4(M_B-M)} \exp(-10^{0.4(M_B-M)}),$$  

where $\alpha$ is the faint-end slope of the galaxy luminosity function. We adopt $\alpha = -1.3$ for the faint-end slope (e.g. Faber et al. 2007) and $M_B = -5 \log h = -19.8$ following Chen et al. (2010a). The mock galaxy sample spans a luminosity range between 0.01$L_*$ and 10$L_*$. As discuss below, we also repeat the Monte Carlo simulations with different faint-end slope values, $\alpha = -1.2$ and $\alpha = -1.4$ and our findings remain the same.

Next, we determine the optical size of each galaxy in the mock catalog according to the luminosity-size relation from Cameron & Driver (2007),

$$\log (R_{50}) = -0.1 M_B - 1.35$$  

where $R_{50}$ is the half-light radius, the radius within which the galaxy emits half of its total flux. For a galaxy of $M_B$, the half-light radius is drawn from a Gaussian distribution about the mean luminosity-size relation with a 1-σ width of 0.4 dex in the log $R_{50}$ space. To include the majority of the galaxy light, the radius that contains 90% of the total flux $R_{90}$ is more relevant in our study. We therefore convert $R_{50}$ to $R_{90}$, assuming an exponential surface brightness profile.

Next, we determine the [OII] luminosity $L_{[OII]}$ for each galaxy assuming that the rest-frame $B$-band fluxes trace the mean profile of [OII] emission. The expected $L_{[OII]}$ is then calculated according to the correlation between $M_B$ and $L_{[OII]}$ found in deep survey data. Based on the study of Zhu et al. (2007), we find that the $M_B$ vs. $\log L_{[OII]}$ correlation can be characterized by

$$\log [L_{[OII]}/(\text{erg s}^{-1})] = 35 - 0.3 M_B$$  

with a 1-σ scatter of $\sigma_{L_{[OII]}} = 0.3$ dex. Note that Equation (4) is an empirical relation observed quantities. It does not include dust extinction corrections. The inferred $L_{[OII]}$ can therefore be directly compared to what is observed in the stacked SDSS QSO spectra. For a galaxy of $M_B$, $L_{[OII]}$ is drawn from a Gaussian distribution about the mean $M_B$-$L_{[OII]}$ relation with a 1-σ width of 0.3 dex in the log $L_{[OII]}$ space.

To examine whether or not our mock galaxy sample is representative of the field galaxy population, we present the [OII] luminosity distribution of our mock galaxy sample in Figure 2 along with the observed [OII] luminosity function of $z \sim 1$ galaxies from different deep surveys (Takahashi et al. 2007; Zhu et al. 2009). All the empirical measurements have been converted to have the same cosmological parameters adopted in our analysis. Figure 2 demonstrates that we reproduce the observed [OII] luminosity function with the mock galaxy sample for the luminous galaxy population. At the faint-end, the observations suffer from survey incompleteness (e.g. Zhu et al. 2009) and therefore the observed space density represents a lower limit to the underlying faint galaxy population.

Next, we model each galaxy in the mock catalog as a round disk and randomly place the galaxy within $\approx 10''$ of a QSO sightline and at redshift between $z = 0.4$ and $z = 1.4$. We compute the corresponding physical projected distance of the galaxy based on the redshift and angular distance to the QSO. For each disk, we also assign a random inclination angle with respect to the observer and a random position angle of the major axis of the inclined disk with respect to the line connecting the galaxy and the QSO.

To determine the fraction of the luminous disk that overlaps the SDSS fiber centered at the QSO, we adopt the size of each disk galaxy $R_{90}$ and its relative distance and orientation to the QSO. We de-project the inclined disk and determine the galactocentric distance $R$ of each point $(x, y)$ in the disk according to

$$R^2(x, y) = r^2(x, y) \left[1 + \cos^2(\theta - \alpha) \tan^2i \right]$$  

where $r$ is the projected radius on the plane of the sky, $\alpha$ is the position angle of the major axis of the inclined disk, $\theta$ is the azimuthal angle of point $(x, y)$ from the major axis, and $i$ is the inclination angle of the disk. The expected [OII] emission from the galaxy in the QSO spectral data is then computed by integrating all the light within $R_{90}$ of the disk that falls in the 3'' diameter fiber. We consider two different surface brightness profiles: (1) a flat, top-hat profile and (2) an exponential profile for this calculation. If the luminous disk does not overlap the 3'' diameter fiber, then we set $L_{[OII]} = 0$. Finally, we divide the computed $L_{[OII]}$ by the physical area of a 3'' diameter fiber at the redshift of the

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mock galaxy in order to calculate its [O II] luminosity surface density $\sum L_{\text{[O II]}}$ that would be recorded in an SDSS QSO fiber.

### 2.2 The Mock Mg II Absorber Catalog

The mock Mg II catalog is formed by calculating the expected Mg II absorption strength in the spectrum of the background QSO for every galaxy in the mock galaxy catalog. To determine the associated Mg II absorption strength of a galaxy in the QSO spectrum, we adopt the uniform gaseous halo model of Chen et al. (2010a). Under this model, the Mg II absorber strength for a galaxy at projected distance $\rho$ is characterized by a mean relation of

$$W_r(2796) = \frac{W_0}{a_h \sqrt{\rho^2/a_h^2 + 1}} \tan^{-1} \left( \frac{R_{\text{gas}} - \rho^2}{a_h^2 + \rho^2} \right) \tag{6}$$

and dispersion $\sigma_{\log W_r} = 0.233$, where $R_{\text{gas}}$ is the gaseous radius of the Mg II halo, $a_h$ is the core radius and is $a_h = 0.2 R_{\text{gas}}$ and $\log W_0 = 1.24 \pm 0.03$. The gaseous radius is determined based on the galaxy $B$-band luminosity following a power-law model,

$$\frac{R_{\text{gas}}}{R_{\text{gas},*}} = \left( \frac{L_B}{L_{B,*}} \right)^{\beta}, \tag{7}$$

for which Chen et al. (2010a) found a best-fit characteristic radius of $R_{\text{gas},*} = 75 h^{-1}$ kpc for an $L_*$ galaxy and a scaling index of $\beta = 0.35$. The scaling relation between gaseous radius and galaxy $B$-band luminosity is understood as more massive galaxies are surrounded by more extended halos (e.g. Tinker & Chen 2008; Chen et al. 2010b). In addition to the spatial profile of the extended Mg II gas, Chen et al. (2010a) also measured a high gas covering fraction $\kappa$ within $R_{\text{gas}}$. Specifically, they found a mean covering fraction of $\kappa_{0.3} \approx 100\%$ for absorbers of $W_r(2796) \geq 0.3 \AA$ at $\rho < 0.4 R_{\text{gas}}$ and $\kappa_{0.3} \approx 70\%$ at $\rho \leq R_{\text{gas}}$. The gas covering fraction increases with decreasing $W_r(2796)$ threshold and decreases with $\rho$ (see Figure 10 in Chen et al. 2010a).

For each simulated galaxy, we compute the expected $W_r(2796)$ by randomly sampling the mean relation Equations (6) within the observed scatter $\sigma_{\log W_r}$. For simulated dwarf galaxies with $R_{\text{gas}} < \rho$, we set $W_r(2796) = 0$. Including the large scatter ($\sigma_{\log W_r}$) in the computation of $W_r(2796)$ allows the possibility of galaxies at small $\rho$ producing Mg II absorbers that are much weaker than the mean. Although every galaxy at $\rho < R_{\text{gas}}$ in the mock sample is expected to produce a Mg II absorber, the gas covering fraction measured at a given $W_r(2796)$ threshold is not 100%.

For a mock sample of 200,000 galaxies, the procedure described above produces a mock sample of $\sim 23,000$ Mg II absorbers of $W_r(2796) \geq 0.3 \AA$ at $z = 0.4 - 1.4$. The frequency distribution function of the mock Mg II absorber sample is presented in Figure 3. For comparison, we also include in Figure 3 the model from Prochter et al. (2006) that best describe the incidence of Mg II absorbers identified at $z = 0.4 - 2.3$ in their blind survey. Aside from the offset in the normalization, Figure 3 shows that the frequency distribution function of the mock Mg II absorber sample follows the shape of the best-fit model of Prochter et al. (2006). The difference in the incidence of mock Mg II absorbers (up to 20%) for different adopted faint-end slope of the galaxy luminosity function is understood by the relatively steep dependence of halo gas cross section on galaxy luminosity, $\sigma_{\text{gas}} = \pi R_{\text{gas}}^2 \propto L_B^{0.7}$ from Equation (7). Adopting known galaxy luminosity functions at $z < 1$ from Faber et al. (2007) and the scaling relation of Equation (7), we expect to find (following Equation 8 below) a number density of $n(z) \approx 0.8 (0.2)$ per line of sight for Mg II absorbers of $W_r(2796) > 0.3 (1.0)$ A. Our model therefore well reproduces the observed absorber statistics at $z < 1$ (e.g. Nestor et al. 2005; Prochter et al. 2006).

### 3 ANALYSIS

Using the mock galaxy and Mg II absorber catalogs, we proceed to examine the relation between $W_r(2796)$ and $L_{\text{[O II]}}$ of Mg II absorbers. For each Mg II absorber in the mock catalog, we know from our simulation the location and luminosity of the absorbing galaxy. We have also calculated according to the procedures described in Section 2.1 the fraction of galaxy light that would be recorded in the SDSS QSO fibers. We can therefore directly compare our simulation data with the observations of M11.

We present in Figure 4 the distribution of $W_r(2796)$ and $\sum L_{\text{[O II]}}$ of the mock Mg II absorber sample. The top panel shows the $W_r(2796) - \sum L_{\text{[O II]}}$ distribution of individual Mg II absorbers, including detections (dots) and non-
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Figure 3. The frequency distribution function of the mock Mg II absorber sample. As in Figure 1, the dotted, solid, and dashed histograms represent mock absorber samples from simulated galaxies of faint-end slopes of $\alpha = -1.2$, $-1.3$, and $-1.4$, respectively. For comparison, we also include the observed absorber frequency distribution function from Prochter et al. (2006) for Mg II absorbers found at $z = 0.4 - 2.3$.

Figure 4. The $W_{\text{MgII}}$ vs. $\sum L_{\text{[O II]}}$ distribution of the mock galaxy and absorber samples, in comparison to observations of M11. The dots in the top panel represent individual Mg II absorbers with detectable emission fluxes in the QSO spectra from their absorbing galaxies. Recall that these are calculated by dividing the expected [O II] line flux in the fiber with the corresponding physical area of the 3" fiber at the redshift of the absorber. The arrows at the bottom row indicate the presence of absorbing galaxies with $\sum L_{\text{[O II]}} = 0$ (non-detections), because their optical disks do not overlap with the fiber. For completeness, the bottom panel shows the fraction of Mg II absorbers that have $\sum L_{\text{[O II]}} = 0$. The (red) stars in the top panel represent the median values of $\sum L_{\text{[O II]}}$ for all Mg II absorbers (including detections and non-detections) in each $W_{\text{MgII}}$ bin with the 1-$\sigma$ dispersion indicated by the errorbars. The dash-dotted line shows the best-fit power-law model (Equation 1) of the observed $W_{\text{MgII}} - \langle \sum L_{\text{[O II]}} \rangle_{\text{med}}$ correlation from M11. The solid (blue) circles represent the mean $\sum L_{\text{[O II]}}$ averaged over all Mg II absorbers in each $W_{\text{MgII}}$ bin. Note that the stars fall below the locus defined by individual dots because of non-detections quantified in the top panel.

4 DISCUSSION AND SUMMARY

We have carried out a Monte Carlo study to investigate the effect of differential aperture loss of extended emission from intervening galaxies in SDSS fibers. We generate a mock galaxy sample based on known empirical relations that describe the luminosity and size distribution of the general galaxy population uncovered in deep surveys. The mock galaxy sample is accompanied by a mock Mg II absorber detections (indicated by the arrows). The bottom panel shows the fraction of Mg II absorbers for which the absorbing galaxies are not expected to overlap the fiber and therefore have $\sum L_{\text{[O II]}} = 0$ in the QSO spectra. It is clear that a growing fraction of galaxy light is missed in the QSO spectra for absorbers of decreasing strength due to the $W_{\text{r}}(2796)$ vs. $\rho$ anti-correlation (e.g. Chen et al. 2010).

To reproduce the observations in SDSS QSO spectra, we divide the mock catalog of 23,000 Mg II absorbers into subsamples according to their absorption strengths. Following the procedure described in M11, who formed a median QSO spectrum at the rest-frame of the Mg II absorbers and measured the associated [O II] emission line flux, we compute the median value of [O II] luminosity surface density $\langle \sum L_{\text{[O II]}} \rangle_{\text{med}}$ for all Mg II absorbers in each $W_{\text{r}}(2796)$ bin, including those with $\sum L_{\text{[O II]}} = 0$. To estimate the scatter, we repeat the Monte Carlo simulation 100 times to generate 100 mock samples of galaxies and Mg II absorbers. We measure the 1-$\sigma$ dispersion in $\langle \sum L_{\text{[O II]}} \rangle_{\text{med}}$ among the 100 mock samples. The stars and the associated errorbars in Figure 4 represent the computed $\langle \sum L_{\text{[O II]}} \rangle_{\text{med}}$ and the associated dispersion in each $W_{\text{MgII}}$ bin.

For comparison, the best-fit power-law model of the observed $W_{\text{MgII}}(2796) - \langle \sum L_{\text{[O II]}} \rangle_{\text{med}}$ correlation (Equation 1) from M11 is included in Figure 4 as the dash-dotted line. The M11 model is found to match well with the simulated data. However, both fall below the locus defined by individual dots because of non-detections quantified in the bottom panel. We also calculate the mean [O II] flux $\sum L_{\text{[O II]}}$ expected in the stacked SDSS QSO spectra, averaged over all Mg II absorbers in each bin including non-detections. The results are shown in solid circles in Figure 4.
sample that is generated based on a simple assumption that extended gaseous halos are a common and generic feature of distant galaxies and the gaseous extent scales proportionally with galaxy mass. For each absorber in the mock sample, the luminosity and projected distance of the absorbing galaxy are known, allowing us to make predictions for the observed relation between $W_r(2796)$ and the associated $L_{[\text{OII}]}$, in SDSS QSO spectra.

Our study shows that combining the known $W_r(2796)$ vs. $\rho$ anti-correlation of MgII–galaxy pairs (e.g., Chen et al. 2010a) and differential fiber selection of MgII absorbing galaxies (Figure 1) reproduces the observed $W_r(2796)$ vs. $L_{[\text{OII}]}$ correlation in the SDSS QSO spectra without additional fine-tuning or scaling. The results of our study indicate that the observed $W_r(2796)$ vs. $L_{[\text{OII}]}$ correlation of MgII absorbers in SDSS data is likely due to a differential fiber selection bias and does not provide a physical understanding of the origin of the MgII absorber population.

On the basis of the observed $W_r(2796)$ vs. $L_{[\text{OII}]}$ correlation, M11 further attempted to draw connections between the number density evolution of MgII absorbers $n(z)$ and the cosmic star formation history of the universe as characterized by the comoving [O II] luminosity density $\ell$. Given a good agreement between $n(z)$ and $\ell$, the authors argue that outflows are the mechanism responsible for MgII absorption.

The Monte Carlo simulation presented in Section 2 also allows us to address the agreements in these measurements under a simple, generic halo model. It is clear from Figures 3 & 4 that both the frequency distribution function of MgII absorbers and the galaxy [O II] luminosity function are well reproduced in our mock galaxy and absorber samples with no preference in starburst systems. Although under the simple halo model MgII absorbers do not directly probe star-forming disks like high column density damped Lyα absorbers (e.g., Wild et al. 2007), they trace the halo gas of distant galaxies. If more massive galaxies are surrounded by more extended MgII absorbing gas (Equation 7), then $n(z)$ is calculated according to

$$n(z) = \frac{c}{\Omega_0} \frac{(1+z)^2}{\Omega_M(1+z)^3 + \Omega_A} \int dL \Phi(L, z) \epsilon_{\text{gas}} L_{[\text{OII}]}$$

where $c$ is the speed of light, $\Phi(L_B, z)$ is the galaxy luminosity function, $\epsilon_{\text{gas}}$ is the incidence of extended gas that is the product of halo gas covering fraction and the fraction of galaxies with extended gaseous halos, and $\sigma_{\text{gas}}(L)$ is the cross section of the gaseous halo. As mentioned in § 2.2, the mean covering fraction of MgII absorbing gas is found to be high, roughly 100% for absorbers of $W_r(2796) \geq 0.3$ Å at $\rho \lesssim 0.4 R_{\text{gas}}$ (Chen et al. 2010a). Such high covering fraction is consistent with the analysis presented in Kacprzak et al. (2008) for a scaling index of $\beta = 0.35$.

Combining Equations (4) and (7) yields

$$\sigma_{\text{gas}}(L) = \frac{\epsilon_{\text{gas}} (\pi R_{\text{gas}}^2)^*}{L_{[\text{OII}]}^*} L_{[\text{OII}]}^0 \approx \frac{\epsilon_{\text{gas}} (\pi R_{\text{gas}}^2)^*}{\Omega_{\text{gas}}} L_{[\text{OII}]}^*$$

Substituting Equation (9) into Equation (8) leads to

$$n(z) \approx \frac{\epsilon_{\text{gas}} (\pi R_{\text{gas}}^2)^*}{\Omega_{\text{gas}}} \int dL \Phi(L, z)$$

where $\epsilon(z)$ is defined so that $1/\epsilon(z) = (c/H_0)(1+z)^2/\sqrt{10^9 (1+z)^3 + \Omega_{\Lambda}}$. The same redshift dependent factor is defined in Equation (7) of M11. Equation (10) shows that the number density evolution of absorbers naturally follows the comoving [O II] luminosity density, $\ell_{[\text{OII}]}(z)$, if extended gaseous halos are a common and generic feature of field galaxies. One can therefore apply $n(z)$ for constraining the cosmic star formation history, or apply known co-moving luminosity density for constraining the fraction of absorbers originating in galactic halos (Chen et al. 2000).

In practice, as illustrated in M11 the SDSS 3″ fibers define a survey volume of [O II] emitting galaxies. The comoving [O II] luminosity density, $\ell_{[\text{OII}]}(z)$, can be estimated according to

$$\ell_{[\text{OII}]}(z) = \frac{\Delta L_{[\text{OII}]}^*}{\Delta V_c}$$

$$= \frac{\Delta z}{(1+z)^2 \Delta r} A(z) d\Omega (\Delta r)$$

$$= \epsilon(z) \sum_{L_{[\text{OII}]}} n(z),$$

where $\Delta L_{[\text{OII}]}^*$ is the total [O II] luminosity observed in a coadded QSO spectrum, $\Delta N$ is the total number of MgII absorbers over the survey redshift pathlength $\Delta z$, and $L_{[\text{OII}]}^*$ is the mean [O II] luminosity averaged over the entire galaxy (absorber) population. It is clear that Equation (11) resembles Equation (10) and that $\ell_{[\text{OII}]}(z)$ can be estimated based on the product of $n(z)$ and the mean [O II] luminosity surface density averaged over all MgII absorbers.

We present in Figure 4 the mean [O II] luminosity surface density $\sum L_{[\text{OII}]}$ measured in the 3″ SDSS fibers and averaged over the number MgII absorbers in each $W_r(2796)$ bin (solid circles). The mean values can be characterized by

$$\sum L_{[\text{OII}]} = a_{\gamma''} \left[ \frac{W_r(2796)}{1 \text{Å}} \right]^{b_{\gamma''}}$$

where $a_{\gamma''} = 6.6 \times 10^{37}$ erg s$^{-1}$ kpc$^2$ and $b_{\gamma''} = 1.1$ (solid line in Figure 4). This correlation applies to a 3″ survey cylinder at $z = 0.4 - 1.4$. Note that because of the extreme bimodal distribution of $\sum L_{[\text{OII}]}$ in which a large fraction of absorbers have $\sum L_{[\text{OII}]} = 0$, the median value $\langle \sum L_{[\text{OII}] \text{med}} \rangle$ is expected to be significantly smaller than the mean $\sum L_{[\text{OII}]}$.

While Equation (11) provides a useful tool for estimating the co-moving star formation rate density $\dot{\rho}_*$. The observations of MgII absorbers in SDSS QSO spectra (as shown cleverly in M11), we note that the observed strong $W_r(2796)$ vs. $L_{[\text{OII}]}$ correlation in SDSS data is shaped primarily by a differential fiber loss of the observed [O II] flux and therefore unphysical. To illustrate the fiber selection bias in driving the apparent correlation in Figure 4, we repeat the Monte Carlo analysis described in § 2 for 15″ diameter fibers. This is five times the aperture size of SDSS spectra. At $z \approx 1$, such a large aperture covers an area of roughly 40 h$^{-1}$ kpc projected radius from QSO lines of sight, sufficient to cover the majority of the light from galaxies pro-
producing strong Mg II absorbers ($W_r(2796) \gtrsim 1$ Å). Figure 5 shows the distribution of $W_r(2796)$ and $\sum L_{[O II]}$ measured over $15^\prime\prime$ diameter fibers for the mock Mg II absorber sample. The mean [O II] flux $\sum L_{[O II]}$ share a similar slope as the median [O II] flux $\langle \sum L_{[O II]} \rangle_{\text{med}}$ within the $15^\prime\prime$ diameter aperture and the slope is consistent with $b_{15^\prime\prime} = 0$ (solid line in Figure 5).

In summary, we have demonstrated that (1) because of the observed $W_r(2796)$ vs. $\rho$ anti-correlation (e.g. Chen et al. 2010a), galaxies at larger projected distances produce on average weaker MgII absorbers and weaker (or zero) $L_{[O II]}$ in SDSS QSO spectra and that (2) because of the extreme bimodal distribution of $\sum L_{[O II]}$ in which a large fraction of absorbers have $\sum L_{[O II]} = 0$, the median value $\langle \sum L_{[O II]} \rangle_{\text{med}}$ can be significantly smaller than the mean $\sum L_{[O II]}$. Together these effects strengthen the apparent $W_r(2796) - \langle \sum L_{[O II]} \rangle_{\text{med}}$ correlation of M11.

Consequently, empirical correlations between star-forming properties of galaxies and statistical properties of QSO absorbers do not provide the unambiguous evidence necessary to discriminate between infalling clouds and outflows as the mechanism for producing Mg II absorbing clouds at $\rho > 50$ kpc of a galaxy. While outflows are a natural product of starbursts, gas accretion provides the fuels for star formation in galaxies. As discussed by previous authors, mass is likely a more fundamental factor that determines the properties of gaseous halos around galaxies (e.g. Steidel et al. 1994; Ledoux et al. 2006; Chen et al. 2010b) and more massive galaxies can support more extended gaseous halos. Given that models that do not require outflows can also reproduce the empirical correlations between absorber and star formation properties, we caution drawing conclusions in favor of outflows based on simple correlations between absorber and star formation properties.

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